

Combining survey and administrative data using state space models

Stephen Horn¹, Ray Czaplewski²

¹Australian Government Department of Families, Housing, Community Services and Indigenous Affairs, e-mail: stephen.horn@fahcsia.gov.au

²US Forest Service, Rocky Mountain Research Station, IWFIA, e-mail: rlczaplewski02@fs.fed.us

Abstract

Even as access to transactional data has been transformed by harnessing electronic flows, use of satellite imagery, research access to linked customer level records, and harmonising collections across jurisdictions, official statisticians are under pressure to detect significant turning points within response times and resolutions that cannot be handled by present estimation methods.

State space models can be used to combine sources of data efficiently while respecting quality demands in advising government decision making. Specifically we phrase the measure problem as how to combine high quality, high cost, unit level information obtained from a sparse sample with ‘short’ granular population views in an optimal manner with calculable error structure. We indicate the potential of recursive predictive methods to deliver satisfactory estimates from repeated surveys, and from systems for monitoring public forest cover and for welfare payment assurance.

Keywords: Kalman filters, measurement error, restriction estimators

1. Introduction

The task of an official statistician is changing. Building purpose-constructed collection frameworks backed by high profile censuses no longer drives work programs. This established order is being overshadowed by the search for authoritative inferential methods when augmenting expensive, carefully designed and executed, collections using administrative registers of reasonable quality, and cheap byproduct transactional data (‘big’ data) captured in the course of government, social or commercial business, with little or no discernible design¹.

National surveys, grounded in sampling theory were developed through the 1930s and 1940s, operationalized from the 1950s and elaborated and qualified thereafter. They have come to be relied on as the principal source of official series even as production constraints and contested demands on them from a many faceted user community

¹ Encapsulated in remarks by then Director of the US Census Bureau Groves (2011) in a blog post

exposed their limitations. In consequence surveys are being reconceptualised as only one of several equipotent sources of data².

Broadening the collection base, preserving quality and improving responsiveness are to be achieved within a standing budget constraint. In consequence methods interest has moved from the absolute question: how to design a collection that can guide policy positions, to how to manoeuvre ill-fitting operations to meet emergent policy challenges.

Adapting the production of statistics in familiar standardised formats within an increasingly strange external environment focussed attention from the 1990s, and excited methods activity in at least four directions: a renewed effort to harmonise concepts and methods; a drive to bring models into estimation systems within deteriorating conditions for survey collection (cost and response); application of statistical discipline to database strategies as use of large data stores in a public decision environment was grasped; subjecting the activity of official statistical production to strictures of quality assurance. This flowering is manifest in international conferences, themed city meetings; and regional practitioner workshops initiated during the period in question.

Official statistics is evolving from a compendium of material collected under privilege and in a controlled statutory environment to be released at regular intervals as a quality guaranteed product, to an information system capturing transactions at far finer levels than previously envisaged in collection frameworks, the volumes far larger, more inchoate and more immediate than in established databases, and coverage not respecting state but rather natural boundaries of the activity in question. The policy demand on official numbers too has changed, partly responding to opening of government to more players, partly the multi-layering and regionalisation of policy beyond state confines, and partly because of the compounding of public administration through external impacts, and through general equilibrium consequences of individual or social acts (such as global impacts of unregulated commercial activity in one market or by one firm). It is now not sufficient or appropriate to assume a static economic model for human or firm behaviour when that behaviour can be tracked in granular detail through time.

Not only does this opening reflect shifting concepts of social structure, geography or jurisdiction. Deficiencies in accepted frameworks of inference have become apparent: instrument integrity can no longer exclude the rich conditionality that exists between individual measures and a social or economic support. Panel surveys have been used both for convenience and cost, and to capture life course statistics (whether dealing with people or firms) and have as such been staple fare in the margin of official statistics. Because of the absence of accepted rules for stochastic inference over time their rich covariance structure has been overlooked in justifying estimates within the official record. Likewise monitoring the national estate has entailed complex survey designs along with mapping methods, but is now being pushed to capture focal damage and incident effects beyond the reach of either ground or aerial surveys or remote sensing

² Although this shift is uneven. As Wallgren and Wallgren (2011) point out, administrative data plays a more central role in the conceptualisation of official statistics in the Nordic countries who historically have had access to multiple registers for compiling statistics.

systems on their own. Risk assurance in transfer payment accounting requires selected full entitlement reviews and access to administrative records – once again inference can be built by recursive incorporation of system information and expert observation.

2. How does this translate to methods?

We can summarise the methods challenge:

- How to infer across a continuous decision support where linear interpolation is no longer credible
- How to build series where what is of interest is not directly measurable using available instruments
- How to build an affordable and responsive information service that matches the dynamics of policy at a variety of levels of conception (topic, geography, legal statute, sociology, system of production)
- How to justify release of hybrid statistical information, equivalently how to assure credibility to published material – whether in summary (aggregated) form or in unit form or as a source for different avenues of release
- How to assign weight to different sources of correlated information – ranging from purposeful statistical design to ‘big data’ transaction capture.

It might equally be expressed as ‘build algorithms to...’ using the conceit of Beulens and colleagues (2012). We interpret an algorithm as a method for extending stochastic design in time and space using resampling, Bayes theorem and nonparametric optimisation, or equally problem reduction using models and iterated numerical means.

The inspiration for tackling this problem in its full generality has come from results in Knottnerus (2003) specifically Chapter 12, building on the concept of model assistance expounded in Saerndal, et al (1992). Knottnerus demonstrates that generalised regression estimators are special cases of a new class of Restriction Estimator (RE) and its recursive extension (RRE). His figure 12.2 (p347) represents the key result. Knottnerus (2003) throughout emphasises the familial connection between Gaussian and Bayesian statistics, and systems theory and numerical analysis. It is the remarkable convergence in these results which gives credibility to the program as articulated in Beulens et al (2012)

The RRE offers a solution to the problem of optimal prediction of an unobservable but estimable quantity in a granular environment generated by a continuous background process where there is a reasonable postulate of correlation between the manifold evolution and that of the probe (Czaplewski, 2010b).

On the one hand this formulation lends itself, as sketched below, to spatial analysis or process control; on the other it offers to transform the utility of surveys and administrative series to deliver decision support for a wide class of policy questions, typically the subject of surveys, but leveraging the ubiquity of statistically commensurable by-product data, and parametral restrictions generated by prior knowledge and design.

The elements of this method are a panel or repeated survey (the probe) using a probability design that is time dependent (allowing the sample and the design to change in time); an independent source of auxiliary data defining a low dimensional high accuracy support for the probe; a priori correlation between key indicator variables and process-driven (administrative, geographic, demographic, fiscal) rules; and frames for sampling and estimating surveyed quantities. The manner in which successive realisations of the probe and support system are composited will optimise final estimate efficiencies. The results apply equally to time series smoothing and to static calibration.

This would appear to be ignoring the compounding of errors encountered in the drive toward data integration. Bakker (2011) asks in the absence of an overarching theory whether integrating source information at unit level can constitute a method at all. As remedy Zhang (2012) offers a “2-phase life-cycle model of integrated statistical microdata” (p43 fig1), locating error in the different production processes and using an audit sample derived, “..probabilistic measure of individual discrepancy”. Zhang takes the total survey error construction as it applies to the field effects of probability sampling in the public domain (see Groves et al 2004), and applies it to error propagated by an administrative source and beyond that to error integrally across a variety of sources. For this the RE seems well adapted. Thus Zhang (p51) refers to relevance error, an analogue of system innovation, and later (p53) to “misclassification errors generating noise at the moment of production, which must be distinguished from the [signal]”. Czaplewski (2010b) has demonstrated advantage of RRE techniques in dual spatial survey-census data subject to misclassification. Interpreting ‘empirical equivalence’ (Zhang 2012 p56) as a step in recursive restriction estimation effectively repositions the microdata problem within the new sample survey theory expounded by Knottnerus.

3. Formalism

We wish to infer qualities of a population of statistical units evolving in time and within a given domain topology, that is a way of defining scope with rules for decomposition into subdomains. While the topology is fixed, the boundary may evolve. The domain topology would support both administrative regions and sampling frameworks. Observations of the population come from a high dimensional unit probe repeated at fixed (or floating) intervals, and represented in the spatial domain by a time delimited probability sample. The probe collects signals of time and space continuous processes that affect the state of units of the population for the purpose of estimating the evolution of a population key decision indicator (in time).

To support the probe, a second data source collects low dimension frequently repeated measures of the population, or some activity of the population, but giving status insight through correlation with the probe variables. The probe and its support are linked by a model in the form of a contingency table that relates probability inference laws applying to the probe to auxiliary information, itself subject to measurement error. In a first estimation phase this model is used in the sample design for the probe – optimal

clustering, stratification and allocation of sample to strata. A second phase builds strength to the sample estimates in adjustment to counter frame and field defects, and calibration.

In a third phase the back history in model assisted estimation and the (quasi) continuous back history in the support are recursively combined to optimise characteristics of an estimator for extending inference to the entire support and projecting inference forward in time, alternatively at one point in time, recursively incorporating measure constraints. This step is carried out by use of a mathematical filter that mitigates high variability in the probe estimates at subdomain levels, and bias predictions from the support series to the target indicators in a systematic and in certain conditions optimal way.

This method is well suited to dynamic graphical representation, and to advanced methods of estimate validation. Its generality makes it a candidate for a wide class of signal extraction applications common to official statistics. It addresses specifically the limitations imposed by rising cost to maintain survey quality, and the emerging availability of low cost universal transaction data alluded to in the introduction.

It operates for production of indicators, and internally for error estimation, representing data quality in terms of signal extraction and measure error filtering. Effectively it remains a design based method, but assisted by time series models supporting recursion (state space modelling in discrete time); and models for association (mapping) between a design-based estimation procedure and administratively generated auxiliary information on the population (generalised regression). This approach conforms to and partly generalises the steps Zhang (2012) proposes to conceptualise and measure the statistical properties of integrated official data. It remains to build and demonstrate it in realistic settings. We sketch three cases where a solution on these lines is suggestive.

4. Applying Restriction Estimation

4.1 Panel and Repeated Surveys

Consider a complex survey design to collect population information on one or more occasions from one or several samples of clustered units located in time (one or several waves) and space (stratified interpenetrating or overlapping clusters). The information is needed to support policy decisions concerning a topic of public interest. Represent this requirement as an ordered set of statistical indicators and attached reliance measures.

Reliance measures are derived from an analysis of residuals to a generalised regression model of target variables against auxiliary information at the probe points,

The estimation apparatus incorporated in the survey design provides an initial value at points corresponding to the survey reference and those subdomains for which reliable survey estimates can be obtained. It is desired to predict the values that target indicator set takes within a continuous support – typically forward to the present (it is unusual for probe reference points to coincide with reporting times) and beyond to a predictive near

future, and to subdomains appropriate to the policy situation (planning regions; basins of contagion etc.) with optimal variance/ bias properties attached to the predictor.

The probe is supported by an address register that gives accurate counts of a particular target domain (low income households) by household structure and residential location, updated fortnightly; together with some demographic and economic information. The correlation between target and auxiliaries is affected by sample error in the probe. The latter is bounded by the areal support allowed by the survey. It is used to wrap these correlations into the sample design (construction of frame, stratification, allocation of sample to strata) and estimation procedures and establish benchmarks. This leaves out the error implied in the selection/ availability of support (coverage bias, lags, other response and scope limitations, cost).

A Bayesian recursion procedure produces a prediction model that extends beyond the point in time probe estimators, with formal properties. The system is refreshed historically, so that predictions from the model can be refined through each iteration of the probe. This recurrence predictor

- a) Builds strength from previous probes and continuous support evolution
- b) draws attention to covariate models allowing for application in optimal designs and improved fixed point estimates
- c) allows dynamic predictions in space (subject to the domain topology defining the state vector

while remaining within a formal design framework, with a straightforward theoretical exposition. The quality of estimates is conditioned by the availability and quality of the support, and the predictive capacity of the filter³, and will be reflected in the credibility properties of the indicators.

Where the support assistance is concentrated at a point in time and has low power in modelling performance (diffuse case) the restriction predictor reduces to the survey estimate with its limited inference capability. Where support variables span the dynamic predictive space, the predictors assume (continuous) properties of the support itself. Between these extremes the predictor optimally combines the information from the probe and the support, improving on both as information sources

4.2 Payment Process Control

The probe is a repeated stratified random sample survey of customers with annual refreshment of sample design, trimesterly field issue and data return and quarterly public release. Model assistance (generalised regression) is used for published estimates. Calibration is against marginal totals (outlays and average customer numbers) that are derived from the accounting system on a fortnight by fortnight basis. The series is supported by an administrative database of social security transactions, assembling

³ Measured by the covariance matrix relating auxiliary and target variables -

customer characteristics typically required for determining eligibility for payment. The database is used in designing and drawing the sample, and to link probe information to payment history (forwards and backwards).

The performance indicator around which the series is built is mispayment rate (the consolidated discrepancy between what is paid and pay entitlement, represented as proportion of total outlay for performance monitoring and assurance purposes). This rate requires an elaborate (and expensive) survey apparatus to be accurately and consistently determined. The high cost of approaching individual customers and the low incidence of mispayment motivate optimally compositing survey and administrative information. Furthermore representing the target measure as a filtered time series makes the recasting of the problem from one of audit to one of statistical process control natural, and accessible to service managers, and policy analysts.

This apparatus incidentally allows a broader application to the health of the payments system as a whole – measuring performance against generally accepted social security objectives through using household structural information picked up in the probe – but not collected administratively - to extend the capacity of administrative data resource. This use suggests application to ad hoc customer surveys with more general topic coverage; and adds to the case of regular monitors of the customer population to evaluate attitudes, circumstances and capacities on and off payments. See (Horn 2008).

4.3 Forest Resource Estimation

The probe is a simple systematic sample of permanent PSUs on a 5-km grid that covers the entire USA, 120000 of which reside in forests. Forest and tree-level field measurements are made for a 10-percent non-overlapping interpenetrating subsample each year. Each panel supports a design-unbiased estimator for indicators of forest condition and extent, with independent sampling errors among panels. The PSUs within each panel are re-measured once every ten years such that decadal changes for each PSU are known. This permits design-unbiased estimates of decadal change from each panel.

In addition, remotely sensed imagery from space-borne satellites is available each year. These include pixel-level measurements of reflected multispectral light. The synoptic coverage is well suited for detection of changes in land use and catastrophic disturbances (e.g., large wildfires). While relatively rare at an annual time-scale and across extensive landscapes, these changes can be significant in aggregate, scantily represented in a sparse systematic sampling frame, and the subject of important analyses. The set of pixels fully covers the entire nation, and are thus, analogous to administrative information in surveys of human endeavours.

Forest dynamics have long been studied with assistance from deterministic process models, which predict annual changes in forest composition at the scale of an individual PSU. There has been a long history of deterministic econometric models that predict changes at broad landscape-scales driven by markets for wood products and competing land uses. While these models are often fit with PSU-level data from sample-surveys of

forests, predictions from those models are rarely used to improve time-series of sample-survey estimates.

Presently, annual estimates for large areas take the form of a five-year moving average of estimates from the most recent five panels. All pixels within a single-date of remotely sensed imagery are classified into the categories of “forest” and “nonforest”, the geographic location of each PSU is registered to this imagery. Furthermore, each PSU is classified regarding its geopolitical membership (e.g., state, municipality), and these are cross-classified with the binary remotely sensed categories for post-stratification. Geopolitical post-stratification assures that area statistics agree with official census statistics.

While these methods are simple and robust, they do have limitations. In any dynamic landscape that is not at equilibrium, the five-year moving average suffers from lag-bias if the moving average is treated as an estimator of conditions during the terminal year. Analyses of changes over time are limited to measured changes for each PSU over ten years, and the moving average confounds interpretations of annual changes. Many cross-classified strata have few PSUs. Post-stratification precludes potential gains from many other sources of remotely sensed data, especially detection of rapid changes in land use and catastrophic disturbances. These simple methods are insufficient for reliable estimates for small areas using wealth of available auxiliary information.

Model-based estimators could gain strength from the aforementioned deterministic models. However, model-based estimators pose risks from prediction bias. Risk may be managed through judicious attention to residual differences between model predictions and unbiased sample survey estimates. Analyses of residuals can reveal patterns in model prediction errors. The resulting surprises can detect early symptoms of unexpected change and focus attention on subtle trends in poorly-modelled deterministic processes. More details are in (Czaplewski and Thompson 2008).

5. Discussion

The idea behind the recursive restriction estimator is not entirely new – as Czaplewski points out it is equivalent to the multivariate composite indicator and a form of the static the Kalman filter for which there exists a large literature (Czaplewski 2010a p19). What is surprising is the natural way that it can be put to use to settle theoretical problems surrounding de facto hybrid estimation employed in official statistics. 20 years ago model-assistance brought auxiliary data into sample survey theory and introduced the generalised regression estimator but left unresolved the cross over between sampling and measurement error. Rephrasing the problem in Bayesian terms it is possible to bring both sorts of error together in a unified theory, respecting design principles, while allowing for extra design constraints outside of the sampling sphere.

The robustness of the theoretical apparatus aside, these methods remain limited by availability of algorithms required for heavy duty matrix manipulations. Even here RRE

has something to offer through its link to the Kalman filter: “the engineering perspective contributes essential solutions ..to numerical problems [that have] posed a stubborn obstacle to optimal estimation” Czaplewski op cit. In other developments – in this case in data linkage and automated edit and imputation - Winkler reports important progress in developing workable data matching and linking algorithms. It is not farfetched to imagine rephrasing the data linkage problem – until now largely computational, within the language of recursive restriction estimation.

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