

Shiftwork and the Real Business Cycle

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Abstract

We study the impact of introducing shiftwork into a real business cycle model on: productivity, employment, hours and output. Our model of shiftwork allows for non-simultaneous production with different labor inputs within a period, in which the workweek of capital and capacity utilization are determined endogenously. The model is estimated by maximum likelihood using the Kalman filter and the last forty years of quarterly U.S. data. Our estimates suggest shiftwork helps to explain U.S. business cycle fluctuations. We find that shiftwork is a critical ingredient of the business cycle, and that employment during the late shift is very procyclical. The estimated variability of total factor productivity is much smaller than is usually required to generate US business cycle fluctuations. In the presence of shiftwork, capacity utilization does not vary a lot in the business cycle frequency, although it remains a vital ingredient of real business cycle theory. Furthermore, the estimated conditional correlations between labor markets variables and the stochastic components of the model are in agreement with the predictions of RBC theory.

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1 Introduction

This paper presents evidence that shiftwork plays a substantial role in real business cycle (RBC) theory. Shiftwork is acknowledged as an important element of technology by students of the production function at the micro and aggregate levels. Bresnahan and Ramey (1994), Hamermesh (1989), Mayshar and Halevy (1997), Mayshar and Solon (1993), and Shapiro (1993,1996) show that shiftwork serves as an important margin for firms. For example, Mayshar and Solon (1993) estimate that late shift employment accounts for more than one-third of the variation in aggregate employment while only being about one-sixth of aggregate employment.

The extensive evidence about shiftwork has been largely neglected by real business cycle theory. According to Prescott (1998), this aspect of firms' technology provides

“A Margin of adjustment that has not been introduced into any applied general equilibrium analysis of the business cycle is the option to vary the number of shifts a plant is operated.”

A goal of this paper is to rectify this neglect.

Another goal of this paper is to present evidence which shows that RBC theory is a powerful tool for understanding aggregate fluctuations. Recent work by Gali (1999) questions the ability of RBC theory and technology shocks to explain U.S. business cycle fluctuations. Gali presents estimates of the conditional correlation of the permanent (transitory) component of the output-labor ratio and either employment or hours that are more negative than 0.80 (greater than 0.25). He considers these correlations to be evidence that rejects RBC theory. We present an RBC model which explains these correlations without recourse to non-market clearing, monetary or ad hoc factors.

We incorporate shiftwork into a one-sector RBC model to pursue these goals. Rather than a firm choosing the number of shifts, we fix the number of shifts to study the implications of the compositional affects for the real business cycle. Our shiftwork-RBC model allows a firm to choose its capacity utilization – the rate at which capital is transformed into capital services – besides running a regular shift and a swing shift. Household preferences reflect the presence of shiftwork in technology because the disutility of hours and employment varies across shifts. In particular, we adapt the preferences Cho and Cooley (1994) and Bils and Cho (1994) develop to a shiftwork environment.

Our shiftwork RBC model is different than the straight time-overtime model that Hansen and Sargent (1988) develop and study and estimated further analyzed by Hall (2000). Rather than an overtime shift, we assume the firm continuously operates a swing shift. Production occurs non-simultaneously on the two shifts within the same period, but with a different set of employees (potentially) working different shift lengths.

We are not the first to motivate a RBC model with shiftwork. Burnside and Eichenbaum (1996) use shiftwork to argue their model of capital utilization can be viewed as a reduced-form of a technology that has a variable number of shifts of fixed employment and

length.¹ The model we present allows shift length to vary endogenously, but contains a fixed number of shifts, two². Burnside (2000) and Hornstein (2002) also construct RBC models with shiftwork. The former paper gives firms a choice to open and close plants and shifts within a plant. An implication is that the volatility of the measured total factor productivity, the Solow residual, can be overstated by as much as 50 percent. Hornstein shows that shiftwork yields a divergence between the workweek of capital and the workweek of labor. This suggests standard approaches to technology measurement that use the workweek of labor to proxy for the workweek of capital are biased.

An obstacle to the study of shiftwork in a RBC model is the lack of aggregate data on this aspect of the labor market. The decomposition of hours worked into shifts is only rarely reported. For example, Burnside and Eichenbaum restrict employment and hours to be fixed across shifts because it collapses shiftwork into capacity utilization which reflects movements in capital services. This eliminates any compositional effects across shifts and is difficult to reconcile with the available evidence. For example, Mayshar and Solon (1993) find that aggregate employment in the regular shift is five (three) times higher than in the swing shift in aggregate (manufacturing).

We avoid this problem by our approach to estimation of the parameters of our shiftwork-RBC model. Subsequent to linearizing our shiftwork-RBC model, it is cast in state space form to appeal to the Kalman filter and its associated maximum likelihood estimator. Thus, we are able to employ the Kalman smoother to obtain time series of employment and hours across the two shifts. All of the estimates this paper reports are based on U.S. sample data that begins in 1955Q1 and end in 1998Q4.

We find that RBC theory with shiftwork provides a more complete explanation of aggregate fluctuations, particularly for technology, capacity utilization, employment, hours, output, and consumption. Our estimates of labor-augmenting total factor productivity (TFP) indicate that its volatility relative to the measured Solow residual is about one-half, which is in line with evidence Burnside (2000) presents. Further, this measure of labor-augmenting TFP lacks the disconcerting wiggles around the oil price shocks of the 1970s and rapid recover thereafter often seen in estimates of TFP. A dynamic decomposition of variance reveals that the labor-augmenting TFP of our shiftwork-RBC model accounts for more than 20 percent of the fluctuations in output, consumption, and employment up to forecast horizons of five years.

Estimates of swing shift employment and hours show the importance of shiftwork for RBC theory. The estimates of swing shift employment backed out from the Kalman smoother exhibit business cycle fluctuations not present either in actual aggregate employment or estimated regular shift employment. Surprisingly, our estimates of swing employment reveals that its peaks and troughs match five of the last seven NBER-dated business cycle peaks and all but one of its trough during our sample period. Although swing shift hours are more volatile than actual aggregate hours and regular shift hours, the business cycle character of swing shift hours is far less pronounced than swing shift employment. Nonetheless, the

¹Greenwood, Hercowitz, and Huffman (1988) are the first to appreciate the implications of capacity utilization for RBC theory.

²Basu (1996) describes a production similar to the one Burnside and Eichenbaum study.

volatility and persistence of swing shift hours appear to more closely replicate the predictions of a proto-typical RBC model.

Our results indicate that RBC theory yields valuable insights into the U.S. business cycle. Similar to the arguments of King and Rebelo (1999), Burnside (2000), and Hornstein (2002), our shiftwork-RBC model generates an economically powerful description of the U.S. business cycle. We compute the Gali correlations aggregating up from the estimated shift employment and hours series. On the basis of this data, we estimate the Gali-correlation of the permanent components to range from -0.18 for employment to nearly 0.50 for hours. The transitory component is less than -0.83 for employment and -0.98 for hours. These results are closer to the predictions of RBC theory and observations from the actual data. We argue that RBC theory is far needing any life-support technology on the basis of this evidence.

The next section of the paper outlines our model of shiftwork. Section 3 describes our solution and estimation methods along with the sample data. We present and discuss results in section 4. Section 5 concludes.

2 Shiftwork in a RBC Model

We construct a dynamic stochastic general equilibrium model that contains a technology with two non-simultaneous shifts, a regular or *A* shift and a swing or *B* shift, in this section. These shifts introduce composition effects into aggregate labor variables because there is variation along the extensive margin, employment, and the intensive margin, hours, across shifts. Aggregate output follows from summing across shifts. We modify the Cho and Cooley (1994) and Bils and Cho (1994) preferences to have households respond to firm demands for variable employment and hours across shifts in a fashion similar to Hornstein (2002).

2.1 Technology

The production technology of shift *i* is constant returns to scale (CRS). The firm takes its date *t* capital stock, K_t , the realization of exogenous labor-augmenting technology, Z_t , and any other exogenous shocks as given when choosing its rate of capacity utilization, v_t and shift *i* labor input, $N_{i,t}$, $i = A, B$. These ingredients are combined in the per worker-per hour production function

$$\frac{Y_{i,t}}{N_{i,t}} = \mathcal{F} \left(K_t \left(\frac{N_{i,t}}{v_t} \right)^{-1}, Z_t \right).$$

This technology differs from the one Burnside and Eichenbaum (1996) employ. We allow labor input to vary across the two shifts rather than holding it fixed. However, we impose the same time-varying capacity utilization rate across shifts. The restriction on capacity utilization and flexibility in labor input across shifts implies in the workweek of capital and the workweek of labor do not move with each other one-for-one³. This snaps the link between

³Hornstein (2002) has made this point using a slightly different technology

the work week of capital and the workweek of labor giving these objects the opportunity to have greater independence over the business cycle.

Aggregate output, Y_t , is time additive in shift A and B output⁴. We parameterize shift i technology with a Cobb-Douglas function and capital share of θ , $0 < \theta < 1$. This yields the aggregate production function

$$Y_t = (v_t K_t)^\theta Z_t^{1-\theta} [N_{A,t}^{1-\theta} + N_{B,t}^{1-\theta}]. \quad (1)$$

This assumes that the firm operates the B shift continuously no matter how small the employment rate or hours of this shift.⁵

Capacity utilization generates time-variation in depreciation. We follow Greenwood, Hercowitz, and Huffman (1988) and Burnside and Eichenbaum (1996) to describe the law of motion of the capital stock

$$K_{t+1} = I_t + (1 - \delta_0 - \delta_1 v_t^\varphi) K_t \quad 0 < \delta_0, \delta_1 < 1, \quad 0 < \varphi, \quad (2)$$

where I_t denotes investment in period t . The depreciation parameter δ_0 captures ‘rust and dust’ depreciation. Basu and Kimball (1997) present evidence this represents about 40 percent of total depreciation. Time-varying or ‘wear and tear’ depreciation is a nonlinear function of capacity utilization, $\delta_1 v_t^\varphi$. Burnside and Eichenbaum (1996) argue that wear and tear depreciation dominates its rust and dust associate. Since the elasticity of wear and tear depreciation, φ , determines the response of capital services to any shock, this parameter determines the power capacity utilization has to generate a business cycle propagation mechanism.

2.2 Preferences

We extend the Cho and Cooley (1994) preferences that impose costs on utility given household choices of employment and hours⁶. Given the representative household can send its members to work either A shift or B shift, the daily utility of an employed member of the household is represented by

$$U(c_i, h_i) = u(c_i) - \nu_i(h_i), \quad i = A, B.$$

This utility function assumes additive separability in consumption and leisure. It imposes standard conditions on $u(\cdot)$ and $\nu_i(h_i)$. In particular, the latter is increasing and convex for $i = A, B$. Also, we assume the utility cost of working either A shift or B is not equal.

⁴This follows a long tradition in the straight time-overtime literature, which dates back to Lucas (1970).

⁵Hamermesh (1989), Bresnahan and Ramey (1994), Hall (2000), and Shapiro (1996) show that it is important for firms to be able to alter the number of shifts. This margin acts as a buffer for firms to vary their production across states of the world. However, when aggregating up the different firms to the economy’s level, it is reasonable to assume that there always exist firms that operate a late shift.

⁶Bils and Cho (1994) work with similar utility function, but add unobserved effort.

The impact on utility of having to supply an additional hour late in the afternoon or late evening is not the same.

Each unit of time during a period an agent can work h_A hours in shift A or work h_B hours in shift B or not work at all. Hence, the expected utility of our representative household is

$$[u(c_A) - \nu_A(h_A)]e_A + [u(c_B) - \nu_B(h_B)]e_B + u(c_{NE})(1 - e_A - e_B)$$

A worker views e_i as the probability of working in shift i . The presence of fair lotteries allows the household to calculate the probabilities e_A and e_B and implies consumption is independent of employment. Therefore, expected utility reduces to

$$u(c) - [\nu_A(h_A)e_A + \nu_B(h_B)e_B]$$

Cho and Cooley argue that it is costly in utils for the household to replace home production when one of its members enters the labor market. This introduces a fixed cost, $\psi_i(e_i)$, into the utility of that member of the household at work on shift i . Note that the opportunity cost of home production in utility is independent of the length of shift i . We posit that the cost to a B shift worker of replacing home production differs from a A shift worker because coordination costs vary through the day for the household. There are conventions that some activities are carried out only when the A shift operates, for example, children's education. Hence, working B shift imposes higher costs in lost home production.

The implication for expected felicity (utility minus participation costs in the labor market) is

$$\mathcal{U}(c, h_A, e_A, h_B, e_B) \equiv u(c) - [\nu_A(h_A) + \psi_A(e_A)]e_A - [\nu_B(h_B) + \psi_B(e_B)]e_B. \quad (3)$$

Note that from the aggregate view point, e_i represents the employment rate of shift i . The expected lifetime utility of the representative household is

$$\mathbf{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \mathcal{U}(c_t, h_{A,t}, e_{A,t}, h_{B,t}, e_{B,t}) \right\}, \quad (4)$$

where \mathbf{E}_0 is the mathematical expectations operator conditional on date 0 information.

Our specification of the representative household's utility function is taken from Cho and Cooley and is similar to the parameterization Hornstein (2002) uses in his RBC model of shiftwork. The utility of consumption is logarithmic, the disutility of hours worked in both shifts has a constant elasticity of $1 + \eta$, but with different intercepts, ϕ_{1A} and ϕ_{1B} , respectively. The cost of employment in shift i is isoelastic with respect to e_i with elasticity $1 + \tau$ in both shifts but with different intercepts ϕ_{2A} and ϕ_{2B} , respectively.

2.3 The Impulse Structure and Resource Constraint

We impose a technology shock and government spending shock on the shiftwork-RBC model. The shock to labor-augmenting technology, Z_t , is taken to be a random walk with drift

$$\ln[Z_{t+1}] = \ln[Z_t] + \gamma + \varepsilon_{t+1} \quad 0 < \gamma, \quad \varepsilon_{t+1} \sim \mathbf{N}\left(0, \sigma_\varepsilon^2\right), \quad (5)$$

γ is the deterministic trend of labor-augmenting technology.

The stationary and exogenous government spending shock fluctuates around the ratio of the level of government spending, G_t , and output, Y_t . We assume the transitory government spending shock, $g_t = G_t/Y_t$, evolves as an AR(1)

$$\ln[g_{t+1}] = (1 - \rho_g) \ln[g^*] + \rho_g \ln[g_t] + v_{t+1}, \quad |\rho_g| < 1, \quad v_{t+1} \sim \mathbf{N}\left(0, \sigma_v^2\right), \quad (6)$$

where g^* denotes the population or steady state government spending-output ratio. The shock innovations ε_t and v_t are restricted to be uncorrelated at all lags and leads.

The resource constraint

$$Y_t = C_t + I_t + G_t \quad (7)$$

which the economy faces closes the economy and

$$N_{i,t} = e_{i,t} h_{i,t} \quad i = A, B, \quad (8)$$

constrains the labor market to have positive equilibrium A shift and B shift wages.

2.4 Optimality and Equilibrium

We solve the social planner's problem. This involves maximizing the expected lifetime utility function of the household (4), given the period utility function (3), over the uncertain streams of C_t , $e_{A,t}$, $h_{A,t}$, $e_{B,t}$, $h_{B,t}$, v_t , and K_{t+1} against the constraints (7), (1), (8), and (2) taking the exogenous processes (5) and (6) which produce Z_t and g_t and the initial condition K_0 as given.⁷ The first-order necessary conditions yield optimality conditions for $h_{A,t}$, $e_{A,t}$, $h_{B,t}$, $e_{B,t}$, v_t , and K_{t+1}

$$\left[\phi_{1i} h_{i,t}^\eta e_{i,t} \right] c_t = (1 - \theta) (v_t K_t)^\theta (Z_t e_{i,t})^{1-\theta} h_{i,t}^{-\theta}, \quad i = A, B, \quad (9)$$

$$\left[\phi_{1i} \frac{h_{i,t}^{1+\eta}}{1+\eta} + \phi_{2i} e_{i,t}^\tau \right] c_t = (1 - \theta) (v_t K_t)^\theta (Z_t h_{i,t})^{1-\theta} e_{i,t}^{-\theta}, \quad i = A, B, \quad (10)$$

⁷This assumes the problem is convex in order to decentralize the economy to generate the same characterization of allocations. We acknowledge that opening and closing late shifts represents an important decision for an individual firm, especially when the firm runs multiple plants. Micro studies by Hamermesh (1989), Bresnahan and Ramey (1994), and Hall (2000) discuss the importance of the "non-convexity" of the cost structure for firm decision making. Mayshar and Halevy (1997) provide models of shiftwork in firms that have this type of non-convexity. However, aggregating over plants, firms and industries implies there some workers are always operating the swing shift. Hence, the assumption of an interior solution is consistent with the aggregate production function we consider.

$$\frac{\theta}{\varphi} \frac{Y_t}{K_t} = \delta_1 v_t^\varphi, \quad (11)$$

and

$$1 = \beta \mathbf{E}_t \left\{ \frac{C_t}{C_{t+1}} \left[\theta \frac{Y_{t+1}}{K_{t+1}} + 1 - \delta_0 - \delta_1 v_{t+1}^\varphi \right] \right\}, \quad (12)$$

respectively. It is necessary that along any candidate equilibrium path the optimality conditions (9) – (12) be satisfied. The transversality condition

$$\lim_{j \rightarrow \infty} \beta^{t+j} \mathbf{E}_t \left\{ \frac{K_{t+j+1}}{C_{t+j}} \right\} = 0$$

is sufficient for the existence of an equilibrium. Goods market equilibrium consists of the law of motion of capital (2) and the aggregate resource constraint (7), while (8) defines it for the labor market.

The optimality conditions (9) – (11) capture the intratemporal allocations of hours, employment, and capital services. Shiftwork matters for business cycle fluctuations to the extent that workers care about their intratemporal employment schedule. If the disutility of work differs across shifts – say, the preference is to work on the *A* shift rather than the *B* shift – the intratemporal marginal product of capital becomes non-constant. The results is that there exists an optimal allocation of employment across shifts which interacts with the optimal choice of capacity utilization.⁸

This requires workers to enjoy leisure in utils more when they obtain it later in a period (or have higher home production). The disutility of work must be greater for the *B* shift, although workers on this shift are compensated for this at the margin. The disparities in disutility workers suffer across shifts must be reflected in the utility function parameters on the left side of equations (9 and 10). This drives the compensation workers receive which drives a premium for *B* shift work. Thus, the composition of shiftwork is generated, in part, by the labor supply schedules implied by household utility functions.

The choice of capacity utilization, v_t , reflects the extent to which physical capital is transformed into efficiency units of capital input. Higher rates of capital utilization generate faster depreciation of capital and a smaller capital-output ratio according to the optimality condition (11). Capacity utilization acts as a business cycle propagation mechanism when it generates more persistence and variability in the service flow of capital.

This is clear from inspection of the Euler equation (12). Persistence in v_t imposes costs on the response of K_{t+1} to a given shock which translates into persistence and serial correlation in the aggregate quantity variables along the equilibrium path. Shiftwork deepens this idea because the intratemporal allocation of labor creates persistence and variability in the marginal product of capital that works in the same direction as v_t . Since shiftwork snaps

⁸Mayshar and Halevy (1997) and Hornstein argue that this composition effect is important for understanding movements in technology at the micro and macro level.

the link between the workweek of capital and the workweek of labor, shiftwork enhances the propagation mechanism of the model.

The composition effects of shiftwork have important implications for the measurement of technology. A standard productivity accounting device is the Solow residual. In our shiftwork-RBC model, the Solow measure of TFP is

$$\ln STFP_t = \frac{\ln Y_t - \theta \ln(v_t K_t)}{1 - \theta} - \ln N_t = \ln Z_t + \frac{\ln(1 + \mu_t^{1-\theta})}{1 - \theta} - \ln(1 + \mu_t),$$

where $\mu_t = N_{B,t}/N_{A,t}$. Thus, any shock to the composition of employment and labor hour inputs across shifts causes TFP to be measured incorrectly. If $\mu_t < 1$, $\ln Z_t < \ln STFP_t$. This is true whenever $N_{A,t}$ is above its steady state value. Also, the growth rate of $\ln STFP_t$ is always more volatile than the growth rate of $\ln Z_t$ (as long as the sum of the variances of the last two terms to the right of the last equality dominate their covariance).

3 Solution and Estimation Methods

The shiftwork-RBC model is solved with standard techniques. This is conditional on the values of the parameters of the model. We employ a mix of calibration and estimation to set parameter values. The estimator we use borrows from Sargent (1989) and Ireland (2001). This allows us to evaluate our shiftwork-RBC model along a number of dimensions.

3.1 The Linearized Solution

We solve the model subsequent to stochastically detrending Y_t , C_t , and K_{t+1} in the optimality conditions (9) – (12) and the equilibrium conditions (2) and (7). Stochastic detrending by Z_t yields, for example, $\hat{Y}_t = Y_t/Z_t$ and $\hat{K}_{t+1} = K_{t+1}/Z_t$. The next step is to compute the steady state and (log) first-order Taylor expansion of the optimality and equilibrium conditions around the deterministic steady state. The result is a two-sided expectational difference equation in the capital stock with the solution

$$\tilde{K}_{t+1} = \mu_K \tilde{K}_t + \mu_\varepsilon \varepsilon_t + \mu_g \tilde{g}_t, \quad (13)$$

where $\tilde{K}_{t+1} = \ln \hat{K}_{t+1} - \ln K^*$ and K^* denotes the steady state capital stock. The coefficients of the equilibrium law of motion of the capital stock, (13), are computed using an algorithm devised by Zdrozny (1998). The equilibrium path of the endogenous state variable, \tilde{K}_{t+1} , and the exogenous state variables, ε_t and \tilde{g}_t , generate the path of the “flow” vector \mathcal{C}_t which contains \tilde{C}_t , $e_{A,t}$, $h_{A,t}$, $e_{B,t}$, $h_{B,t}$, v_t , and \tilde{Y}_t . This is described by

$$\mathcal{C}_t = \pi_S \mathcal{K}_t, \quad (14)$$

where $\mathcal{K}_t = [\tilde{K}_t \ \varepsilon_t \ \tilde{g}_t]'$ and π_S is a seven-by-three matrix.

3.2 The Kalman Filter and Maximum Likelihood

An issue for any model shiftwork that wants to connect to actual data is there is a paucity of sample observations on shiftwork employment and hours, especially at the quarterly frequency. We avoid this problem by utilizing Kalman filter-maximum likelihood estimation (KF-MLE) technology developed by Sargent (1989) and refined by Ireland (2001). Sargent grafts a restricted first-order vector autoregressive, VAR(1), measurement error process onto the flow equation of the state space system implied by (13) and (14). The restrictions are that the VAR(1) matrix is diagonal as is the covariance matrix of the VAR(1) errors. Ireland alters the measurement process to be an unrestricted VAR(1) to soak up misspecification error generated by linearizing of the model, measurement error in the actual data, and the inadequacies of the RBC model.

The KF-MLE approach needs the state vector \mathcal{K}_t and the flow vector \mathcal{C}_t to be redefined to match the available sample data along with the addition of the measurement error process.⁹ This involves writing the system (13) and (14) as a state equation

$$\mathcal{S}_{t+1} = F\mathcal{S}_t + \lambda_{t+1}, \quad (15)$$

a measurement equation

$$\mathcal{Y}_t = H\mathcal{S}_t + \mathcal{V}_t, \quad (16)$$

where the \mathcal{V}_t is the vector of measurement errors with VAR(1) dynamics

$$\mathcal{V}_{t+1} = D\mathcal{V}_t + \xi_{t+1}, \quad (17)$$

where ξ_{t+1} is the vector of measurement error innovations. We assume $\mathbf{E}\{\lambda_{t+j} \xi_{t+s}\} = 0$, for all j and s . In this case, the state space, measurement, and error vectors become $\mathcal{S}_t = [\widetilde{K}_t \widetilde{Y}_{t-1} \ \varepsilon_t \ \tilde{g}_t]'$, $\mathcal{Y}_t = [\Delta \ln Y_t \ \ln C_t/Y_t \ \ln G_t/Y_t \ \ln \delta_t \ \ln e_t \ \ln h_t]'$, $\lambda_{t+1} = [\varepsilon_{t+1} \ v_{t+1}]'$, $\mathcal{V}_{t+1} = [V_{1,t+1} \ \dots \ V_{6,t+1}]'$, and $\xi_{t+1} = [\xi_{1,t+1} \ \dots \ \xi_{6,t+1}]'$.¹⁰ The state space system (15) – (17) implies the vector autoregressive moving average (VARMA) process

$$\mathcal{Y}_t = D\mathcal{Y}_{t-1} + H\mathcal{S}_t - DHS_{t-1} + \xi_t. \quad (18)$$

Hence, the KF-MLE is equivalent to estimating a VAR(1) restricted by the theoretical MA(2) process imposed by the linearized shiftwork-RBC model and the cross-equation restrictions of VAR(1) measurement process. The innovations of the VARMA process (18) is the basis of the KF-MLE as discussed in Hamilton (1994).

3.3 Data

The estimate period covers from 1955Q1 to 1998Q4 with earlier data available for lagged conditioning information. We define C_t to be the sum of nondurable and services expenditures,

⁹The data is described below.

¹⁰This assumes \mathcal{Y}_t is demeaned.

I_t is real gross private domestic investment plus government investment plus expenditure on consumer durables, and government expenditures on goods and services includes the federal, state and local levels. All of these series are per capita, at constant 1996 prices, and seasonally adjusted at annual rates. We work with civilian employment seasonally adjusted and h is total hours in all non-agricultural establishments. Per capita employment is defined as civilian employment divided by civilian labor force. Per capita hours are total hours over civilian employment times 1369.¹¹

Construction of the depreciation data follows a procedure established by Burnside and Eichenbaum (1996). Capital stock data from the Bureau of Economic Analysis is linearly interpolated from the annual to quarterly frequency. The net stock of capital is composed of residential and non-residential elements plus consumer durables. Burnside and Eichenbaum calculate date t depreciation as

$$\delta_t = 1 - \frac{K_{t+1}}{K_t} + \frac{I_t}{K_t},$$

given quarterly series for K_{t+1} and I_t . According to Burnside and Eichenbaum, this renders δ_t free of measurement error while K_t may be measured with error.

3.4 Calibration

Our shiftwork-RBC model has a large parameter vector. Given the dimension of \mathcal{Y}_t , the implication is that we are limited in the number of model parameters identified by the KF-MLE. Thus, we must calibrate several model parameters.

The calibrated parameters and their values appear in table 1. The values of β , $\phi_{1,A}$, $\phi_{2,A}$, η , τ , and φ shown in table 2 reflect choices made in other RBC studies. Christiano and Eichenbaum (1992a) seem to be the first to set β at $1.03^{-0.25}$. The preference parameters $\phi_{1,A}$, $\phi_{2,A}$, η , and τ are taken from Bils and Cho (1994) and Cooley and Cho (1994). These authors argue these calibrated values reflect a reasonable tradeoff between the evidence from micro studies and the demands of RBC theory.

We select φ to equal 1.56. This is the estimate Burnside and Eichenbaum (1996) report. Conditional on this value of φ and steady state capacity utilization, v^* , estimates δ_0 and δ_1 are available. We use these estimates to evaluate the importance of the rust and dust and wear and tear aspects of depreciation. Note that v^* is set to the sample average of the capacity utilization series constructed at the Federal Reserve Board.

The remaining bit of the calibrate ties down the steady state in the labor market. We have need for four steady state values, e_A^* , h_A^* , e_B^* , and h_B^* . Mayshar and Solon (1993) present evidence that about one-sixth of aggregate employment is sent to the swing shift. Hence, we let $e_A^* = 5\bar{e}/6$ and $e_B^* = \bar{e} - e_A^*$, where \bar{e} denotes the MLE of the aggregate employment e_t . Steady state hours on A shift are calibrated to estimates found in Hall

¹¹The consumption, investment, and government expenditures data is taken from the FRED data bank at the Federal Reserve Bank of St. Louis. Employment and hours series are from the Bureau of Labor Statistics data base.

(1996). His estimates of the lower bound of a fixed length straight time shift imply that an A shift worker spends $0.29 = (451.1 - 48.5)/1369$ per unit of time endowment at the job. The result is that the KF-MLE produces an estimate of h_B^* .¹²

In order to identify the structural parameters of the model, we drop $\ln(G_t/Y_t)$ from the first order autoregressive process of the measurement error process. As a result, this observed variable is tied directly to the model's prediction for the government expenditure shock and the parameters ρ_g and σ_v .

4 Results

Our parameter estimate are reported in Table 2. We find that the standard deviation of the technology shock innovation is low compared to most estimates reported in the literature. Our point estimate for σ_ε is 0.0039, and a 95% confidence interval is (0.0027, 0.0051). This is at least 20% lower than the lowest standard deviation of the TFP component we found elsewhere in the literature. For example, Burnside and Eichenbaum (1996) report a 95% confidence interval of (0.006, 0.008). That is, our model with shiftwork is able to mimic the time series of aggregate variables with considerably less volatility in the technology shock. Furthermore, as seen in Figure 1, the model's estimate of TFP does not exhibit wiggles around the recessions of the late 1960s to early 1970s, the two oil price shocks and the 1990-1 recession. According to our Forecast Error Variance Decomposition (Table 5), in spite of its lower variation, the model's TFP explains more than 20% of the variation of output, consumption and employment for up to five years ($t = 20$) forecast horizon.

The mechanism that allows this model to magnify relatively small technology shocks into large variations in aggregate variables is the late shift. Our model mimics the responsiveness of the late shift to aggregate conditions as reported by Shapiro (1993, 1996) and Mayshar and Solon (1993). A one percent change in aggregate employment implies a 0.79 percent change in the day shift employment, and 2.12 percent in late shift employment¹³. This is because the disutility of hours and employment in the late shift is much higher than the day shift. As can be seen from Figure 3, employment in the late shift varies considerably over the business cycle in a very procyclical manner. The high shift premium required to induce workers to work in the B shift, gives firms the option to cut their employment in the B shift drastically, during times of slow growth. Hence, the cost of recession falls mostly on late shift workers. As can be seen from Figure 3, our estimated late shift employment corresponds very closely to the NBER's peaks and troughs (except 1990-1991). Employment in the day shift is much less volatile than the late shift. The relative volatilities range from 0.145 to 0.223. The hours in the late shift show very weak relation to business cycle variations in the second half of the sample. The steady state estimate of hours in the late shift (h_B^*) is 0.3802. This is higher than in the day shift, since B shift represent the evening and night shift together¹⁴.

¹²These restriction are imposed on the steady state and not on the transition path to the steady state.

¹³This is done calculating the elasticity of e_{it} with respect to e_t ($i = A, B$). Similar result hold for hours..

¹⁴Further allocation of employment between those two shifts are not reliable (see Mayshar and Solon, 1993).

To induce a household to give up home production for B shift production rather than A shift production, requires a shift premium. If we decentralize the economy (like Cho and Cooley (1994)) the wage premium for working in the late shift would be:

$$\frac{\frac{\partial Y_t}{\partial N_{B,t}}}{\frac{\partial Y_t}{\partial N_{A,t}}} = \left(\frac{h_{A,t}e_{A,t}}{h_{B,t}e_{B,t}} \right)^\theta \quad (19)$$

Evaluated at the steady state, this is approximately 47%. This number is relatively higher than numbers reported by micro studies at the plant level. Kostiuk (1990), Bresnahan and Ramey (1994) and Shapiro (1995) report an average shift premium of only five percent in the US. Kostiuk argues that this underestimates the true premium since there is no correction for workers heterogeneity. Shapiro argues that due to rotation and long-term contracts, part of the premium is reflected in higher base wage. When he corrects for this, he estimates the shift premium to be about 25 percent. Studies from the United Kingdom (UK National Board for Prices and Incomes, 1970) report an average wage premium of 25 percent as well. Our higher estimate is a result of two factors. First, we calibrate the steady state employments in the day and night shift to five sixth and one sixth of total employment respectively (Mayshar and Solon (1993)). As seen clearly from (19), it will have a direct effect on the shift premium in the steady state, except the indirect effect on h_B^* . Second, since this is a representative household economy, we can not account for the heterogeneity in labor supply as argued by Kostiuk (1990). In spite of these drawbacks, we believe that our calibration strategy of relying on a fairly reliable estimate of steady state employment in the two shifts, dominates a strategy of matching a shift premium of 25%, which is only roughly estimated for the US economy. A better model, which would account for heterogeneity across households, is left for future work.

Our standard structural parameter estimates are similar to earlier studies that allow for variable capital utilization or overtime (Burnside and Eichenbaum, 1996; Hall, 1996; Ireland, 2001). The capital share is estimated at 30%. Using our methodology of calibrating φ and estimating δ_0 and δ_1 we can not reject the hypothesis of no dust and rust depreciation, while δ_1 is estimated at 0.0281 (p-value is smaller than 1%). Hence our findings are consistent with Burnside and Eichenbaum (1996), and not with the Basu and Kimball (1996) specification of depreciation. This conclusion focuses attention on the role of capital utilization. Its estimated values, using all the sample data, is plotted in Figure 2. Our series is much less volatile than the FRB Capital Utilization series (relative volatility of 0.71), and does not exhibit business cycles movements like the Federal Reserve's series. This series is more persistent than the Federal Reserve's series: half life of its first order autoregressive coefficient is almost 5 years, compared to two years for the FRB's capacity utilization series. This result questions the importance of capital utilization over the business cycle frequency. Although it is possible that with shiftwork, capital utilization operates at lower frequencies, it remains to test whether depreciation itself has a time trend that is independent from capital utilization.

We find that the government spending shock is persistent, ρ_g is estimated at 0.9136. It is interesting that the standard deviation of the innovation in the government spend-

ing shock σ_v is estimated at 0.0123, which is almost three times higher than the standard deviation of the innovation of the technology shock. This finding may be related to our identification strategy that excluded the government spending from the autoregressive process of the measurement error.

The estimated matrix of the first order vector autoregressive measurement error process is reported in Table 3. The process is stationary, with highest absolute eigenvalue of 0.978. The estimated innovations covariance matrix of the measurement error process is presented on Table 4.

4.1 Implication for the Labor Market

Gali (1999) argues that real business cycle theory fails empirically since productivity and hours move in an opposite direction to the positive correlation predicted by RBC. His methodology is to use a structural VAR, identified by the restriction that only technology shocks may have a permanent effect on labor productivity. He reports that the conditional correlation between what he identifies as technology shock (the permanent component of labor productivity) and labor input is negative (-0.82 for hours and -0.84 for employment), while the correlation between the non-technology shock (that is, the transitory component of labor productivity) and labor input is positive (0.26 for hours and 0.64 for employment).

If we use Gali's identification scheme on the estimated values of hours and employment of our shiftwork model, we get the following conditional correlations:

The correlation of the permanent component of productivity (TFP estimated from our model), and hours (employment) is 0.46 (-0.18). The correlation of the transitory component of productivity and hours (employment) is -0.83 (-0.98). If we use the sample hours (employment), instead of the estimated series, the correlation is 0.03 (0.07).

The reason for our results is twofold: first, our TFP estimate is much smoother and less volatile than Gali's. As discussed above, using the standard TFP results in a biased estimate of TFP when there are compositional changes in employment. Second, our decomposition of the labor input into the two shifts, allows to account for relatively higher labor productivity during the late shift. This compositional effect, was suggested before by Mayshar and Solon (1993), Mayshar and Halevy (1997) and Shapiro (1993,1996).

We conclude that rejection of the real business cycle theory based in labor market performance, is unwarranted since the time dimension of labor employment and production is an important ingredient of the this market.

5 Conclusions

This paper presented evidence that shiftwork is an important element of real business cycle theory. We grafted a simple shiftwork structure into a proto-typical RBC model. Estimation of the model finds that shiftwork contributes to smoother, less volatile technology shocks. Although smaller in size, they have an important role in output, consumption and employment fluctuations.

The availability of shiftwork technology weakens the role of capacity utilization for explaining business cycle fluctuations (Burnside and Eichengreen, 1996). However, capacity utilization has an important role in explaining capital accumulation and depreciation dynamics. We found that shiftwork highlights the role of the workweek of capital for business cycle fluctuations (as argued by Shapiro 1993, 1996). Moreover, shiftwork can help to explain the small correlation of productivity and hours (or employment). This is because a model that abstracts from shiftwork, results in a possibly biased estimate of the technology shock.

However, our simple model of shiftwork has some problems that should be worked out in future research. The estimated cost (in utiles) in moving from home production to the swing shift are very high relative to the disutility of working in the day shift (approximately ten fold both in employment and in hours). This translates into a long late shift and a high shift premium. We conjecture that the source of these difficulties is the representative household framework in combination with the empirical observation that the late shift employment is only one fifth of the day shift employment. Furthermore, the model presented above, assumes differential preferences for the timing of employment during the day and night. Future modeling should account for heterogeneity across households as well as to ask the basic question: how did human society converge to a norm in which the great majority of work is done during the same daily time interval? Although it could have been that evolutionary processes caused humans to function as diurnal animals, technology which has been available in the last fifty years (mainly electricity) should have had some mitigating effect and decrease the cost of working in the late shift¹⁵. Answering why the economy is in an equilibrium in which majority of work is done during the day shift, and the late shift serves mainly as buffer should incorporate a fundamental discussion of the aggregate production function, the coordination cost associated with production, and heterogeneity across households.

¹⁵Especially that the cost of working in the day shift has increased due to higher transportation cost (in time) to and from the workplace.

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Table 1: Calibration of Model

Parameters	Steady State
$\beta = 1.03^{-0.25}$	$e_A^* = \frac{5}{6}\bar{e}$
$\phi_{1,A} = 13.50$	$e_B^* = \frac{1}{6}\bar{e}$
$\phi_{2,A} = 1.40$	$h_A^* = 0.29$
$\eta = 2.00$	$v^* = 0.82$
$\psi = 1.67$	
$\varphi = 1.56$	

Table 2: Parameter Estimates

Parameter	Estimate	Standard Error
$\phi_{1,B}$	109.3534	36.9390
$\phi_{2,B}$	12.3622	2.9574
θ	0.2903	0.0082
δ_0	0.0003	0.0008
δ_1	0.0281	0.0011
γ	0.0038	0.0009
σ_ε	0.0039	0.0006
g^*	0.1901	0.0020
ρ_g	0.9136	0.0169
σ_ξ	0.0123	0.0007
$\frac{C}{\bar{Y}}$	0.5869	0.0060
$\frac{K}{\bar{Y}}$	9.0918	0.5367
δ	0.0208	0.0015
\bar{e}	0.9353	0.0068
\bar{h}	0.3084	0.0070
h_B^*	0.3802	0.0422

Table 3: Estimates of AR(1) Matrix of Measurement Error Process

	ΔY_t	$\frac{C_t}{Y_t}$	δ_t	e_t	h_t
ΔY_{t-1}	0.4641	-0.4167	1.3253	0.3421	0.2497
	(0.1107)	(0.0934)	(0.5641)	(0.0473)	(0.0614)
$\frac{C_{t-1}}{Y_{t-1}}$	-0.0189	0.8610	0.3631	0.0153	0.0575
	(0.07102)	(0.0628)	(0.3730)	(0.0283)	(0.0388)
δ_{t-1}	-0.0132	0.0112	0.9350	-0.0007	-0.0019
	(0.0081)	(0.0061)	(0.0310)	(0.0024)	(0.0036)
e_{t-1}	-0.1710	-0.442	-0.0025	0.9796	0.0920
	(0.1185)	(0.1082)	(0.6349)	(0.0453)	(0.0607)
h_{t-1}	0.0339	-0.0017	0.0942	0.0023	0.9636
	(0.0457)	(0.0386)	(0.2119)	(0.0164)	(0.0236)

All variables in logs, modulus of largest eigenvalue is 0.9780, and ML standard errors in parentheses.

Table 4: Estimates of Error Covariance Matrix of Measurement Error Process

	ξ_{1t}	ξ_{2t}	ξ_{3t}	ξ_{4t}	ξ_{5t}
ξ_{1t}	0.0065 (0.0006)	-0.00003 (0.000006)	0.0002 (0.00003)	0.00002 (0.000002)	0.00002 (0.0000003)
ξ_{2t}		0.0065 (0.0004)	-0.0002 (0.000005)	-.0.000001 (0.00002)	-0.00001 (0.000003)
ξ_{3t}			0.0339 (0.0020)	0.00007 (0.00003)	0.00007 (0.00002)
ξ_{4t}				0.0031 (0.0002)	0.00006 (0.00001)
ξ_{5t}					0.0047 (0.00003)

Standard deviations along the diagonal, covariances above the diagonal, and ML standard errors in parentheses.

Table 5: FEVD with Respect to Technology Innovation

Horizon	Y_t	C_t	δ_t	e_t	h_t
1	40.03	56.55	9.95	23.03	7.62
2	42.16	66.61	14.13	32.96	15.66
3	41.67	67.55	13.86	33.90	16.44
4	29.71	56.01	12.22	34.68	16.35
8	19.45	30.26	1.41	36.55	13.89
12	22.34	22.69	2.88	33.46	13.49
16	23.06	24.14	3.22	27.54	14.62
20	23.20	23.66	1.74	23.47	15.95
40	22.80	22.91	0.39	13.72	19.53

Figure 1: Solow Residual and TFP

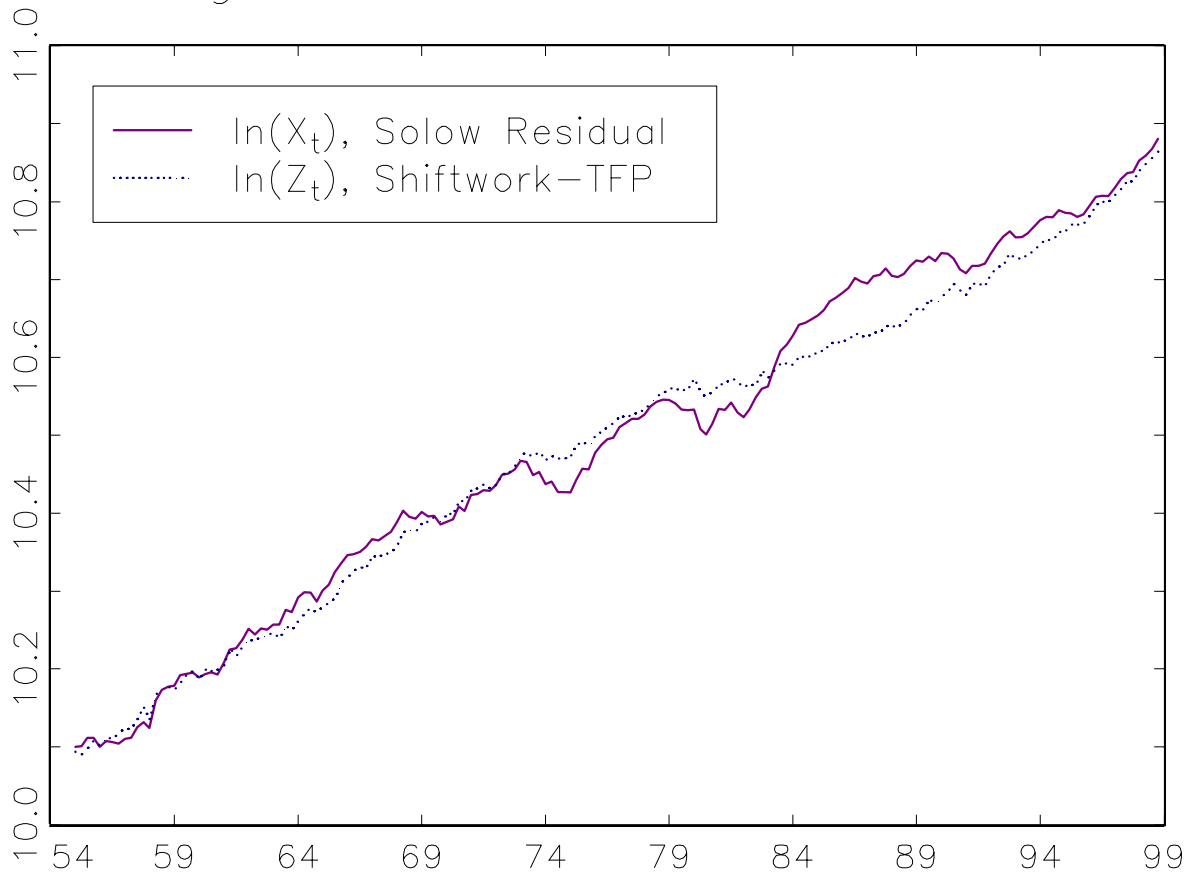


Figure 2: Capacity Utilization under Shiftwork

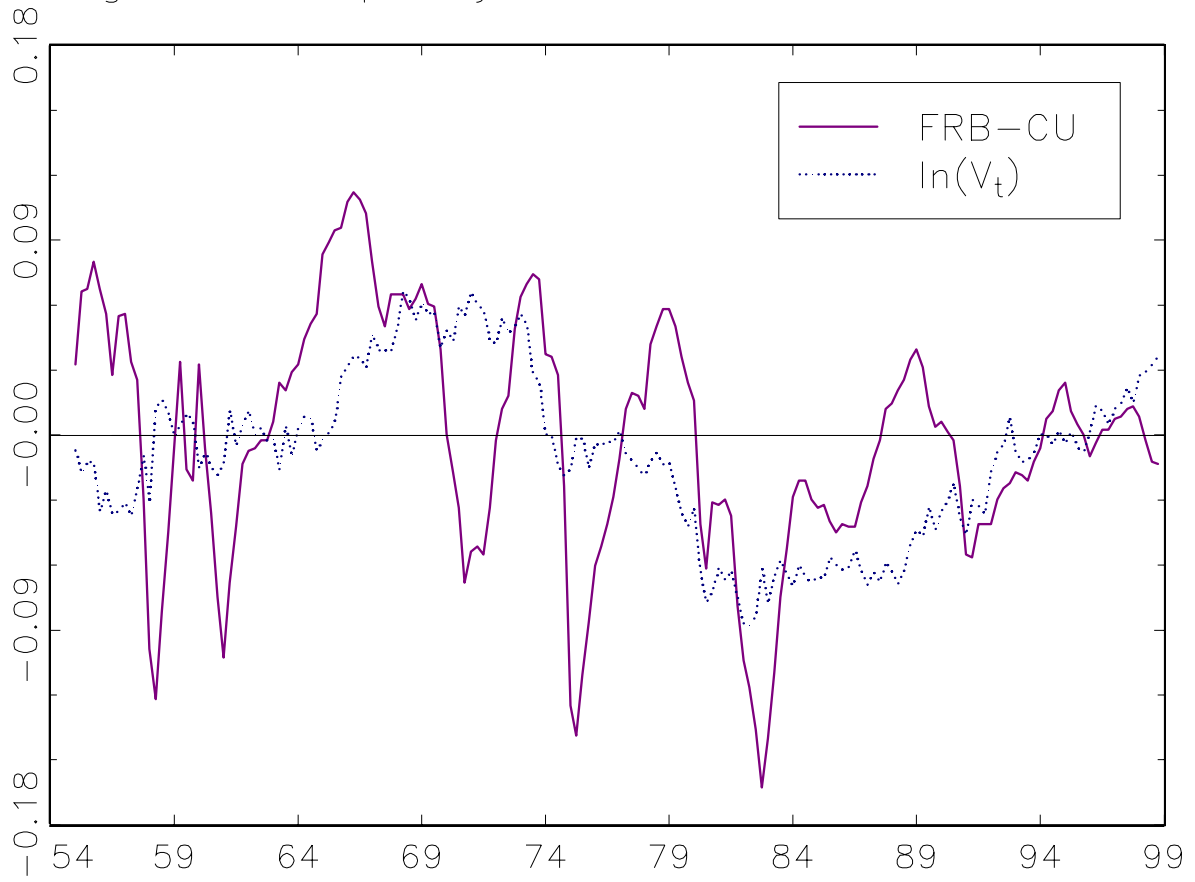


Figure 3: Employment and Shiftwork

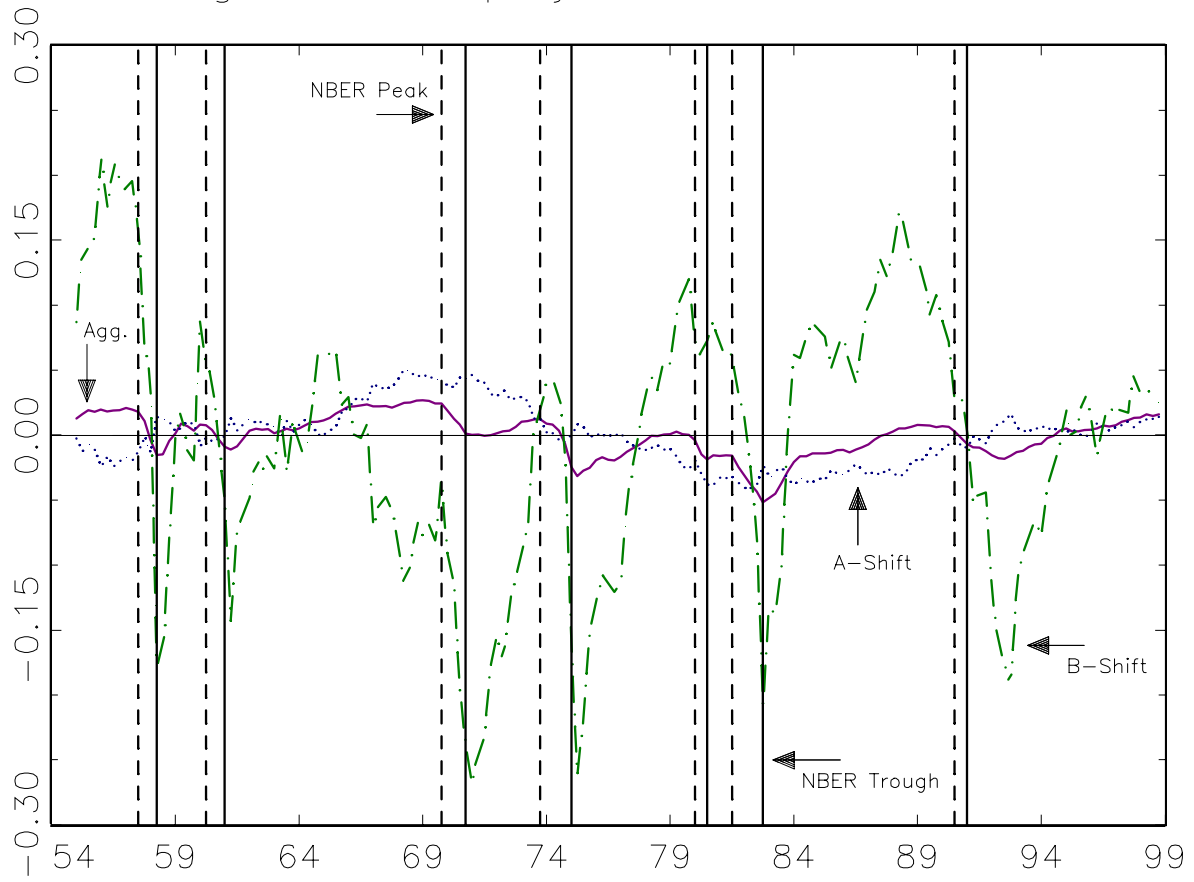


Figure 4: Hours and Shiftwork

