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# Mortality and the business cycle: evidence from an estimated DSGE model for Germany

Farzaneh Shamsfakhr<sup>1</sup>

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## Abstract

This study addresses the relationship between transitory macroeconomic conditions and health by analyzing the dynamics of death over business cycle fluctuations in Germany during 1998:Q4–2014:Q4. A dynamic stochastic general equilibrium (DSGE) model with population growth is developed to incorporate demographic shocks including mortality. The estimation results indicate that mortality in Germany is counter-cyclical, suggesting that health in Germany deteriorates during recessions whereas it improves over economic expansions. Moreover, the structure of mortality is found to vary with respect to the business cycles. While for most of the sample period non-working population seems to be more exposed to death during recessionary times, there are evidences of higher fatality of working people in Germany during the recent financial and economic crisis. In the light of the demographic change that Germany is currently experiencing, findings of this study have important implications for health policies concerning aging as well as working-age population.

## 1 Introduction

While there is not much doubt on the favorable health outcome of long-lasting economic growth, the consequences of short-term economic upturns on individuals' well-being have become quite a controversy. The argument was primarily triggered by Ruhm (2000), who found a pro-cyclical pattern in mortality in the US during 1972–1995. The counter-intuitive nature of Ruhm's finding inspired further analysis on the relationship between mortality, as one of the main indicators of the overall health status, and transitory economic conditions. Similarly, using the same method as Ruhm, Gerdtham and Ruhm (2006) capture pro-cyclical variations in mortality for OECD countries during 1960–1997, which is found to hold for different sources of death in these countries. Besides, additional investigations have been through to unveil the

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different aspects of this phenomenon and the mechanisms at work, which can also be specific to economic and social settings of a country (Lee 1997). Altogether, changes in lifestyle, quality of sleep, nutrition, and leisure time; an increase in work-related strain, working pace, and time; and work-related accidents following strengthening the economy and intense use of labor in response to high demand are identified as the main causes of pro-cyclicality of fatality observed in industrialized countries.<sup>1</sup>

Although based on existing literature one can hardly draw a clear conclusion on the channels through which temporary economic variations can lead to death, mortality is shown to be cyclical and time varying related to business cycles. The current paper aims to examine these features through a unique approach, which has been barely applied by previous studies. I develop and estimate a non-linear DSGE model to investigate the dynamics of mortality over business cycle fluctuations in Germany. This study makes a multi-fold contribution to the existing empirical studies. Firstly, the non-linear estimation allows to capture the possible time variability of mortality variations with respect to economic oscillations. Second, contrary to all the preceding works, no specific restrictive pre-assumption about links between mortality, or other measures of health, and economic variables is imposed in the model; instead, the data is let to talk. Furthermore, observing both variables of GDP and employment in the model allows to track the changes in death with respect to different measures of the business cycle, which in turn reconciles with the prior arguments. Also, the presence of population growth in the model makes it possible to infer the health outcome of both working people and those out of the labor market. In addition, including the components of demographic change in the model enables the study of the behavior of fertility and migration along with mortality. Lastly, since economic enhancement is usually anticipated to be a driver of both output and employment, by involving different shocks in the model, I am able to disentangle, at the same time, the possible effects of technological advances, from changes in hours worked concerning mortality, the task that could not be exercised by traditional empirical analysis.

The rest of this paper is organized as follows: the next chapter has a brief but comprehensive review of the strands of arguments on the health outcome of business cycles. Section 3 outlines the model used for the estimation. The elements incorporated in the model in order to analyze the dynamics of mortality are explained in this chapter. Section 3 describes the data and the estimation strategy. Estimation results described in tables and figures are discussed in details in Section 4. Finally, Section 5 summarizes the findings of the study and concludes.

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<sup>1</sup> Some studies still do not support these notions. A microdata analysis in Finland by Böckerman et al. (2007) shows that obesity decreases during economic upturns measured by employment rate. However, they do not capture any significant effect of economic expansions on physical activity. Likewise, Colman and Dave (2014) find empirical evidence of a drop in fast food intake and expenditure on physical activity during recessions in the US, due to the following income effect on households' resources. Nonetheless, the ultimate outcome on health is shown to be moderate and uncertain. Also, Johansson (2004)'s analysis of average hours worked per employee over economic successions and its transitory effect on health in 23 OECD countries during 1960–1997 indicates that, controlling for income, higher working hours during phases of economic upturns is associated with less mortality.

## 2 Literature review

Ruhm (2000) shows that in the US during 1972–1995 unemployment rate is negatively related to total mortality, as one percentage point increase in state's joblessness declines the fatality rate by 0.5 to 0.6%. He also observes a reduction in physical activity and an increase in smoking, obesity, and unhealthy intake over temporary economic growth in the US. Through a closer examination of microdata, Ruhm (2003) finds that deterioration of physical health during economic upturns is more pronounced among employed Americans.

Neumayer (2004) and Granados (2005) replicate (Ruhm 2000)'s analysis for German and Spanish data, respectively, and find a pro-cyclical pattern for aggregate mortality, and for the majority of death causes in these countries. Granados (2005) attributes the death pattern in Spain mainly to traffic-related injuries, which is amplified following economic recoveries. Similarly, Lin (2009) finds evidences of health improvement over economic downturns in Asia-Pacific countries over the period 1976 to 2003.

On the contrary, some other research captures counter-cyclical patterns of mortality over economic fluctuations. This shape of variations is usually attributed to the pressures of job losses and economic distresses during recessions, which lead to higher stress, and unhealthy behaviors such as greater tendency to smoke and alcohol consumption that impair the health conditions and consequently increase mortality rates.<sup>2</sup> In this regard, it is discussed that the presence of some sort of insurance schemes might alleviate the recessions' hardships that consequently changes the magnitude or direction of effects. However, the cross-country analysis of Gerdtham and Ruhm (2006) suggests the stronger pro-cyclical effects in countries with relatively inferior social security system.

Following these contradictory findings, some literature criticizes the use of unemployment rate as the measure of business cycle due to possible time lags between business cycles and employment variations.<sup>3</sup> Accordingly, based on Probit models, Gerdtham and Johannesson (2005) apply other business cycle indicators rather than unemployment rate including GDP variants and find a counter-cyclical mortality risk that is only significant for men and is more noticeable for working-age ones in Sweden during 1981–1996.

Furthermore, some others have favored studying age-specific mortality instead of overall death fluctuations. Miller et al. (2009) closely searches the mechanisms behind pro-cyclical behavior of mortality in the US captured by Ruhm (2000), by repeating his analysis with lengthy data until 2004 and running the regression for a wider range

<sup>2</sup> Almost all the empirical literature are unanimous that the rate of suicides increases over economic recessions (Ruhm 2000; Granados 2005; Edwards 2008; Lin 2009). The only exception, presumably, is Neumayer (2004) who shows that suicide is pro-cyclical in Germany.

<sup>3</sup> Clark and Summers (1982) also suggest that unemployment rate is a misleading measure of labor market condition since it does not reflect the variations in participation in response to changes in aggregate demand. Instead, employment rate is a better indicator of the labor market dynamics.

of age groups. Their results demonstrate the most (pro-) cyclical mortality rates for those age groups with probably the lowest labor force participation, including the young adults between 18 and 24. However, the age group over 80 contributes the most (about 70%) to overall mortality fluctuations. Based on these findings, Miller et al. suggest that mechanisms behind pro-cyclical behavior of mortality should be sought out of labor market and beyond the individuals' own health and work behavior, factors that Miller et al. attribute to business cycle externalities. They also go rather further by analyzing the age-specific pattern of different causes of death over business cycles, and they find no evidence of work-stress-related deaths among working population. There is more empirical evidence of pro-cyclical variations in the health status of the age groups with small labor market attachments in developed countries (Stevens et al. 2015; Rolden et al. 2013). These findings are suggestive of other contributing factors rather than job-related stress, such as air pollution, social support, or caregiving, in the mortality of elderly people during economic expansions. Comparatively, employing the same approach as Ruhm (2000) for Canadian data, Ariizumi and Schirle (2012) observe that the pro-cyclical pattern found for the US does not hold for aged population in Canada who rather enjoy specific elderly health care facilities provided by the Canadian government. Nevertheless, the working-age population in Canada still shows a pro-cyclical mortality over economic fluctuations.

In addition, it is discussed that the relationship between macroeconomic conditions and mortality may alter over time. Consequently, some recent studies have examined this link with more recent data. Ruhm (2015) extends his analysis to 2009 for the US and concludes that over the last three decades, total mortality changed from being strongly pro-cyclical to being mostly unrelated to business cycles. Similarly, Tekin et al. (2013) do not capture any evidence of the effects of the recent financial crisis on health behavior in the US. Also, based on aggregate data for the US over 1961–2010 and using a time-varying parameter (TVP) model, Lam and Piérard (2017) conclude that in recent years, the destructive influence of increased working hours on individuals' health status during upward economic fluctuations is dominated by the positive effect of medical developments for most of the age groups. Nevertheless, they still observe a pro-cyclical movement in mortality caused by motor vehicle accidents although this pattern has weakened over time.

Finally, some prior research looks at mortality behavior among different socio-economic groups. Edwards (2008) finds that the pro-cyclical mortality in the US is limited to working-age males with high school or higher educational attainment. In addition, Xu (2013) find evidence of worsening the mental health of educated employed individuals during the economic boost.

These studies, although with opposing results, address different aspects of individuals' health behavior over economic fluctuation. Accordingly, the possible dissimilarity in health outcome of working and non-working populations pointed out by the literature is worthy of attention. Nonetheless, as these studies mainly rely on regression analysis, they can be highly subject to omitted variables biases. The DSGE approach employed by this study resolves this quandary also and, at the same time, fulfills some other gaps in the literature.

### 3 The model

The benchmark new Keynesian DSGE model with nominal price and wage rigidities and frictions in consumption and investment introduced by Fernández-Villaverde and Rubio-Ramírez (2006) is employed as the baseline model for this study. In a closed-economy framework, following Burriel et al. (2010), I adjust the model to be expressed in per-capita terms and extended along a balanced steady-state growth path determined by technology and population growth. As described later, the presence of population growth in the model allows to explore the behavior of mortality, as one of the component parts of population change, over business cycle fluctuations. A detailed description of the model is presented below.

#### 3.1 Households

It is assumed that the economy is inhabited by a continuum of homogeneous households indexed by  $j$  with the following lifetime utility function:

$$E_0 \sum_{t=0}^{\infty} \beta^t L_t d_t \{ \log(c_{jt} - hc_{jt-1}) + v \log \frac{m_{jt}}{p_t} - \varphi_t \psi \frac{(l_{jt}^s)^{1+\gamma}}{1+\gamma} \} \quad (1)$$

where  $c_{jt}$  is per-capita consumption,  $m_{jt}/p_t$  per-capita real money balances, and  $l_{jt}^s$  per-capita hours worked.  $L_t$  denotes the size of infinity-lived households that changes by population growth.  $\beta$  indicates the discount factor,  $h$  the habit persistence, and  $\gamma$  the inverse of Frisch labor supply elasticity. Variables  $d_t$  and  $\varphi_t$  represent an intertemporal preference shock and a labor supply shock, respectively, and are formulated as a first-order autoregressive process AR(1):

$$d_t = \rho_d d_{t-1} + \sigma_d \varepsilon_{d,t} \quad \text{where } \varepsilon_{d,t} \sim N(0, 1) \quad (2)$$

$$\varphi_t = \rho_\varphi \varphi_{t-1} + \sigma_\varphi \varepsilon_{\varphi,t} \quad \text{where } \varepsilon_{\varphi,t} \sim N(0, 1) \quad (3)$$

##### 3.1.1 Population dynamics

The size of the household  $L_t$  is supposed to follow a random walk with drift:

$$L_t = L_{t-1} \exp(\Lambda_L + z_{L,t}) \quad \text{where } z_{L,t} = \sigma_L \varepsilon_{L,t} \quad \text{and } \varepsilon_{L,t} \sim N(0, 1). \quad (4)$$

Accordingly, the population growth is defined as follows:

$$\gamma_t^L = \frac{L_t}{L_{t-1}} = \exp(\Lambda_L + z_{L,t}) \quad (5)$$

where  $\Lambda_L$  corresponds to steady-state growth of population.

In demographic terms, the natural change in population is triggered by three components of death, birth, and migration. I use this notion and incorporate these three

features in population growth. This adjustment simply allows the study of the dynamics of mortality within this set-up. By definition, I design the population growth as follows<sup>4</sup>:

$$\gamma_t^L = (\gamma_t^B)^{\alpha_B} (\gamma_t^D)^{-\alpha_D} (\gamma_t^M)^{\alpha_M} \quad (6)$$

where  $\gamma_t^B$ ,  $\gamma_t^D$ , and  $\gamma_t^M$  respectively represent the growth of birth, death, and net migration. Parameters of  $\alpha_B$ ,  $\alpha_D$ , and  $\alpha_M$  indicate the rate of corresponding events. The vital events of births and deaths, also net migration, are supposed to be exposed to three shocks that, in turn, stimulate the changes in population through changes in mortality, fertility, and migration. These processes are accordingly formulated as follows, with persistence around their corresponding mean:

$$\gamma_t^B = \exp(\Lambda_B + z_{B,t}) \quad (7)$$

$$\gamma_t^D = \exp(\Lambda_D + z_{D,t}) \quad (8)$$

$$\gamma_t^M = \exp(\Lambda_M + z_{M,t}) \quad (9)$$

Households can trade an amount of Arrow-Debreu securities  $a_{jt+1}$ , that pay one unit of consumption in event  $\omega_{j,t+1,t}$  purchased by household  $j$  at time  $t$  at real price  $q_{jt+1,t}$ . Households also hold an amount  $b_{jt}$  of government bonds that pay a nominal gross interest rate of  $R_t$ . It is assumed that  $a[1]=0$ ,  $a'$  and  $a''>0$ . In addition, households own the capital  $k_t$  that earns a market real rental rate  $r_t$  and is formed based on following law of motion:

$$\gamma_{t+1}^L k_{jt} = (1 - \delta)k_{jt-1} + \left(1 - \kappa[\gamma_t^L \frac{x_{jt}}{x_{jt-1}}]\right)x_{jt} \quad (10)$$

where  $\delta$  is the depreciation rate of capital and  $\kappa[\cdot]$  is an adjustment cost function such that  $\kappa[\Lambda_x] = 0$ ,  $\kappa'[\Lambda_x] = 0$ , and  $\kappa''[\Lambda_x] > 0$ .  $\Lambda_x$  specifies the growth rate of investment. Given these assumptions, the household's per-capita budget constraint reads as follows:

$$\begin{aligned} c_{jt} + x_{jt} + \frac{m_{jt}}{p_t} + \frac{b_{jt+1}}{p_t} + \int q_{jt+1,t} a_{jt+1} d\omega_{jt+1,t} \\ = w_{jt} l_{jt}^s + (r_t u_{jt} - \Phi[u_{jt}])k_{jt-1} + \frac{1}{\gamma_t^L} \frac{m_{jt-1}}{p_t} + R_{t-1} \frac{1}{\gamma_t^L} \frac{b_{jt}}{p_t} + \frac{1}{\gamma_t^L} a_{jt} + T_t + F_t \end{aligned} \quad (11)$$

where  $w_{jt}$  indicates the real wage, and  $u_{jt} > 0$  shows the intensity of capital utilization. Moreover,  $\Phi[u_{jt}]$  is the physical cost of use of capital in resource terms. It is assumed that  $\Phi[1] = 0$ ,  $\Phi'$  and  $\Phi'' > 0$ . Also,  $T_t$  is the lump-sum transfer, and  $F_t$  is the profit of the firm.

<sup>4</sup> Population aged 15 years and over are considered in this study; thus, the birth variable is entered into the model with a lag of 56 periods, since liveborns normally take 14 years to join the sample population.

Therefore, the first-order conditions for the representative household with respect to  $c_{jt}$ ,  $b_{jt}$ ,  $u_{jt}$ ,  $k_{jt}$ , and  $x_{jt}$  take the following forms:

$$d_t(c_{jt} - hc_{jt-1})^{-1} - hE_t\beta\gamma_{t+1}^L d_{t+1}(c_{jt+1} - hc_{jt})^{-1} = \lambda_{jt} \quad (12)$$

$$\lambda_{jt} = E_t \left\{ \beta \lambda_{j,t+1} \frac{R_t}{\Pi_{t+1}} \right\} \quad (13)$$

$$r_t = \Phi'[u_{jt}] \quad (14)$$

$$q_{jt}E_t\gamma_{t+1}^L = \beta E_t\gamma_{t+1}^L \left\{ \frac{\lambda_{j,t+1}}{\lambda_{jt}} \left( (1-\delta)q_{j,t+1} + r_{t+1}u_{j,t+1} - a[u_{j,t+1}] \right) \right\} \quad (15)$$

$$\begin{aligned} 1 = & q_{jt} \left( 1 - \kappa \left[ \gamma_t^L \frac{x_{jt}}{x_{j,t-1}} \right] - \kappa' \left[ \gamma_t^L \frac{x_{jt}}{x_{j,t-1}} \right] \gamma_t^L \frac{x_{jt}}{x_{j,t-1}} \right) \\ & + E_t\beta\gamma_{t+1}^L q_{j,t+1} \frac{\lambda_{j,t+1}}{\lambda_{jt}} \kappa' \left[ \gamma_{t+1}^L \frac{x_{j,t+1}}{x_{jt}} \right] \gamma_{t+1}^L \left( \frac{x_{j,t+1}}{x_{jt}} \right)^2 \end{aligned} \quad (16)$$

with (marginal) Tobin's  $q_t$ , defined as  $\frac{Q_t}{\lambda_t}$  the ratio of two Lagrangian multipliers in the Lagrangian function related to household's maximization problem.

The differentiated labor supplied by each household in each period  $l_{jt}^s$  is accumulated by intermediate good producers through the following production function:

$$L_t^d = L_t \left( \int_0^1 (l_{jt}^s)^{\frac{\eta-1}{\eta}} dj \right)^{\frac{\eta}{\eta-1}} = L_t l_t^d \quad (17)$$

where  $0 \leq \eta \leq 1$  is the elasticity of substitution among different types of labor, and  $l_t^d$  and  $L_t^d$  represent per-capita and aggregate labor demand, respectively. Subject to this production function, intermediate good producers maximize their profit:

$$\max_{l_{jt}} w_t L_t l_t^d - \int_0^1 w_{jt} L_t l_{jt}^s dj \quad (18)$$

with  $w_{jt}$  showing the differentiated labor wages and  $w_t$  the aggregate wage.

This delivers the per-capita labor demand function and aggregate wage as follows:

$$l_{jt}^s = \left( \frac{w_{jt}}{w_t} \right)^{-\eta} l_t^d \quad (19)$$

$$w_t = \left( \int_0^1 w_{jt}^{1-\eta} dj \right)^{\frac{1}{1-\eta}} \quad (20)$$

Households follow Calvo price setting to set their wages. In this sense, it is assumed that in each period, only a fraction of households  $(1 - \theta_w)$  update their wage  $w^*$  and

the rest  $\theta_w$  index their wage to inflation in the previous period. Indexation is adjusted by  $\chi_w \in [0, 1]$  parameter. This yields the real wage as follows:

$$w_t^{1-\eta} = \theta_w \left( \frac{\Pi_{t-1}^{\chi_w}}{\Pi_t} \right)^{1-\eta} w_{t-1}^{1-\eta} + (1 - \theta_w) w_t^{*1-\eta}$$

### 3.2 Final good producer

Perfectly competitive final good producer aggregates intermediate goods  $y_{it}$  using the following design:

$$y_t = \left( \int_0^1 (y_{it})^{\frac{\epsilon-1}{\epsilon}} di \right)^{\frac{\epsilon}{\epsilon-1}} \quad (21)$$

where  $\epsilon$  is the substitution elasticity among intermediate goods. Maximizing its profit subject to the production function, the final good producer arrives at the following input demand function:

$$y_{it} = \left( \frac{p_{it}}{p_t} \right)^{-\epsilon} y_t^d \quad (22)$$

$$p_t = \left( \int_0^1 p_{it}^{1-\epsilon} di \right)^{\frac{1}{1-\epsilon}} \quad (23)$$

with  $y_t^d$  indicating final good producer's aggregate per-capita demand and  $p_t$  indicating aggregate price.

### 3.3 Intermediate good producers

The technology used by intermediate good producer  $i$  is Cobb-Douglas and expressed (in per-capita terms) as follows:

$$y_{it} = A_t k_{it-1}^\alpha \left( l_{it}^d \right)^{1-\alpha} - \phi \quad (24)$$

where  $\phi$  is the fixed cost of production and  $A_t$  is the level of technology with the following law of motion:

$$A_t = A_{t-1} \exp(\Lambda_A + z_{A,t}) \text{ where } z_{A,t} = \sigma_A \varepsilon_{A,t} \text{ and } \varepsilon_{A,t} \sim N(0, 1). \quad (25)$$

$\mu_t^z$  determines the long-run growth of output and is given as:

$$\mu_t^z = \exp(\Lambda_A + z_{A,t}) \quad (26)$$

In a perfectly competitive factor market, intermediate good producers rent inputs so as to:

$$\frac{k_{it-1}}{l_{it}^d} = \frac{\alpha}{1-\alpha} \frac{w_t}{r_t} \quad (27)$$

These firms also apply Calvo-pricing fashion. Therefore, the price index evolves as follows:

$$1 = \theta_p \left( \frac{\Pi_{t-1}^\chi}{\Pi_t} \right)^{1-\epsilon} + (1 - \theta_p) (\Pi_t^*)^{1-\epsilon} \quad (28)$$

with  $\Pi_t^* = \frac{p_t^*}{p_t}$ .

Accordingly, the first-order condition for the optimization problem of the firms with respect to  $p^*$  reads as follows:

$$E_t \sum_{\tau=0}^{\infty} (\beta \theta_p)^\tau \tilde{\gamma}_t^L \lambda_{t+\tau} \left\{ \left( (1 - \epsilon) \left( \prod_{s=1}^{\tau} \frac{\Pi_{t+s-1}^\chi}{\Pi_{t+s}} \right)^{1-\epsilon} \frac{p_t^*}{p_t} + \epsilon \left( \prod_{s=1}^{\tau} \frac{\Pi_{t+s-1}^\chi}{\Pi_{t+s}} \right)^{-\epsilon} m_{c_{t+\tau}} \right) y_{t+\tau} \right\} = 0 \quad (29)$$

where  $\theta_p$  specifies the Calvo parameter and  $\chi$  is the price indexation parameter. The real marginal cost is indicated by  $m_{c_t}$  and obtained as follows:

$$m_{c_t} = \left( \frac{1}{1 - \alpha} \right)^{1-\alpha} \left( \frac{1}{\alpha} \right)^\alpha \frac{w_t^{1-\alpha} r_t^\alpha}{A_t} \quad (30)$$

The first-order condition can be re-written recursively, in terms of two discretionary terms of  $g_t^1$  and  $g_t^2$ , as the following equations:

$$g_t^1 = \lambda_t m_{c_t} y_t + \beta \theta_p E_t \gamma_{t+1}^L \left( \frac{\Pi_t^\chi}{\Pi_{t+1}} \right)^{-\epsilon} g_{t+1}^1 \quad (31)$$

$$g_t^2 = \lambda_t \Pi_t^* y_t + \beta \theta_p E_t \gamma_{t+1}^L \left( \frac{\Pi_t^\chi}{\Pi_{t+1}} \right)^{1-\epsilon} \left( \frac{\Pi_t^*}{\Pi_{t+1}^*} \right) g_{t+1}^2 \quad (32)$$

Given that with fully flexible prices  $p^* = \frac{\epsilon}{1-\epsilon} p_t m_{c_{t+\tau}}$ , the first-order condition can be expressed as follows:

$$g_t^1 \epsilon = g_t^2 (\epsilon - 1) \quad (33)$$

### 3.4 The central bank

The monetary authority sets the nominal interest rates based on the Taylor rule:

$$\frac{R_t}{\bar{R}} = \left( \frac{R_{t-1}}{\bar{R}} \right)^{\gamma_R} \left( \left( \frac{\Pi_t}{\Pi} \right)^{\gamma_\Pi} \left( \frac{\gamma_t^L \frac{y_t}{y_{t-1}}}{\exp(\Lambda_L + \Lambda_A)} \right)^{\gamma_y} \right)^{1-\gamma_R} \quad (34)$$

The monetary policy is conducted through open market operations that are supported by lump-sum transfers  $T_t$  defined as follows in order to guarantee the zero

deficit:

$$T_t = \frac{1}{\gamma_t^L} \frac{\int_0^1 m_{jt} dj}{p_t} - \frac{1}{\gamma_t^L} \frac{\int_0^1 m_{jt-1} dj}{p_t} + \frac{1}{\gamma_t^L} \frac{\int_0^1 b_{jt+1} dj}{p_t} - R_{t-1} \frac{1}{\gamma_t^L} \frac{\int_0^1 b_{jt} dj}{p_t} \quad (35)$$

Therefore, the aggregated budget constraint of households is given as follows:

$$c_t + x_t = w_t l_t^d + (r_t u_t - \mu_t^{-1} a[u_t]) k_{t-1} + F_t \quad (36)$$

### 3.5 Aggregation

The (per-capita) aggregate demand of the final good is derived as follows:

$$y_t^d = c_t + x_t + \mu_t^{-1} a[u_t] k_{t-1} \quad (37)$$

Considering the production and demand function for each intermediate good and integrating over all firms, one arrives at the following aggregate condition for goods market:

$$c_t + x_t + \mu_t^{-1} a[u_t] k_{t-1} = \frac{A_t (l_t^d)^{1-\alpha} (u_t k_{t-1})^\alpha - \phi z_t}{v_t^p} \quad (38)$$

with  $v_t^p = \int_0^1 \left(\frac{p_{it}}{p_t}\right)^{-\epsilon} di$

For labor market, integrating over all households delivers the aggregate condition as follows:

$$l_t^d = \frac{l_t}{v_t^w} \quad (39)$$

with  $v_t^w = \int_0^1 \left(\frac{w_{it}}{w_t}\right)^{-\eta} di$ , and  $l$  and  $l^d$  indicating (per-capita) aggregate labor supply and labor demand, respectively.

Finally, under the Calvo-pricing setting, price and wage distribution measures evolve as follows:

$$v_t^p = \theta_p \left( \frac{\Pi_{t-1}^x}{\Pi_t} \right)^{-\epsilon} v_{t-1}^p + (1 - \theta_p) (\Pi_t^*)^{-\epsilon} \quad (40)$$

$$v_t^w = \theta_w \left( \frac{w_{t-1}}{w_t} \frac{\Pi_{t-1}^{xw}}{\Pi_t} \right)^{-\eta} v_{t-1}^w + (1 - \theta_w) (\Pi_t^{w*})^{-\eta} \quad (41)$$

## 4 Estimation

### 4.1 Data

Six time series including key macroeconomics variables of real GDP growth, real consumption  $CON_t$  growth, per-capita employment (in terms of hours worked)  $HOURS_t$  growth, in addition to population growth  $\gamma_t^L$  components including the growth rate

of birth  $\gamma_t^B$ , death  $\gamma_t^D$ , and net migration  $\gamma_t^M$  are used to estimate the model. As the model is specified in per-capita, the trivial aggregate variables over population  $L_t$  can be implicitly defined by generic variables as follows:

$$GDP_t = L_t y_t^d$$

$$CON_t = L_t c_t$$

The non-demeaned quarter-to-quarter growth rates calculated as log differences of the variables are used for estimation. To match these observed series with stationarized<sup>5</sup> model variables which are expressed in per-capita in logs, three subsequent measurement equations are included in the model:

$$\begin{bmatrix} D(\log GDP_t) \\ D(\log CON_t) \\ D(\log HOURS_t) \end{bmatrix} = \begin{bmatrix} y_t^d - y_{t-1}^d \\ c_t - c_{t-1} \\ l_t^d - l_{t-1}^d \end{bmatrix} + \begin{bmatrix} \mu_t^z + \gamma_t^L \\ \mu_t^z + \gamma_t^L \\ - \end{bmatrix}$$

where  $\mu_t^z = \frac{A_t}{A_{t-1}}$  indicates the stationary growth rate of technology. Including  $\mu_t^z$  in the observation equations accounts for the mean in the observable growth rates.<sup>6</sup>

The empirical analysis is put through using German data on a quarterly basis during 1998:Q4–2014:Q4.<sup>7</sup> The datasets are collected from different sources. German GDP and consumption series are taken from the OECD statistics database (OECD.stat). The data on total hours worked by part-time and full-time employees in Germany are gathered from the Institute for Employment Research (IAB). Demographic statistics of death,<sup>8</sup> birth, and migration in Germany are captured from the European Commission database (Eurostat). Population aged 15 years or more with foreign citizenship provided based on Labour Force Survey (LFS) are used to extract the figures for net migration to Germany. All the series are on quarterly basis and seasonally adjusted.

## 4.2 Parameters

As a common practice, only a fraction of parameters are estimated and the rest which can not be easily identified in the data are fixed. The calibration of parameters and the choice of the priors for estimated parameters mainly follow the empirical DSGE

<sup>5</sup> The model variables are detrended by technology process  $A_t$ , with the exception of hours worked which are stationary.

<sup>6</sup> It should be noted that population growth  $\gamma_t^L$  does not affect the model variables as they are stated in per-capita terms.

<sup>7</sup> The availability of migration figures constraints the length of the sample. On the other hand, considering the fact that following reunification in 1991, the data from eastern Germany was added to German statistics, this sample time can stay far enough from any possible bias in demographic data induced by discrepancy in life-event patterns between East and West Germany and the significant East–West German migration after reunification.

<sup>8</sup> The age distribution of death is not available for Germany on a quarterly basis and for the sample period. However, according to official statistics, in average, roughly 0.4% of death in each year in Germany is related to the proportion of population below 15 years old, which, in turn, does not raise any concern about biased results.

literature. These parameters are basically constructed based on micro-level data and/or inferred from long-run macroeconomics time series averages. Similarly, the parameters designed based on the US data are usually applied in DSGE models of the Euro Area. Accordingly, a few existing exercises of DSGE model estimations for Germany such as Jondeau and Sahuc (2004), Pytlarczyk et al. (2005), and Hristov (2016) also adopt the standards of parameter values which are mostly drawn from Smets and Wouters (2003).

The values assigned to the prior mean of the three parameters indicating the average birth rate  $\alpha_B$ , mortality rate  $\alpha_D$ , and rate of net migration  $\alpha_M$ , which are specific to this study, are computed based on Germany's statistics on population, live birth, death, and net migration within the sample period obtained from the Federal Statistical Office of Germany (Das Statistische Bundesamt). The prior mean of three other parameters including steady state of mortality growth  $\lambda_D$ , birth growth  $\lambda_B$ , and migration growth  $\lambda_M$  is set based on the arithmetic mean of the corresponding data in the estimation sample.

The choice of prior distributions is based on standard practice considering the theoretical boundaries within which the parameters are defined. Accordingly, the non-negative parameters such as standard deviations of the shocks are assumed to have an inverse gamma distribution. Persistence parameters of shocks, price and wage rigidities, consumption habits, and share parameters in population growth, which are all bounded between 0 and 1, are supposed to follow a beta distribution. The rest of the parameters that are unbounded are assigned a normal distribution. Tables 1 and 2 summarize the parameterization of the model.

**Table 1** Calibrated parameters

Parameter		Value
Discount factor	$\beta$	0.99
Depreciation rate	$\delta$	0.025
Capital share	$\alpha$	0.30
Capital utilization	$\Phi$	4.00
Fixed cost of production	$\phi$	0.00
Capital adjustment costs	$\kappa$	0.001
Indexation wages	$\alpha_B$	0.70
Indexation prices	$\alpha_M$	0.70
Calvo prices	$\theta_p$	0.70
Calvo wages	$\theta_w$	0.70
Elast. of subs. labor	$\eta$	10.00
Elast. of subs. goods	$\epsilon$	10.00
Taylor policy rule inflation	$\gamma_\Pi$	1.50
Taylor policy rule interest rate	$\gamma_R$	0.70
Taylor policy rule output	$\gamma_y$	0.50
Steady-state inflation	$\Pi$	1.00

Table 2 Priors and parameter estimates

Parameter	Prior distribution		Posterior distribution		10%	90%
	mean	stdev.	mean	stdev.		
Habit persistence	$h$	0.70	0.01	0.008	0.70	0.73
Labor disutility	$\psi$	4.00	1.00	0.94	2.37	5.67
Inv. Frisch elasticity	$\gamma$	2.00	0.10	0.06	1.79	2.12
Death rate	$\alpha_D$	0.01	0.0001	0.0001	0.009	0.01
Birth rate	$\alpha_B$	0.009	0.0001	0.0001	0.008	0.009
Migration rate	$\alpha_M$	0.001	0.0004	0.0002	0.0003	0.0009
Persistence of shocks						
Technology growth rate	$\Lambda_x$	0.004	0.001	0.001	0.003	0.005
Death growth rate	$\Lambda_B$	0.001	0.01	0.004	−0.007	0.008
Birth growth rate	$\Lambda_D$	−0.001	0.01	0.002	−0.005	0.002
Migration growth rate	$\Lambda_M$	0.70	2.00	0.41	0.26	1.59
Time preference	$\rho_d$	0.70	0.10	0.01	0.94	0.98
Labor supply	$\rho_\varphi$	0.70	0.10	0.03	0.83	0.90
Standard deviations of shocks						
Technology	$\exp(\sigma_A)$	0.10	2.00	0.001	0.01	0.02
Time preference	$\exp(\sigma_d)$	0.10	2.00	0.01	0.06	0.10
Labor supply	$\exp(\sigma_\varphi)$	0.10	2.00	0.22	0.70	1.37
Death	$\exp(\sigma_B)$	0.10	2.00	0.003	0.03	0.043
Birth	$\exp(\sigma_D)$	0.10	2.00	0.002	0.01	0.021
Migration	$\exp(\sigma_M)$	0.10	2.00	0.29	2.87	3.85

### 4.3 Bayesian parameter estimation

The model presented in Section 3 is estimated using the Bayesian method, in which the prior assumptions on parameter probabilities are combined with the likelihood of the observed data to characterize the associated posterior distributions. The model is simulated and estimated based on the second-order Taylor approximation using the pruning technique. Therefore, particle filtering or the sequential Monte Carlo (SMC) method is used to compute the likelihood function in the Bayesian analysis. The non-linear approximation of the model allows to track any possible time alteration in the relationship between mortality and business cycles, as it is proposed by prior research. By design, Markov chain Monte Carlo Metropolis-Hasting algorithm is employed to evaluate the posterior density. The model here is estimated with two parallel Markov chains of a sample of 100,000 draws. The estimation is tuned to a Monte Carlo-based optimization routine which computes the posterior mode and initializes the Monte Carlo Markov chain (MCMC) simulation. Table 2 presents the mean, standard deviation, and 10 and 90 percentiles of the estimated posterior distributions of the parameters. The corresponding prior distributions are also displayed in the table.

As it is seen, the parameters indicating household's preferences including habit resistance, labor supply choice, and Frisch elasticity are estimated at the mean fairly close to their assumed prior mean. The same stands for the rate of vital events of birth and death. However, the migration rate parameter is approximated at a much lower mean of 0.06%.

The growth rate of technology is estimated at the lower mean than that assigned to its prior reflecting the average long-term growth rate of German output by roughly 0.3% per quarter. Likewise, the growth rate of live birth replicates the average growth rate of the related data over the sample. Mortality growth however is estimated at a lower mean of 0.04%. The growth rate of net migration is approximated at a higher mean of 0.9.

The autoregressive coefficient of both preference shock and labor disutility shock is estimated at a higher mean of 0.96 and 0.87, respectively. The high persistence of the intertemporal preference shock can explain the fluctuations in the German output growth in the long run, whereas the short-lived deviations in real GDP can be mainly attributed to labor supply shocks as the standard deviation of this shock is shown to be estimated at a notably high mean. As the estimates suggest, the volatility of labor supply shock in Germany can be partly related to immigration as the standard deviation of a shock to net migration growth is evaluated at a high mean of roughly 3.4.<sup>9</sup> The standard deviations of the stochastic shocks to technology, time preference, death, and birth growth are rated at the lower mean.

The visual representation of the prior and posterior densities can be seen in Fig. 10 in Appendix. There does not appear to be enough information in the observed data to upgrade the prior distribution of the labor disutility parameter. Comparatively, the

<sup>9</sup> Mode check plots that can be obtained after the run of the model and used as the preliminary identification diagnosis and a reference for checking the assumptions on prior distributions suggest a higher initial mean for standard deviations of labor supply and migration shocks. However, I intended an estimation with harmonized stochastic processes. Instead, as a robustness check, I re-estimated the model with adjusted priors for the aforementioned shocks and I found the results completely consistent.

prior assumption for labor supply elasticity as well as death and birth rate parameters is shown to perfectly mirror the information in the data. In general, the parameters are found to be strongly identified, and the data seems to be quite informative.

In addition, the stability of the estimation is evaluated with Brooks and Gelman (1998) diagnostic tool of MCMC Convergence. Qualitatively speaking, through this method, one can infer if the sample delivered by the MCMC simulation makes a good representation of the posterior distribution. The corresponding results for individual parameters (univariate) and the whole set of parameters simultaneously (multivariate) in the form of graphs are presented in Appendix (Figs. 11, 12, 13 and 14).

#### 4.4 Effect of shocks

The importance of the shocks in explaining macroeconomic fluctuations can be assessed through analyzing the Bayesian variance decomposition, impulse-response functions (IRFs), and historical decomposition obtained from the estimation. These properties are discussed in this section, mainly with the focus on the effect of mortality shock.

##### 4.4.1 Variance decomposition

The result of unconditional variance decomposition is summarized in Table 3. The figures demonstrate the percentage share of the variations in the key observed variables that are explained by three shocks describing the population dynamics over an infinite horizon.

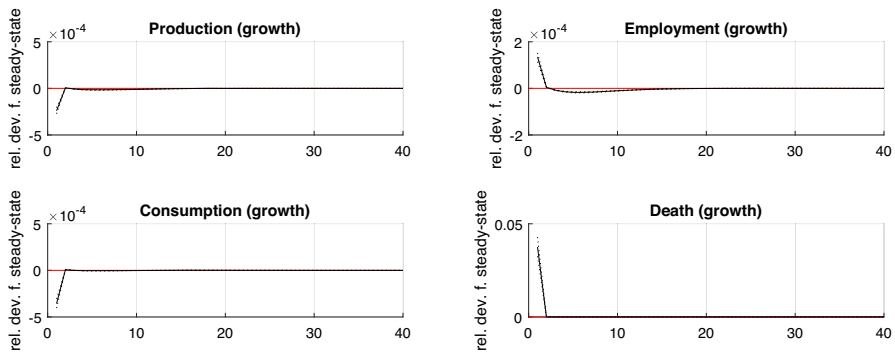
As expected, the major part of the fluctuations in the German economy is determined by other shocks in the model including labor supply, technology, and preference shocks, altogether measure up to more than 98%. The rest is explained by the components of population growth contributing the most to the changes in consumption. Among these three demographic shocks, migration has the most and fertility has the least impact on the German economy. As visible, 0.002 and 0.001% of volatility in respectively GDP and employment growth in Germany is driven by mortality shock.

##### 4.4.2 Impulse-response functions

The reaction of the key variables of the model to stochastic shocks can be identified through IRFs. Figures 1, 2, 3, 4, 5, and 6 depict the trajectory of response of the model to one standard deviation shock over 40 periods (10 years) horizon, drawn as

**Table 3** Variance decomposition

Variable		Shocks	
		Fertility	Migration
GDP	0.002	0.001	0.13
Hours	0.001	0.00	0.04
Consumption	0.02	0.006	1.20

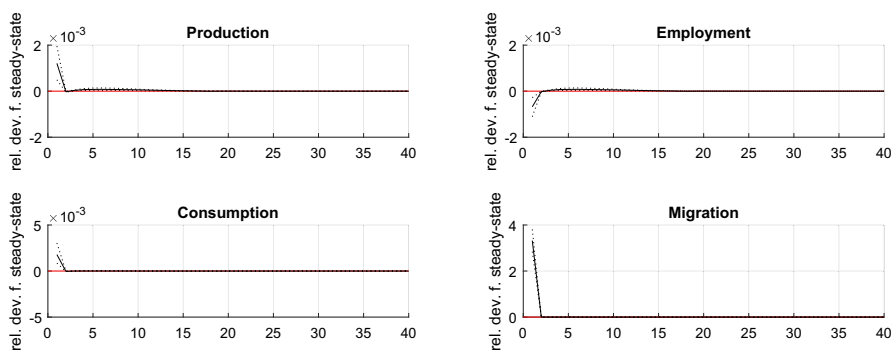


**Fig. 1** Mortality shock

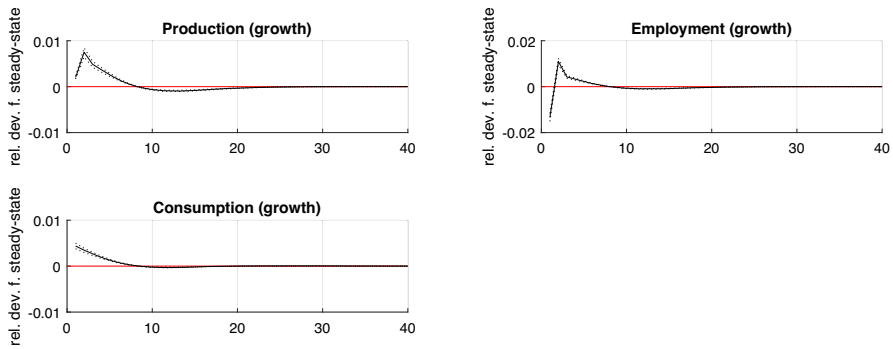
solid black lines surrounded by 90% confidence intervals. Accordingly, the narrow confidence interval seen around the estimated paths indicates a high certainty over the obtained estimates.

As it is seen, the stochastic mortality shock of a size of one percent directly increases the number of deaths by about 0.4%. This leads to a decline in total output growth by about 0.002% and consumption growth by about 0.004%. Following an increase in mortality, the growth of hours worked per head goes up by roughly 0.001% as the first reaction to a fall in the size of the labor force. Nevertheless, within one period, when the impact of the shock seems to disappear, we observe a decline in the supplied labor following the mortality shock. Although the size of the effect on employment is small, it takes about 10 periods to rebound.

Comparatively, the migration shock has a larger impact on the German economy, as 1 standard deviation shock expands the net migration growth by about 3%. This, in turn, adds about 0.01% and 0.02% to GDP and consumption growth, respectively. The effect of the shock on employment is rather small, limiting the growth of hours worked by about 0.007% in the first quarter. Nevertheless, after the first period, there seems to be some small movement in employment stimulated by probably added migrant workers to the market (Fig. 2).



**Fig. 2** Migration shock

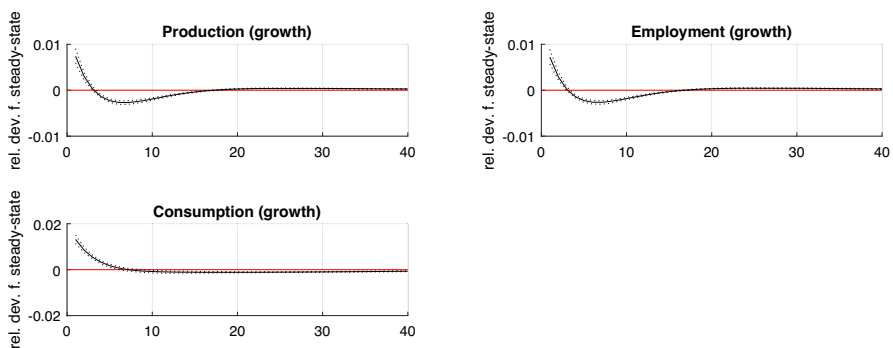


**Fig. 3** Productivity shock

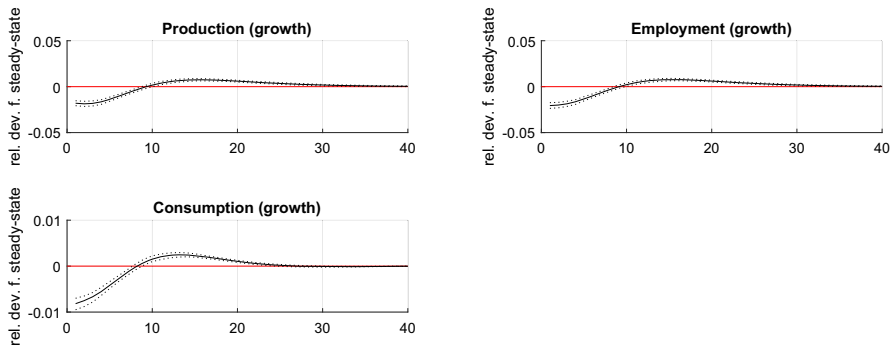
Clearly, a positive shock to technology increases the output and consumption growth in the first period. In response to a 1% shock, output growth goes up by 0.02% and growth rate of consumption by 0.04%. However, in line with Galí (1999), we observe that hours worked respond negatively to the positive technology shock in the first quarter by dropping by about 0.1%. This can be attributed to the price and wage rigidities in the market that lead to a lagged reaction of firms in upgrading the demanded labor services. As can be seen, the growth of hours worked recovers and picks up in the second period that, in turn, reinforces the growth of output. The impact of technology shock to the model fades after almost 20 periods (Fig. 3).

A positive shock to household time preferences encourages their current consumption and increases its growth by 0.1% in the first quarter that consequently boosts the output growth. The following higher demand and production require higher hours of work. As a result, in response to the shock, the growth rate of hours develops by 0.07%. The enhanced growth gradually slows down after the first period, but it takes about 15 periods to rebound (Fig. 4).

In response to a 1% negative labor supply shock, the growth rate of hours worked per unit shortly drops by 0.2%. This translates to a cutback in consumption growth by about 0.08% and a decrease of roughly 0.2% in GDP growth in the first period.



**Fig. 4** Preference shock



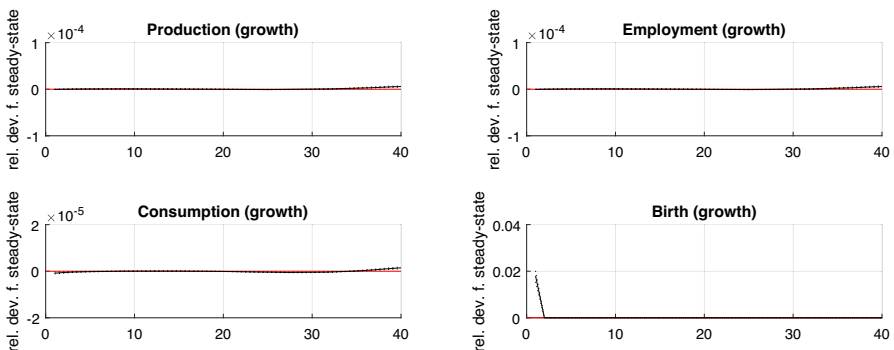
**Fig. 5** Labor supply shock

Following the decrease in employment, the real wages are expected to rise that, in turn, encourage work and subsequently consumption. As a result, as it is evident, in line with employment and consumption, the output growth turns around in the 10th quarter and moves upwards. The volatility caused by the labor supply shock needs about 30 quarters to fade out (Fig. 5).

Finally, a 1% shock to fertility raises the number of live births by roughly 0.2%; however, as expected, this does not have any visible impact on the economy over the first 40 periods after the shock onset (Fig. 6).

#### 4.4.3 Historical decomposition

The contribution of shocks to the historical path of the growth variables can be investigated through historical decomposition figures. As expected, the productivity shock, the preference shock, and the labor supply shock are the main determinants of the change in GDP growth, growth rates of consumption, and hours worked in Germany over the sample time horizon. Accordingly, as the dynamics of mortality is of the main interest in this paper, I focus here only on elements of population change and

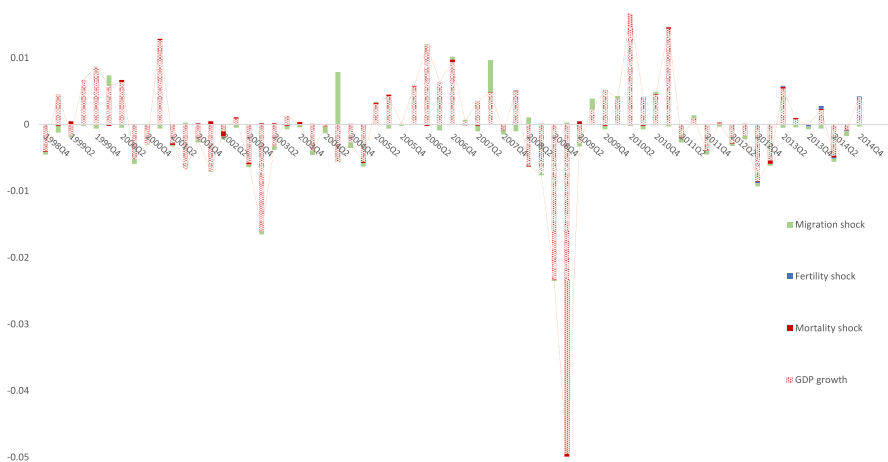


**Fig. 6** Fertility shock

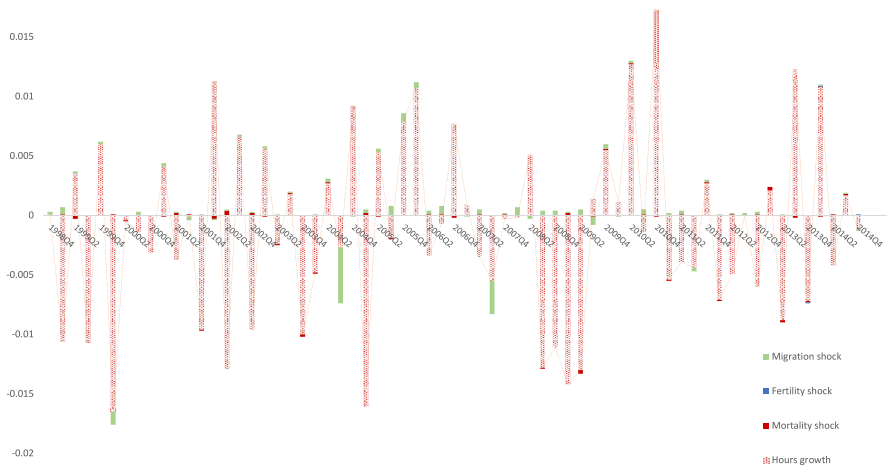
analyze the capacity of a mortality shock, as well as fertility and migration shocks to influence the movement of target variables. Figures 7, 8, and 9 display the historical decomposition of respectively GDP growth rate, consumption growth rate, and growth rate of employment in terms of hours worked. The deviation of the growth variables from their corresponding steady states is plotted in dappled bars. The parts related to the cumulative contribution of shocks to the deviations are filled in solid colors with red, green, and blue representing mortality shock, migration shock, and fertility shock, respectively.

The overall impact of population underlying forces, however small, is obvious, with net migration having relatively the largest and birth event having the least contribution to growth. EU enlargements of 2004 and 2007 and the following labor mobility are clearly captured by the migration shock, indicating a positive contribution of subsequent migration flows to the German production and consumption growth. The positive effect of migration on the German labor market appears to lag. In general, as Fig. 7 suggests, the phases of downward output growth in Germany are correlated with a descending migration growth and contrariwise, displaying a pro-cyclical design of migration in Germany.

Mortality in Germany however shows a different pattern. As Fig. 7 shows, during the sample period, the sequences of upward economic growth are associated with declining death growth while during the episodes of depressed economic growth fatality is seen to develop. Likewise, the negative contribution of the mortality shock to GDP growth during the early 2000s recession as well as the recent financial crisis is worth noting. The negative impact of mortality on GDP growth is especially prominent in the second quarter of 2002 and also in the first quarter of 2009. These evidences demonstrate that mortality in Germany is anti-cyclical. This is in contrast with Neumayer (2004) who finds a negative relationship between the state unemployment rate and aggregate mortality rate for Germany during the years 1980–2000 based on a fixed-effect estimation.



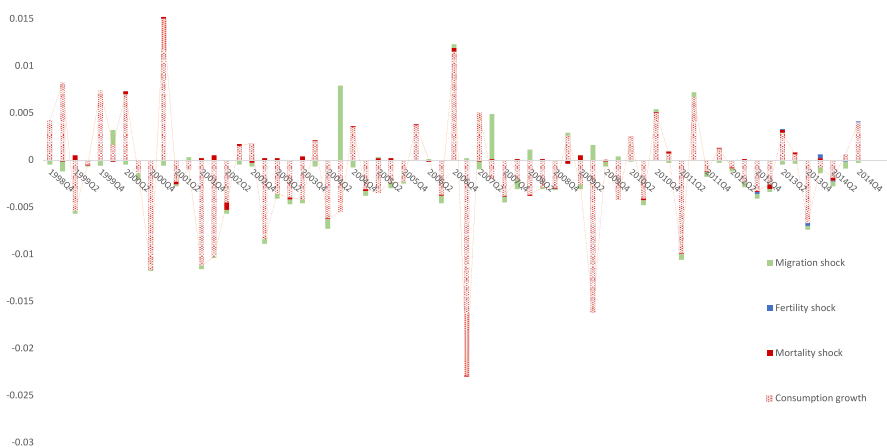
**Fig. 7** Historical decomposition of GDP growth



**Fig. 8** Historical decomposition of employment growth

However, he does not capture a pro-cyclical behavior of mortality for males and for age group 45–65 within a dynamic model.

Tracking the movement of employment over the sample period provides further details on the behavior also structure of mortality in Germany. As an interesting fact, it is seen that except for the periods involved with the recent economic and financial crisis, mortality moves pro-cyclically with respect to employment as the lower growth rate of deaths is shown to proportionately shrink the growth of hours worked (per person) and vice versa (Fig. 8). Since mortality data also includes the population who is out of labor force, this trend, as one could infer, implicitly shows that fatality in Germany mostly involves the non-working population specifically the elderly. However, remarkably, a



**Fig. 9** Historical decomposition of consumption growth

reverse pattern is observed during the Great Recession of 2008. It is seen that in this interval, higher growth of mortality is associated with lower hours worked per person starting in 2008:Q3 when mortality shock is shown to reduce the growth of hours worked. Similarly, following the steep fall in GDP specifically in the first quarter of 2009, we see that developing mortality among people at work mitigates the downward push to employment by a positive contribution to growth of hours worked. In the second quarter of 2009, when the German economy experiences a substantial recovery, the labor market is still slow-moving. At this time, the effect of the death shock on the labor force is relatively strong. It visibly narrows the unemployment and, in turn, absorbs part of the depreciatory impact of sluggish employment growth on GDP. It is plain to see that the mortality shock positively contributes to GDP growth in 2009:Q2.

Lastly, the effect of the fertility shock is observed only at the end of the sample period. It is seen that this shock accommodates a minor part of GDP growth variations from the last quarter of 2014. Likewise, at the same time, this shock marginally contributes to the change in consumption growth. The fertility effect observed here can be mainly attributed to a relatively significant swing in the pattern of pregnancy behavior in Germany during 2002, which, in turn, has delivered a delayed impact on the economy. As the data suggests, there was a relatively strong fall in the number of live births in Germany in the first quarter of 2002 probably resulting from the economic recession involving Germany in the early 2000s. Nevertheless, succeeding the end of recession the country witnessed a large increase in the number of live births in the last quarter of 2002.

#### 4.5 Model evaluation

As the standard practice in the DSGE literature, to assess the fit of the estimated model to the actual data, I compute and compare some statistics generated by the model based on the estimated posterior mean with those of the sample. Motivated by the question of interest, the standard deviation of the growth variable of mortality, in addition to birth and migration growth, and their cross-correlations with contemporaneous output and hours growth are provided and displayed in Table 4.

As is evident, the estimated model is quite effective in replicating the second moments of the actual demographic data in Germany. The volatility inferred by the estimation is almost identical to that of the data. Nevertheless, the model delivers smaller correlations, although with equal signs, with GDP and employment growth compared to what is observed in the data.

**Table 4** Second moments

Variable	stdev.		corr. GDP growth		corr. HOURS growth	
	Data	Model	Data	Model	Data	Model
Death	0.037	0.037	−0.227	−0.072	−0.303	−0.067
Birth	0.015	0.018	0.008	0.005	0.086	0.007
Net migration	3.370	3.326	−0.412	−0.036	−0.060	−0.030

## 5 Conclusion

The impact of transitory macroeconomic shocks on individuals' health status has been questioned by several research. This paper has addressed this issue by analyzing the dynamics of death over business cycle fluctuations in Germany through developing and estimating a non-linear DSGE model that counts for time asymmetries in the data. The results provide evidence of the anti-cyclical of mortality in Germany, suggesting that health in Germany deteriorates during recessions whereas it improves over economic expansions.

Moreover, it is found that the structure of mortality can vary with respect to economic cycles. While for most of the sample period non-working population seems to be more exposed to death, there appears to be a higher fatality of working people during the recent financial and economic crisis. In Germany, working population enjoys favorable insurance schemes and job security provisions that can mitigate the adverse effects of economic hardships; however, this might not be efficient enough under a severe economic downturn. Besides, some other factors outside the labor market can play a determinant role. Perhaps by a deep recession, the opportunity costs of developing unhealthy habits such as alcohol use and smoking among employed people decrease, that consequently impairs their health.

In addition, the counter-cyclical death observed for non-working individuals who are supposedly mostly the elderly<sup>10</sup> shows the vulnerability of older population to economic fluctuation in Germany, although this group has the least attachment to the labor market. Despite the health care insurance coverage for elderly population in Germany, the access of this group to some medical care services might be changing over business cycles.

Overall, the findings of this study highlight the adverse health outcomes of severe economic downturns, underscoring the need for policies that safeguard the health and well-being of the population during economic crises. The recent COVID-19 pandemic was a severe combined health and economic crisis, where government policies could alleviate a part of the economic burden. Notably, during the pandemic, unemployment in Germany increased only moderately, thanks to support measures such as short-time work schemes. These measures likely mitigated the detrimental economic impact of the crisis and their associated effects on public health. However, by forcing an emergency public health response, the pandemic inevitably affected the distribution of public health services. In particular, the public health response prioritized short-term emergency treatment over potential longer-term physical and mental health impairments. Recent studies have highlighted some of the longer-term negative effects of the COVID-19 pandemic on mental health among the adult population (Patzina et al. 2024). Similarly, long COVID, defined as a post-COVID syndrome (Kozłowski et al. 2024), is shown to have had a negative impact on labor supply and labor productivity in the EU (Ramos et al. 2024). This evidence brings to light the need for more targeted interventions that address the longer-term health implications of a crisis and support the most vulnerable groups to these effects.

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<sup>10</sup> According to official German statistics, in average, more than 80% of yearly deaths in Germany is related to people aged over 65 (Statistisches Bundesamt (Destatis), 2017).

## Appendix

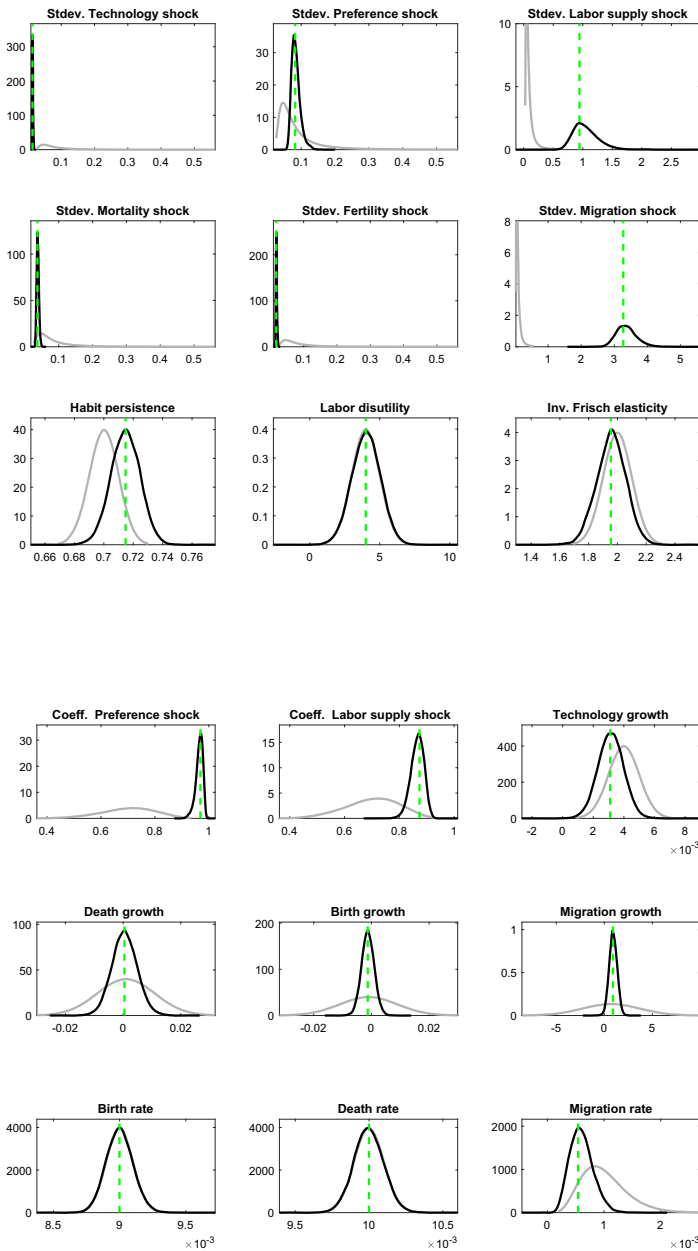
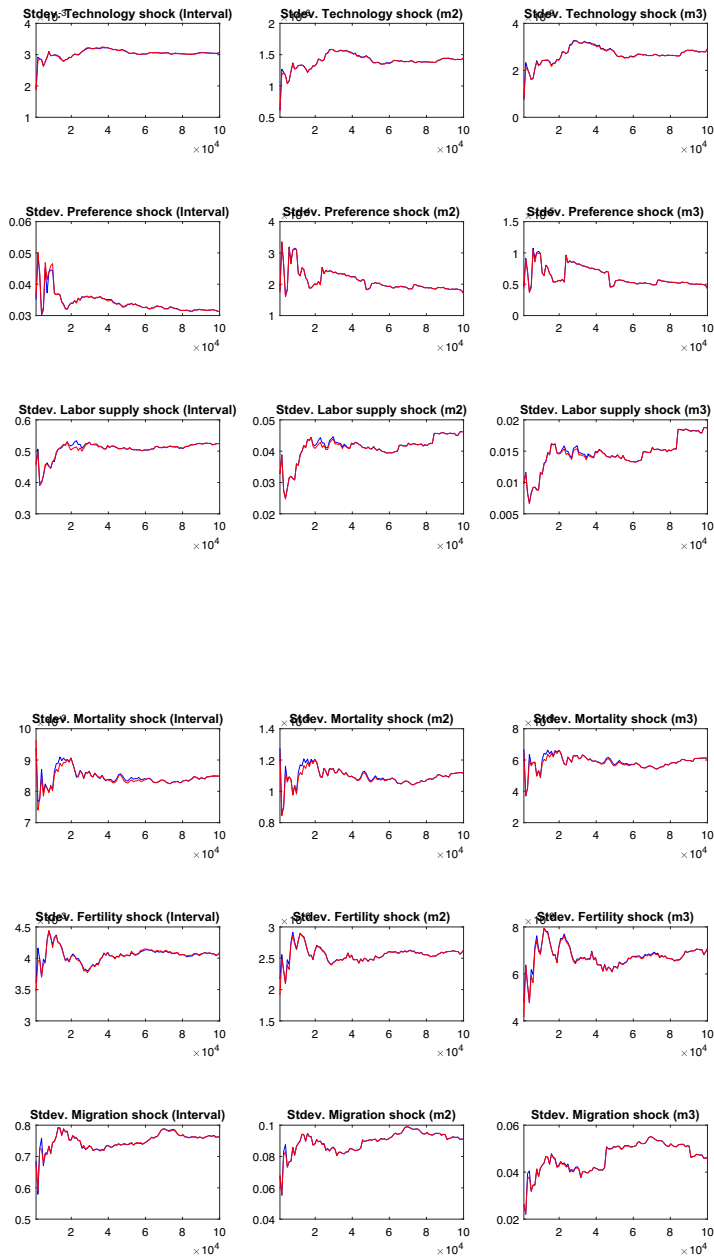


Fig. 10 Prior and posterior distributions



**Fig. 11** Markov chain Monte Carlo univariate convergence diagnostics

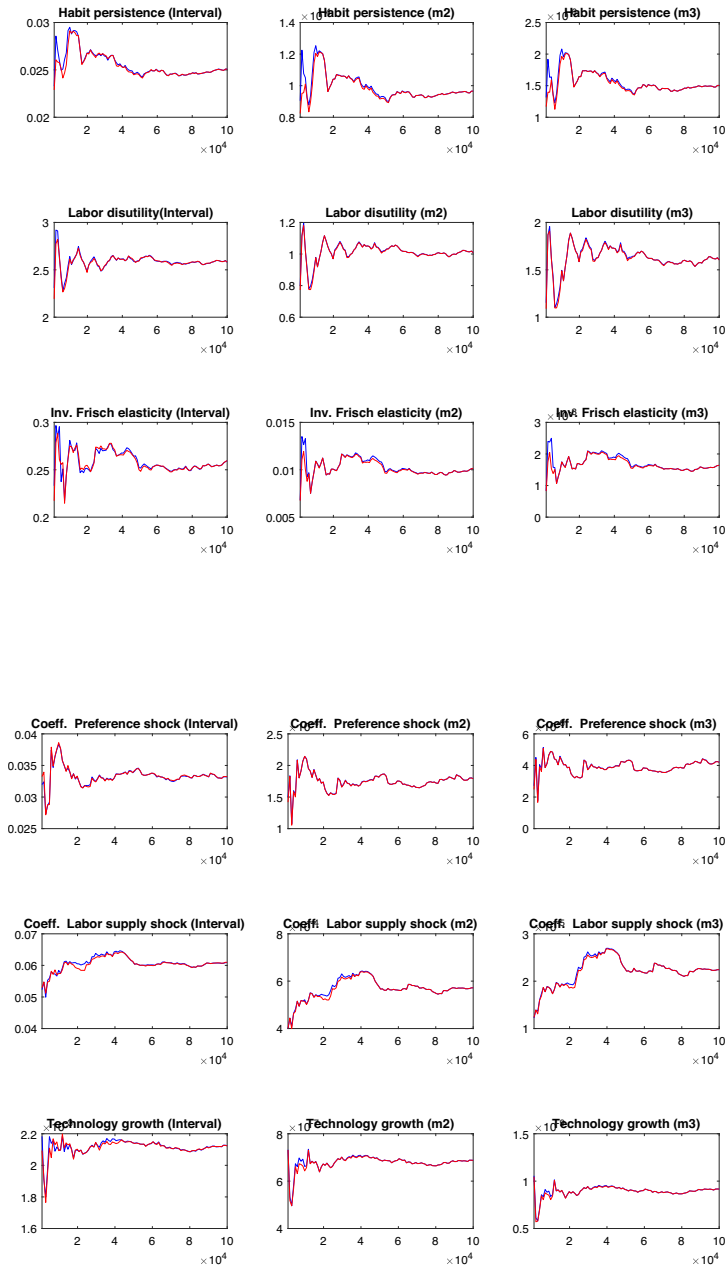


Fig. 12 Markov chain Monte Carlo univariate convergence diagnostics (cont.)

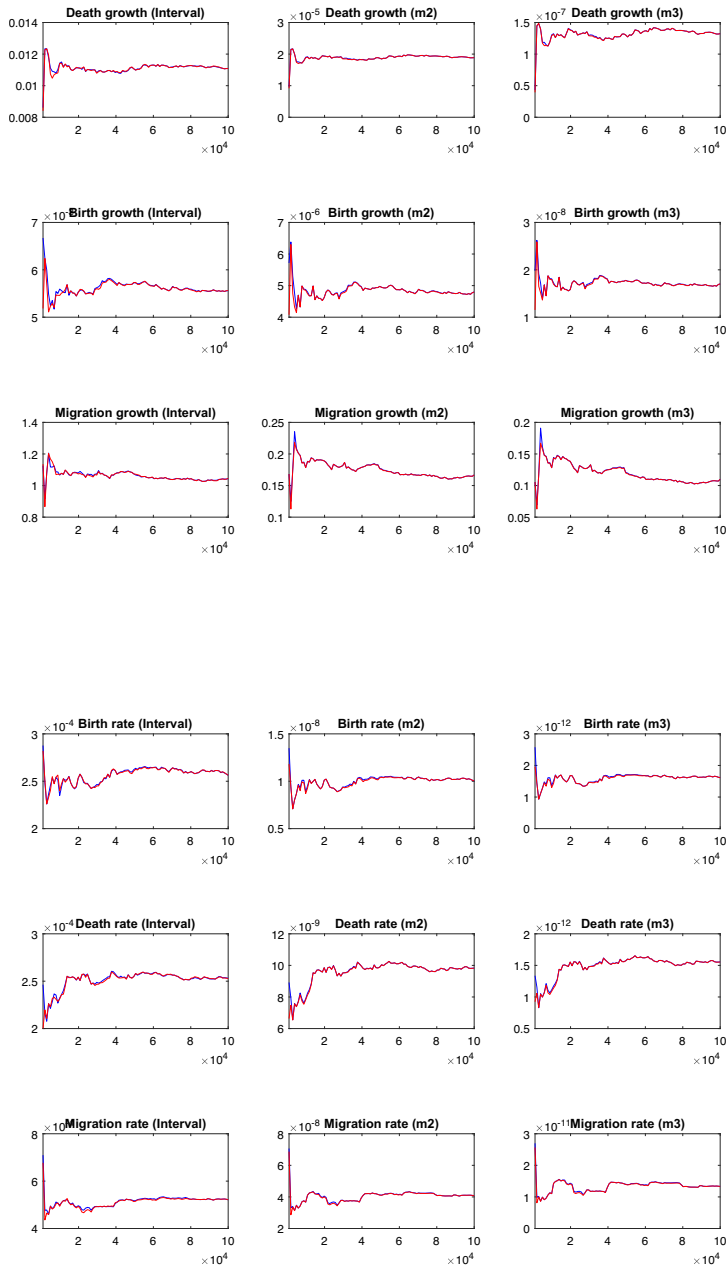
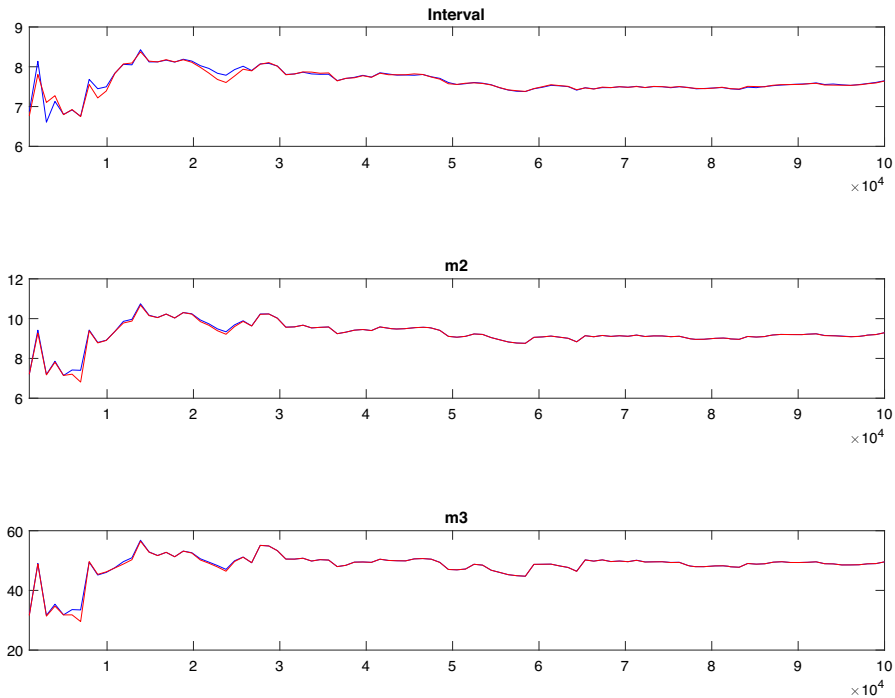


Fig. 13 Markov chain Monte Carlo univariate convergence diagnostics (cont.)



**Fig. 14** Markov chain Monte Carlo multivariate convergence diagnostics

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