ON STRUCTURAL TIME SERIES MODELS AND THE CHARACTERIZATION OF COMPONENTS

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Abstract

Harvey and Todd have recently proposed the use of a structural time series model, where particular structures are imposed upon the unobserved components of an observed series. In this paper some properties of the model are analysed. First, it is seen how it can be expected to fit a large number of series, such as the ones for which X11 or the Airline model are appropriate. Second, it is concluded that a drawback of the model is that identification of the components is achieved by transfering white-noise variation from the irregular to the trend and the seasonal.

Keywords: Structural Time Series Models; X11; ARIMA models; Airline Model; Unobserved Components;Canonical Decomposition.

Introduction

Applied time series analysts, such as the ones working to satisfy the demand of economic policy makers, rely heavily on X11 for unobserved components estimation (most often, for seasonal adjustment), and on ARIMA models for short term forecasting. Over the last years, thanks to the recent work of Box, Bell, Burman, Cleveland, Hillmer, Pierce, Tiao and others, there has been a move towards integration of both operations, in the direction of using ARIMA models for signal extraction also. Two advantages of this approach are, first, that it permits to overcome the limitations of the relatively fixed X11 filters and, second, that the specification of a model offers a systematic framework for analysis.

However, several problems still remain. First, on occasion, the ARIMA models identified through the usual Box-Jenkins criteria offer insatisfactory spectral decompositions. Second, the analytical expressions for the components can be complicated, which limits the usefulness of the model. Also, either because one wishes to avoid the pernicious effects of data-mining, or because a large number of series has to be frequently analysed, it may be desirable to avoid -as much as possible- the identification stage.

Recently, a class of parametric time series models has been proposed, under the name of "structural time series models" (Harvey and Todd, 1983; Harvey, 1981). In the line of Nerlove, Grether and Carvalho (1979), a particular structure is imposed on the traditional trend, seasonal and irregular components; this structure depends on a few parameters. Thus, on the one hand, the structural model has the limitation that the overall implied structure for the series is subject to certain constraints, hence it may be unsuitable for some series. On the other hand, these models possess two convenient features. First, by skipping the identification stage, they avoid the problem of data-mining, while at the same time presenting more versatility than the filters of X11. Second, they provide components which should be expected, to behave properly as trend, seasonal and irregular.

From an applied point of view, these two features are important. However, they will only be meaningful if it is indeed the case that the structural models can represent adequately a large number of series encountered in practice. The purpose of this paper is to look into this question first. Then we compare the components with those obtained with X11 and with the ARIMA based signal extraction method.

1.- THE BASIC STRUCTURAL MODEL

We shall analyse the so-called "basic structural model" (BSM), and consider monthly time series.

The series of interest(or a suitable transformation) is the sum of a trend, a seasonal and an irregular component:

$$y_t = p_t + s_t + u_t \quad . \tag{1.1}$$

The trend can be expressed as:

$$\nabla p_t = \beta_{t-1} + \eta_t \quad , \tag{1.2}$$

where $\nabla = 1-B$ and B is the lag operator. Thus the trend is locally linear, and the slope β_t, follows the random walk:

$$\nabla \beta_t = \zeta_t \quad . \tag{1.3}$$

The seasonal component satisfies the equation:

$$S(B)\ s_t = \omega_t \quad , \tag{1.4}$$

where $S(B)=1+B+...+B^{11}$. Thus the sum of 12 consecutive seasonal components oscillates randomly around zero. The three variables η_t, ζ_t and ω_t, plus the irregular u_t are assumed independent white noises. The only unknown parameters of the model are the four variances:

$$\sigma_u^2,\ \sigma_\eta^2,\ \sigma_\zeta^2,\ \sigma_\omega^2. \tag{1.5}$$

In terms of ARIMA representation, it is easily seen that the trend can be expressed as the IMA (2,1) model:

$$\nabla^2 p_t = (1-\mu B)\, d_t \qquad (1.6)$$

where μ and σ_d^2 are related to σ_η^2 and σ_ζ^2 through the equations:

$$\sigma_\zeta^2 = (1-\mu)^2\, \sigma_d^2$$
$$\sigma_\eta^2 = \mu\, \sigma_d^2 \qquad (1.7)$$

Considering (1.1), (1.2), (1.3) and (1.4), the overall series can be expressed as:

$$z_t = S(B)\, \zeta_{t-1} + \nabla_{12}\eta_t + \nabla^2\omega_t + \nabla\nabla_{12}u_t \; . \qquad (1.8)$$

where

$$z_t = \nabla\nabla_{12}\, y_t \; .$$

Hence z_t follows an MA(13) model, with the parameters and the variance of the innovation being functions of the parameters in (1.5).

From (1.8), the Autocovariance Function (ACVF) of z_t can be computed and, letting γ_k denote the k-lag autocovariance, it is given by:

$$\gamma_0 = 12\,\sigma_\zeta^2 + 2\,\sigma_\eta^2 + 6\,\sigma_\omega^2 + 4\,\sigma_u^2$$
$$\gamma_1 = 11\,\sigma_\zeta^2 - 4\,\sigma_\omega^2 - 2\,\sigma_u^2$$
$$\gamma_2 = 10\,\sigma_\zeta^2 + \sigma_\omega^2$$
$$\gamma_3 = 9\,\sigma_\zeta^2$$
$$\gamma_4 = 8\,\sigma_\zeta^2 \qquad (1.9)$$
$$\gamma_5 = 7\,\sigma_\zeta^2$$

$$
\begin{aligned}
\gamma_6 &= 6\,\sigma_\zeta^2 \\
\gamma_7 &= 5\,\sigma_\zeta^2 \\
\gamma_8 &= 4\,\sigma_\zeta^2 \\
\gamma_9 &= 3\,\sigma_\zeta^2 \\
\gamma_{10} &= 2\,\sigma_\zeta^2 \\
\gamma_{11} &= \sigma_\zeta^2 \qquad\qquad\qquad - 2\,\sigma_u^2 \\
\gamma_{12} &= \qquad - \sigma_\eta^2 \qquad + 4\,\sigma_u^2 \\
\gamma_{13} &= \qquad\qquad\qquad\qquad + \sigma_u^2 .
\end{aligned}
$$

will all other γ_k being zero.

These equations imply a set of restrictions on the ACVF of z_t. They do (overidentify) the parameters and, obviously, not every series could be expected to satisfy them. In terms of the autocorrelations, the equations in (1.9) imply the following constraints:

$$
\begin{aligned}
&\rho_k/\rho_{k+1} = (12-k)/(11-k) \;,\; k = 2,\dots,9 \\
&\rho_k > 0,\; k = 2,\dots,11 \\
&\rho_{12} < 0 \qquad\qquad (1.10) \\
&\rho_{11} > \rho_{13} \\
&|\rho_{12}| > \rho_{13} \;.
\end{aligned}
$$

2.- COMPARISON WITH X11

If y_t denotes a series for which X11 is appropriate, the Autocorrelation Function (ACF) of $\nabla\nabla_{12}\, y_t$ is that given in the first column of Table 1 (Cleveland, 1972). It is seen that all the constraints in (1.10) are satisfied. In particular, setting:

$$\begin{aligned} \sigma_\zeta^2 &= .025\ \gamma_o \\ \sigma_\eta^2 &= .020\ \gamma_o \\ \sigma_\omega^2 &= .010\ \gamma_o \\ \sigma_u^2 &= .050\ \gamma_o\ , \end{aligned} \qquad (2.1)$$

the BSM has the ACF displayed in the second column of Table 1. Both ACF are practically identical. Thus the BSM could be applied to series for which X11 is appropriate and we do know from experience that a large number of economic series fall into that group.

Although the overall implied ACF may be the same, the components are not so. From (1.7):

$$\mu = 1 - \sigma_\zeta/\sigma_d$$

$$\sigma_d^2 - \sigma_d\ \sigma_\zeta - \sigma_u^2 = 0 \quad ,$$

which, for the variances in (2.1), yield $\mu = .34$, $\sigma_d^2 = .058\ \gamma_o$. Hence the trend component for the BSM, becomes, from (1.6),

$$\nabla^2\ p_t = (1 - .34\ B)\ d_t \quad . \qquad (2.2)$$

The BSM seasonal component is given by(1.4) and the irregular is white noise. Let (1.1) represent the X11 decomposition of the series into trend, seasonal and irregular. Using again Cleveland's approximation, the trend and seasonal components are given by:

$$\nabla^2 p_t = (1+.26\ B + .30\ B^2 - .32\ B^3) b_t \qquad (2.3)$$

$$S(B)\ s_t = (1+.26\ B^{12}) c_t \quad , \qquad (2.4)$$

where b_t, c_t and u_t (the irregular) are independent white-noises. Comparing the two trend and seasonal components, X11 is seen to imply additional MA terms, which are likely to induce additional smoothing for both components.

Cleveland's characterization of X11 also includes the ratios $(\sigma_u^2/\sigma_b^2) = 10.1$ and $(\sigma_c^2/\sigma_b^2) = .3$. Write:

$$\nabla\nabla_{12}\ y_t = P_t + S_t + U_t \quad ,$$

where

$$P_t = S(B)\ (1+.26\ B+.30\ B^2-.32\ B^3) b_t$$

$$S_t = \nabla^2\ (1+.26\ B^{12}) c_t$$

$$U_t = \nabla\nabla_{12}\ u_t$$

are the parts of the stationary transformation associated with the trend, seasonal and irregular. Hence:

$$\text{Var}\ (P_t) = 1.877\ \sigma_u^2$$

$$\text{Var}\ (S_t) = .190\ \sigma_u^2$$

$$\text{Var}\ (U_t) = 4\ \sigma_u^2$$

and:

$$\text{Var}\ (\nabla\nabla_{12}\ y_t) = 6.067\ \sigma_u^2\ . \tag{2.5}$$

A similar decomposition of $\nabla\nabla_{12}\ y_t$ for the BSM is given by (1.8), where P_t, S_t and U_t are, respectively the first two, the third and the fourth component of the r.h.s. From (2.1) and the first equation in (1.9), it is obtained:

$$\text{Var}\ (P_t) = 2.267\ \sigma_u^2$$

$$\text{Var}\ (S_t) = .400\ \sigma_u^2$$

$$\text{Var}\ (U_t) = 4\ \sigma_u^2$$

and:

$$\text{Var}\ (\nabla\nabla_{12}\ y_t) = 6.667\ \sigma_u^2\ . \tag{2.6}$$

From (2.5) and (2.6), $\sigma_u^2(\text{X11}) = 1.1\ \sigma_u^2(\text{BSM})$. Hence the variance of the X11 irregular is approximately 10% larger than that of the BSM. All considered, although the components are relatively close for X11 and the BSM, the former seems to remove some of series variation from the trend and seasonal, and transfer it to the irregular.

3.- COMPARISON WITH THE ARIMA BASED METHOD; THE AIRLINE MODEL

Looking at the results obtained by Harvey and Todd for the Prothero-Wallis series, it is seen that, in all six cases, $\sigma_\zeta^2 = 0$. They attribute this result to the small sample bias of exact ML estimation. Be that as it may, it is interesting to analyse the BSM for this case.

When $\sigma_\zeta^2 = 0$, the equations in (1.9) become:

$$\begin{aligned}
\gamma_o &= 2\,\sigma_\eta^2 + 6\,\sigma_\omega^2 + 4\,\sigma_u^2 \\
\gamma_1 &= -4\,\sigma_\omega^2 - 2\,\sigma_u^2 \\
\gamma_2 &= \sigma_\omega^2 \\
\gamma_{11} &= \sigma_u^2 \\
\gamma_{12} &= -\sigma_\eta^2 - 2\,\sigma_u^2 \\
\gamma_{13} &= \sigma_u^2 \quad ,
\end{aligned} \tag{3.1}$$

with $\gamma_k = 0$ for other values of k. Again, the numerical values will depend on the variances of η_t, ω_t and u_t, but it will always be true that:

$$\begin{aligned}
&\gamma_1 < 0 \\
&\gamma_{11} = \gamma_{13} > 0 \\
&\gamma_{12} < 0 \\
&|\gamma_{12}| > |\gamma_{11}| \,.
\end{aligned} \tag{3.2}$$

Consider now the "Airline model" (Box-Jenkins, 1970):

$$\nabla\nabla_{12}\, y_t = (1-\theta_1\, B)(1-\theta_{12}\, B^{12})a_t.$$

The ACVF for $\nabla\nabla_{12}\, y_t$ is given by:

$$\begin{aligned}
\gamma_o &= (1+\theta_1^2)(1+\theta_{12}^2)\sigma_a^2 \\
\gamma_1 &= -\theta_1(1+\theta_{12}^2)\sigma_a^2
\end{aligned}$$

$$\gamma_{11} = \theta_1\ \theta_{12}\ \sigma_a^2 \qquad (3.3)$$

$$\gamma_{12} = -\theta_{12}(1+\theta_1^2)\sigma_a^2$$

$$\gamma_{13} = \theta_1\ \theta_{12}\ \sigma_a^2$$

with all other γ_k equal to zero. If θ_1, $\theta_{12}>0$ -in which case an acceptable decomposition exists (Hillmer-Tiao, 1982)- it is seen that all constraints in (3.2) are satisfied.

A difference between (3.1) and (3.3) is that, in the former, $\gamma_2>0$ while, in the latter, $\gamma_2 = 0$. However, since (3.1) implies $\rho_2 = \sigma_\omega^2/(2\sigma_\eta^2 + 6\sigma_\omega^2 + 4\ \sigma_u^2)$, ρ_2 will typically be very small.

Table 2 compares the ACF of the BSM and the Airline model for different values of the parameters: the two models display ACF which are quite close. After all, both are three-parameter models. One of the parameters -θ_1 or σ_η^2 (more precisely σ_η^2/σ_u^2)- is associated with stability of the trend, similarily θ_{12} and $\sigma_\omega^2/\sigma_u^2$ are associated with the stability of the seasonal component. The third parameter determines, in both cases, the size of the one-step ahead forecast error. Since the BSM implies (for $\sigma_\zeta^2 = 0$)a unit root in the MA expression of $\nabla\nabla_{12}\ y_t$, the approximation should work better for larger values of θ_1 or θ_{12} in (3.3), which is exactly what Table 2 indicates. (Notice that, for large values of σ_ω^2, the BSM can have values of ρ_1 larger than .5, the maximum than can be obtained in the Airline model.)

Thus the BSM can generate ACF similar to those of the Airline model and, from our experience, we know that this ACF characterizes many economic time series. (Ansley, 1984, also shows how some modification of the BSM may approximate the Airline model.)

4. CHARACTERIZATION OF THE COMPONENTS

With observations on y_t alone, identification of the models generating p_t, s_t and u_t in (1.1) poses some problems. The ad-hoc characterization of the components in the BSM guarantee that the models are uniquely identified. This is easily seen by considering (1.9): since the four unknown parameters (σ_ζ^2, σ_η^2, σ_ω^2, σ_u^2) can be expressed as functions of the observable covariances, the model is identified and the parameters can be estimated consistently.

The BSM offers therefore an example where a priori considerations on the components structure identify the model. This is fundamentally due to the limitations on the orders of the MA terms of the components, relative to these of the AR terms (see Maravall, 1978).

For the model based procedure, however, the fact that for both components, p_t and s_t, the order of the AR polynomial equals that of the MA one implies that the model is not identified. Identification is then achieved with an additional assumption: the variance of the irregular is to be maximized; this yields the "canonical decomposition" of Hillmer-Tiao. (The assumption of maximum irregular variance was first introduced by Pierce (1978) and Box-Hillmer-Tiao (1978).)

The specification of models for the signal with AR polynomials of larger order than the MA one, implied in the Harvey-Todd (1983) approach, is a well-established practice (to quote a few examples, see Harrison-Stevens (1976), Engle (1978), Nerlove-Grether-Carvalho (1979), Gersch-Kitagawa (1983); it is also implicit in the literature on autoregressive signals, such as in Pagano (1974), and an elaborate application can be found in Porter et al (1978).) In all these cases, by removing MA terms from the models for p_t and/or s_t, identification is achieved without having to maximize the variance of the irregular

In the final analysis, the selection of a specific decomposition depends basically on the a priori beliefs that the analyst has on what are the desirable properties of a trend, a seasonal and an irregular component. However, there is a point which is worth discussing. We illustrate it for the BSM specification.

4.1. Trend

Consider the trend given by (1.6), and writte:

$$p_t = \pi_t + \varepsilon_t \ , \tag{4.1}$$

where ε_t is white-noise, orthogonal to π_t. From (1.6) and (4.1),

$$(1-\mu\ B)d_t = \nabla^2\ \pi_t + \nabla^2\ \varepsilon_t \ , \tag{4.2}$$

which implies that $\nabla^2\ \pi_t$ has to be an MA(2), say:

$$\nabla^2\ \pi_t = (1-\alpha_1\ B-\alpha_2\ B^2)b_t \quad .$$

Thus the system of covariance equations corresponding to (4.2) is given by:

$$\begin{aligned} 1+\mu^2 &= (1+\alpha_1^2+\alpha_2^2)\sigma_b^2 + 6\ \sigma_\varepsilon^2 \\ -\mu &= (-\alpha_1+\alpha_1\alpha_2)\sigma_b^2 - 4\ \sigma_\varepsilon^2 \\ 0 &= -\alpha_2\ \sigma_b^2 + \sigma_\varepsilon^2 \quad , \end{aligned} \tag{4.3}$$

where, whithout loss of generality, we have assumed $\sigma_d^2 = 1$.

Since there is an infinite number of values for the parameters (α_1, α_2, σ_b^2 and σ_ε^2) which satisfy the system (4.3), the models for π_t and ε_t are not identified. There is, thus, an infinite number of ways in which the BSM trend can be split into trend and (orthogonal) noise.

The pseudospectrum of p_t is given by:

$$f_p(\lambda) = (1+\mu^2-2\mu \cos \lambda)/4(1-\cos \lambda)^2,$$

a monotonically decreasing function in $0 \leq \lambda \leq \pi$. Hence

$$\min_{0\leq\lambda\leq\pi} f_p(\lambda) = f_p(\pi) = (1+\alpha)^2/16 \ .$$

Setting $\sigma_\varepsilon^2 = (1+\alpha)^2/16$, the system (4.3) becomes identified.It is then seen that the first equation minus twice the diference between the second an third yields:

$$1+\alpha_1-\alpha_2 = 0 \ ,$$

or $\alpha(-1)=0$, where $\alpha(B) = 1-\alpha_1 B-\alpha_2 B^2$. Thus all white noise is removed from the trend when π_t is of the type:

$$\nabla^2 \pi_t = (1+B)(1-\alpha B)\ b_t \quad ,$$

and, in terms of the parameters in equations (1.2) and (1.3), the variance of the irregular is then increased by:

$$\sigma_\varepsilon^2 = (\sigma_\zeta^2 + 4\ \sigma_\eta^2)/16 \ .$$

4.2 The Seasonal Component

A similar reasoning applies to the BSM seasonal component, given by:

$$(1+B+...+B^{s-1})s_t = \omega_t ,$$

where s is the number of observations in a year. This is easily seen by considering the simplest case s=2 (i.e., the seasonality is of period 2, appropiate for semi-annual data), in which case:

$$(1+B)s_t = \omega_t .$$

Writting, as before,

$$s_t = \pi_t + \varepsilon_t ,$$

it is obtained that

$$\omega_t = (1+B)\pi_t + (1+B)\varepsilon_t ,$$

which implies that $(1+B)\pi_t$ is an MA(1), say:

$$(1+B)\pi_t = (1-\alpha B)c_t .$$

Setting $\sigma^2_\omega = 1$ the system of covariance equations becomes:

$$1 = (1+\alpha^2)\sigma^2_c+2\ \sigma^2_\varepsilon ,$$

$$0 = -\alpha\ \sigma^2_c + \sigma^2_\varepsilon ,$$

and, again, the BSM seasonal component can be decomposed into "seasonal plus noise" in an infinite number of ways.

The pseudospectrum of s_t is equal to:

$$f_s(\lambda) = 1/2(1+ \cos \lambda) ,$$

a monotonically increasing function in $0<\lambda<\pi$, hence

$$\min_{0<\lambda<\pi} f_s(\lambda) = f_s(0) = 1/4 .$$

Setting $\sigma_\varepsilon^2 = \sigma_\omega^2/4$, it is obtained that all white noise is removed from the seasonal when π_t is given by

$$(1+B)\pi_t = (1-B)c_t ,$$

and $\sigma_c^2 = \sigma_\omega^2/4$.

4.3 Conclusión

In general, when a component is identified by a priori reducing the order of the MA polynomial relative to the AR one, said component will be equal to the sum of another component with the same spectral profile plus orthogonal white-noise. It follows, thus, that identification is achieved by removing white-noise variation from the irregular and superimposing it to the trend and/or seasonal.

If the object of the analysis is forecasting, it is obvious that interchanging noise among the components has no effect on the aggregated forecast. However, if the interest centers on unobserved components estimation, since the characterization of the components is purely based on their stochastic behavior and, in particular, the irregular is assumed to contain the white noise variation, what is the point of labelling as part of the trend or of the seasonal what is simply white noise? Moreover, canonical components (clean of noise) can be easily incorporated in a structural approach by allowing for larger MAs in the components models, containing the factor (1+B) in the trend case, and (possibly) the factor (1-B) in the seasonal (so as to impose $f_p(\pi) = f_s(o) = 0$, respectively.)

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Table 1

ACF: COMPARISON WITH X11

K	X11	BSM
1	-.061	-.065
2	.266	.260
3	.226	.225
4	.201	.200
5	.175	.175
6	.150	.150
7	.125	.125
8	.100	.100
9	.075	.075
10	.046	.050
11	.178	.175
12	-.326	-.320
13	.153	.150
14	-.004	0

Table 2

ACF: COMPARISON WITH THE AIRLINE MODEL

AIRLINE	ρ_1	ρ_2	ρ_{11}	ρ_{12}	ρ_{13}
$\theta_1=.8, \theta_{12}=.8$	-.488	-	.238	-.488	.238
$\theta_1=.8, \theta_{12}=.4$	-.488	-	.168	-.345	.168
$\theta_1=.4, \theta_{12}=.4$	-.345	-	.119	-.345	.119

BSM	ρ_1	ρ_2	ρ_{11}	ρ_{12}	ρ_{13}
$\sigma_\eta^2=1, \sigma_\omega^2=.25, \sigma_u^2=20$	-.490	.003	.239	-.490	.239
$\sigma_\eta^2=1, \sigma_\omega^2=.75, \sigma_u^2=3$	-.486	.040	.162	-.378	.162
$\sigma_\eta^2=1, \sigma_\omega^2=.25, \sigma_u^2=.70$	-.378	.039	.111	-.380	.111

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