Adaptive Benefit-Cost Analysis for Changing a Few of Many Causes

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Two motivating examples

• Example 1: Given data on air pollution concentrations, mortality rates, and costs of pollution control, what control measures should each location implement to maximize net societal benefits?
  – Multiple cities, counties, states, countries care
  – Emissions from A may affect air quality for B
  – Many other causes of mortality (income, education, etc.)

• Example 2: Given data on animal antibiotic use and rates of resistant and non-resistant food poisoning, what policies for animal antibiotic use should each location adopt?
  – How and when should policies be adjusted in light of experience?
  – Many causes of food poisoning (cooking, restaurants, etc.)
BCA principle under uncertainty

• BCA principle: Choose among available decision alternatives or policies to maximize net benefit.
  – Constrained to protect rights
  – Equality-efficiency trade-offs

• BCA under risk (decisions with known consequence probabilities): Maximize expected net benefit (or expected social utility)
  – Harsanyi social utility function is a sum of individual utility functions
Choice under uncertainty (probabilities unknown or uncertain)

• Which is preferable, A or B?
  – All we know is uncertainty intervals for (expected) net benefits of each

• Dominance can help
  – A dominates B
  – A stochastically dominates B if both are uniform distributions

• But what if future information will reduce uncertainties?
  – Optimal waiting
Some possible sources of conflict

• Different preferences for outcomes
• Different beliefs about outcome probabilities
• Different risk tolerances (willingness to gamble)
• Different discount factors and time trade-offs
• Different propensities to wait for better information
• Different attitudes toward future (potential) generations
For one decision-maker, stochastic dynamic programming optimizes choice

- Utilities for outcomes
- Different beliefs about outcome probabilities, given actions
- Different risk tolerances (willingness to gamble)
- Different discount factors and time trade-offs
- Different propensities to wait for better information
- Different attitudes toward future (potential) generations
Two principles for optimal single-person choice under uncertainty

• Maximize expected utility (risk-adjusted net benefit) → Choose A
  – CE(X) = E(X) – (k/2)Var(X)
    • CE(X) = certainty equivalent (selling price) for random variable X
    • k = relative risk aversion in
      u(x) = 1 – exp(-kx)
    • X ~ normal

• Optimism under uncertainty → Choose B
  – UCB1 algorithm: Take action with maximum
    \[ \overline{x}_j + \sqrt{2 \log t / n_j} \]
    • Upper confidence band (UCB) on average reward
    • t = number of trials
    • n_j = number of times action j taken

Two optimization principles for two different decision contexts

• Maximize expected utility → Choose A
  – Applies to **one-shot** choice from a static choice set, \{A, B\}
  – “Pick the option with greatest expected net benefit”

• Optimism under uncertainty → Choose B
  – Applies to **adaptive** trials, learning and decision-making
  – Helps pursue moving targets (“restless bandits”)

• **Q1**: Which better describes real regulatory and policy decisions – one-shot, or adaptive?

• **Q2**: To what extent can we reformulate “Choose expected best policy” problems as “Learn best policy” opportunities?

-------------- A
-------------- B
Machine learning offers key insights into how best to learn from experience

• “Reinforcement learning improves behaviour from evaluative feedback” (Littman, 2015, *Nature*)

• Multi-agent reinforcement learning (MARL) algorithms provide practical ways to collectively optimize exploration-exploitation trade-offs in simple uncertain and changing environments using limited resources

www.nature.com/nature/journal/v521/n7553/full/nature14540.html
In adaptive learning, coordination among team members speeds optimization

- Each agent on the multi-agent team has local actions, observations, and rewards
  - E.g., agent = regional or state regulator
  - reward = lives saved by effective policies or regulations

- Agents sampling the performance of different policies for the same environment can greatly speed learning of optimal policies by sharing information when the value-of-information (VOI) warrants it
  ([www.cse.wustl.edu/~bjuba/papers/CoordVsDec_NIPSWorkshop.pdf](http://www.cse.wustl.edu/~bjuba/papers/CoordVsDec_NIPSWorkshop.pdf))

- Even if different policies return different reward to different agents (e.g., because local environments differ), communication and coordination can still improve team performance
Spatially distributed and decentralized adaptive learning can be effective

- **Distributed control context:**
  - Each agent chooses local actions, but...
  - One agent’s choices may affect another’s local rewards, and...
  - Each agent seeks to maximize sum of rewards (so, team instead of adversaries).
  - Local rewards for actions may drift over time

- **Decentralized decision-making (via Bayesian local control based on dynamic Thompson sampling) quickly approximates centralized optimal decisions** ([http://drum.lib.umd.edu/handle/1903/12540](http://drum.lib.umd.edu/handle/1903/12540))
Applying MARL ideas to regulation: Air pollution, animal antibiotics, etc.

• If the same uncertain causal concentration-response (C-R) function holds everywhere, then sharing data and experiences with different policies across different locations and populations speeds learning/optimization
  – Bottom-up and distributed risk management maximizes learning and solution quality in many problem settings

• Conversely, implementing the same policy everywhere at once minimizes opportunities for adaptive learning and policy optimization, even if it maximizes currently estimated net benefits given current information
  – Failing to learn across multiple locations delays benefits

• If a policy has different effects in different areas, sharing data and results speeds collective learning.
  – “Contextual bandits”
Key caveat: Causal analysis must be done right to learn effectively

• No associational causality
  – Relative risks, burden-of-disease, population attributable fraction, probability of causation, etc.

• No counterfactual causality using unverified causal models and hypotheses

• *Manipulative causality* is what policy-makers need to make informed decisions
  – If we change X, how will Y be changed?

• Predictive causality is a useful objective screen for potential manipulative causality
  – Can be determined from data via information-theoretic algorithms
Example: Intervention study

Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study


Summary

Background Particulate air pollution episodes have been associated with increased daily death. However, there is little direct evidence that diminished particulate air pollution concentrations would lead to reductions in death rates. We assessed the effect of air pollution controls—i.e., the ban on coal sales—on particulate air pollution and death rates in Dublin.

Methods Concentrations of air pollution and directly-standardised non-trauma, respiratory, and cardiovascular death rates were compared for 72 months before and after the ban on coal sales in Dublin. The effect of the ban on age-standardised death rates was estimated with an interrupted time-series analysis, adjusting for weather, respiratory epidemics, and death rates in the rest of Ireland.

Findings Average black smoke concentrations in Dublin declined by 35.6 μg/m³ (70%) after the ban on coal sales. Adjusted non-trauma death rates decreased by 5.7% (95% CI 4–7, p<0.0001), respiratory deaths by 15.5% (12–19, p<0.0001), and cardiovascular deaths by 10.3% (8–13, p<0.0001). Respiratory and cardiovascular standardised death rates fell coincident with the ban on coal sales. About 116 fewer respiratory deaths and 243 fewer cardiovascular deaths were seen per year in Dublin after the ban.

Interpretation Reductions in respiratory and cardiovascular death rates in Dublin suggest that control of particulate air pollution could substantially diminish daily death. The net benefit of the reduced death rate was greater than predicted from results of previous time-series studies.

Introduction

Results of many epidemiological studies have suggested an association between particulate air pollution and daily deaths. Despite these findings, it does not follow that a reduction in particulate air pollution would diminish daily deaths or increase life-expectancy. Great improvements in air quality in Dublin after the introduction of domestic coal-burning regulations offered an opportunity to assess the effects of reduced particulate air pollution on death rates in the general population.

Dublin’s air quality deteriorated in the 1980s after a switch from oil to cheaper and more readily available solid fuels, mainly bituminous coal for domestic space and water heating. Periods of high air pollution were associated with increased in-hospital respiratory deaths.

On Sept 1, 1990, the Irish Government banned the marketing, sale, and distribution of bituminous coals within the city of Dublin. The effect of this intervention was an immediate and permanent reduction in average monthly particulate concentrations. We assessed the effect of the ban of coal on death in Dublin.

Methods

Procedures

We compared air pollution, weather, and deaths for 72 months before (Sept 1, 1984, to Aug 31, 1990) and after (Sept 1, 1990, to Aug 31, 1996) the ban, by seasons. We defined spring as March–May, summer as June–August, autumn as September–November, and winter as December–February. We calculated mean daily air pollution (black smoke and sulphur dioxide) concentrations with measurements from six residential monitoring stations in the city of Dublin (Dublin County Borough). We obtained mean daily temperatures (°C) and mean daily relative humidity (%) from Dublin airport. We calculated the change in mean air pollution and weather variables between the pre- and post-ban periods.
Example: Intervention study

Effect of air-pollution control on death rates in Dublin, Ireland: an intervention study

In conclusion, the ban on coal sales within Dublin County Borough led to a substantial decrease in concentration of black smoke particulate air pollution. After adjustment for age-distribution of the population, known predictors of death (including temperature, humidity, and respiratory epidemics), and death rates in the rest of Ireland as an index of unmeasured secular changes in deaths, we estimated that there were about 243 fewer cardiovascular deaths and 116 fewer respiratory deaths per year in Dublin after the ban on coal sales. These changes were seen immediately in the winter after introduction of the ban. Our findings suggest that control of particulate air pollution in Dublin led to an immediate reduction in cardiovascular and respiratory deaths. These data lend support to a relation between cause and the reported increase in acute mortality associated with daily particulate air pollution. Moreover, our data suggest time-series studies could be underestimating the benefits of particulate air pollution controls.
Example: Intervention study

Figure 1: Seasonal mean black smoke (upper) and sulphur dioxide (lower) concentrations, September 1984–96
Vertical line shows date sale of coal was banned in Dublin County Borough. Black circles represent winter data.
Example: Intervention study

“Adjusted non-trauma death rates decreased by 5.7% (95% CI 4-7, p < 0.0001)”
Example: Intervention study

“No significant reduction was found in total death rates” (Dockery et al., 2013)
Did the ban stop progress?

- Informal causal conclusions are just subjective opinions, with no known validity.
- Since 1960s, the quasi-experimental “O X O” one-group pretest post-test design has been cited as an example of a design that is not valid for causal inference (Campbell and Stanley, 1963, p. 7)
- What’s missing: Learning by using information from control groups outside the ban area
The big ban on bituminous coal sales revisited: serious epidemics and pronounced trends feign excess mortality previously attributed to heavy black-smoke exposure.
Wittmaack K. SF-National Research Centre for Environment and Health, Institute of Radiation Protection, Neuherberg, Germany.

Abstract
The effect of banning bituminous coal sales on the black-smoke concentration and the mortality rates in Dublin, Ireland, has been analyzed recently. Based on the application of standard epidemiological procedures, the authors concluded that, as a result of the ban, the total nontrauma death rate was reduced strongly (−8.0% unadjusted, -5.7% adjusted). The purpose of this study was to reanalyze the original data with the aim of clarifying the three most important aspects of the study, (a) the effect of epidemics, (b) the trends in mortality rates due to advances in public health care, and (c) the correlation between mortality rates and black-smoke concentrations. Particular attention has been devoted to a detailed evaluation of the time dependence of mortality rates, stratified by season. Death rates were found to be strongly enhanced during three severe pre-ban winter-spring epidemics. The cardiovascular mortality rates exhibited a continuous decrease over the whole study period, in general accordance with trends in the rest of Ireland. These two effects can fully account for the previously identified apparent correlation between reduced mortality and the very pronounced ban-related lowering of the black-smoke concentration. The third important finding was that in nonepidemic pre-ban seasons even large changes in the concentration of black smoke had no detectable effect on mortality rates.
Claimed health benefits vanish when control group information is used

Effect of air pollution control on mortality and hospital admissions in Ireland.

Abstract
During the 1980s the Republic of Ireland experienced repeated severe pollution episodes. Domestic coal burning was a major source of this pollution. In 1990 the Irish government introduced a ban on the marketing, sale, and distribution of coal in Dublin. The ban was extended to Cork in 1995 and to 10 other communities in 1998 and 2000. ... In comparisons with the pre-ban periods, no significant reduction was found in total death rates associated with the 1990 (1% reduction), 1995 (4% reduction), or 1998 (0% reduction) bans, nor for cardiovascular mortality (0%, 4%, and 1% reductions for the 1990, 1995, and 1998 bans, respectively). The successive coal bans resulted in immediate and sustained decreases in particulate concentrations ... but no detectable improvement in cardiovascular mortality.
Too late to change perceptions and policy

• “We intend to extend the health and environmental benefits of the ban on smoky coal, currently in place in our cities and large towns, to the entire country. ...

• Benefits of a smoky coal ban include very significant reductions in respiratory problems and indeed mortalities from the effects of burning smoky coal. The original ban in Dublin has been cited widely as a successful policy intervention and has become something of an icon of best practice within the international clean air community. ...

• Research indicated that the ban in Dublin resulted in over 350 fewer annual deaths. An estimate of these benefits in monetary terms put the value at over 20m euro.”

Lesson and conclusions

1. Shifting risk management from “Maximize expected net benefit” to “Learn to maximize true net benefits while minimizing regret” can reverse risk management priorities and recommendations.

2. Maximizing collective net benefits via adaptive team learning requires sharing relevant data, program evaluation results, and learned decision rules.

3. Adaptive learning is much more beneficial than uniform top-down regulation if true causal relationships and policy effects are uncertain
   - Uncertainties arise from variations in and ignorance of other causes, environment, controlled system, etc.

4. To avoid learning ineffective policies, must use valid methods of causal analysis and inference.