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Abstract In this paper I study how financial frictions affect robustness of monetary policy in DSGE models in the case of model uncertainty. The types of frictions I consider are financial accelerator and collateral constraints. Modeling monetary policy in terms of optimal interest rate rules, I find that welfare-maximizing policies for the models with financial frictions are robust to model uncertainty. Policy rule optimal for the basic New Keynesian model is not robust. Thereby I show that when there is uncertainty about what type of frictions is at work, a policymaker exposes economy to risks of significant welfare losses by using a reference model without frictions as economy representation. Using fault tolerance approach I find that modified policy rule optimal for the basic New Keynesian model is robust when it allows to respond to fluctuations in output.

Keywords: Optimal monetary policy rules, Financial frictions, DSGE models, Robustness.

JEL Classification Numbers: E32, E37, E44, E52.

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1 Introduction

It has been claimed that model uncertainty is not a trivial problem for monetary policy-making (Greenspan, 2004; King, 2004). In particular, it is often (if not always) the case that central bank does not know the true structure of economy with full certainty, and thus has to allow for the possibility of economy to be represented by several models. The phenomenon of model uncertainty could be illustrated by a situation when the members of monetary policy committee do not agree on a model that represents the true structure of economy. Thus, a decision on the stance of monetary policy that has to be made by the committee has to be acceptable in all the alternative economy representations in order to be supported by all the committee members, i.e. the policy should be robust to model uncertainty.

A particular relevance of model uncertainty is induced by the fact that in aftermath of the financial crisis 2007-2009 there is a growing debate about what amplification mechanisms are conductive to economic distress. It has been widely acknowledged that financial factors have significantly contributed into the recent economic decline. But which of the factors play the principal role in economic developments is a subject to disagreement; considerable uncertainty surrounds the true amplification mechanism. While there is a number of studies revealing empirical relevance of financial accelerator mechanism: Bernanke et al. (1999), Carlstrom and Fuerst (1997), Mody and Taylor (2004), Aliaga-Diaz and Olivero (2010), Peersman and Smets (2005), Almeida et al. (2006), Cavalcanti (2010); there is also evidence on significance of collateral constraints as a factor behind aggregate fluctuations: Fazzari et al. (1988), Gertler et al. (1991), Gilchrist and Himmelberg (1995), Hubbard et al. (1995), Kashyap et al. (1994). Financial accelerator as a principal factor behind the financial crisis 2007-2009 has been advocated by Krishnamurthy (2010) and Geanakoplos (2009), whereas collateral constraints are supported by Chatterjee (2010) and Peralta-Alva (2011 a,b). Other types of financial factors are also claimed to might have underpinned the crisis: disruption of financial intermediation (Adrian and Shin, 2010; Brunnermeier and Pedersen, 2009; Gertler and Karadi, 2011), the transmission of contagion (Mendoza and Quadrini, 2010), asset price bubbles (Farhi and Tirole, 2011, Martin and Ventura, 2011), credit shocks (Christiano et al., 2008, Del Negro et al., 2010) and other. As a result, different models that incorporate financial factors have been developed recently.

In the meantime there is no agreement about what financial factors are responsible for the recent economic decline, so there is no consensus about what is a "true" model that captures relevant type of frictions. Various models could be used as economy representations for analysis of monetary policy transmission mechanism with different degree of confidence in these models being realistic. This gives rise to relevance of the issue of model uncertainty with respect to financial frictions.

Robustness of monetary policy to model uncertainty has been addressed within several methodological approaches. The first one proposed by Brainard (1967) and developed by Hansen and Sargent (2001a,b, 2002, 2003, 2007) considers robustness with respect to a benchmark model. Alternative models are supposed to lie around the benchmark at some small distance; thus, the set of alternative models could be thought of as being local. Within this approach optimal policy is found by solving minimax problem for the cloud of models surrounding the benchmark. This methodology is employed in a number of works analyzing monetary policy robustness, for example, in Brock and Durlauf (2004, 2005), Giannoni (2002), Marcellino and Salmon (2002), Onatski and Stock (2002) and Tetlow et al. (2001). The range of alternative models considered in these works is restricted by focus of methodology on the small set of reference models; thus, models with significantly different perspectives about inflation persistence, expectations formation or amplification mechanisms could hardly be analyzed in the context of this methodological approach.

An alternative approach to address model uncertainty is model averaging. It was initially advocated by McCallum (1988) who claimed that robust policy should be defined as the one that works well enough in all the models considered; a robust rule might not be the best one for any of the models in the set but it should be acceptable (in terms of losses or welfare costs) for all the alternative models. The principal value of this approach is that it does not require alternative models to be close enough to the benchmark. This is important for analysis of monetary policy transmission mechanism, because possible economy representations are not necessarily similar. Indeed, these are disparate models of economy that one would typically want to take into account when looking for robust monetary policy; this is the case of uncertainty about the factors that are behind the financial crisis of 2007-2009. This is the reason why this paper adheres to model averaging methodology.

Model averaging approach is adopted in a number of works with the aim of arriving at an interest rate rule - Taylor rule or another type of simple rule, - which is robust across a particular set of models. Brock et al. (2007) examine uncertainty about the suite of backward-looking models in style of Rudebusch and Svensson (1999) and hybrid models a la Rudebusch (2002) analyzing model uncertainty with respect to formulations of expectations and lag strength structure. Levine et al. (2008) study different variants of Smets and Wouters model (2003). Levin and Williams (2003) search for a simple rule which is robust to model uncertainty across the set of non-nested models: the basic New Keynesian model, backward-looking model in style of Rudebusch and Svensson (1999) and a hybrid New Keynesian model with backward-looking elements (Fuhrer, 2000). Most of these works analyse the sets of models with competing perspectives about expectations formation and inflation persistence.

In this paper the focus is different. I am motivated by presence of uncertainty about financial factors in DSGE model; therefore I analyze models that are different with respect to financial frictions incorporated in them. In other respects the considered models are similar: in particular, with respect to presence of nominal rigidities in imperfect competition environment, with respect to inflation persistence and expectations' formation. First, this setup allows to see, what impact do different financial factors have on welfare-optimizing policy rules. Second, it reveals whether difference between amplification mechanisms in the models is big enough to generate non-robustness of optimal monetary policy rules. Relevance of robustness' study in this context is stipulated by the fact that adhering to a model that does not capture the "true" type of financial frictions might entail harmful welfare consequences. Thus, I characterize policy rules optimal for each of the models and evaluate welfare consequences of adopting suboptimal policy rules in all the model economies. I also attempt to find policy rules that produce acceptable welfare outcomes in all the models considered: basic New Keynesian model (BNK) , financial accelerator (FA) model and a model with collateral constraints (HCC); I assume that all the models have equal weights as possible representation of economy.

I show that policy rule optimal for the BNK model is not robust to model uncertainty: welfare costs of adhering to it in alternative model economies with frictions are significant, being particularly high for the HCC model. This happens despite the fact that all the models considered put non-competing perspectives about expectations formation and inflation persistence. To see the contribution of financial factors to non-robustness of BNK rule I simulate FA and HCC models with financial frictions in them being inactive. When financial accelerator and collateral constraints mechanisms are "turned off", baseline New Keynesian optimal policy rule yields acceptable welfare outcomes in the FA and the HCC models. Hence, presence of financial factors is the source of fragility of FA and HCC models and the reason of baseline New Keynesian optimal rule non-robustness to model uncertainty.

I demonstrate that policy rules optimal for the FA model and HCC model are robust across the given model set: adopting them in all the models produces acceptable levels of welfare costs. Despite different mechanisms of financial accelerator and collateral constraints - the former works through interaction between firms net worth and their demand for capital, while the latter operates through collateral constraints being tied to housing values on firm and household levels - and despite different types of exogenous shocks hitting economy, both the FA and HCC models call for policy rate to respond to fluctuations in output. In other words, optimal policy in the models with financial factors requires direct output stabilization. This contrasts with optimal policy in the basic New Keynesian setup, when a policymaker aims at price stability and targets inflation, what is sufficient for attainment of the efficient allocation.

Finally, by employing fault tolerance methodology, i.e. by considering welfare implications of deviations from the optimal policies, I obtain the set of policy formulations that are robust to model uncertainty. I demonstrate that significant increase of output coefficient in the policy rule optimal for the basic New Keynesian model results in this rule being robust. I also ascertain that modest changes of parameter values in financial accelerator and collateral constraints models optimal rules do not entail negative welfare consequences. Moreover, welfare improves in the BNK model when increasing interest rate smoothing coefficient in both FA and HCC models' optimal rules.

Monetary policy is modeled here in terms of optimal simple implementable interest rate rules (as in Schmitt-Grohe and Uribe, 2006, Faia and Monacelli, 2005 and Mendicino and Pescatori, 2005). I assume that policymaker is able to commit to a rule. Rules simplicity means that policy rate is a function of a small number of easily observable variables; implementability calls for unique rational expectations equilibrium delivered by a policy rule. Optimality criterion I use is utility-based welfare maximization (as in Schmitt-Grohe and Uribe, 2006 and Faia and Monacelli, 2005). This criterion differs from a conventional approach applied in literature on model uncertainty, which is a quadratic loss function minimization (used, for example, in Cogley and Sargent, 2005, Levin and Williams, 2003, Cogley et al., 2011). On one hand, using welfare maximization to estimate parameters of optimal simple rules allows to stay consistent with microfoundations of the models. On the other hand, this criterion is also not ideal, because within welfare maximization framework it is complicated to incorporate preferences of a policymaker that could affect policy efficiency[1]. Aiming at consistency with models microfoundations, this paper uses maximization of welfare as a criterion of optimality.

In presenting results this paper follows an extension to the model averaging approach proposed by Brock et al. (2007). This extension consists in reporting not only the robust

[1] For example, Caplin and Leahy (1996) and Goodhart (1996) refer to institutional reasons why policymaker might have preference to avoid interest rate reversals. Lowe and Ellis (1997) advocate for relevance of policymakers preferences she might have due to concerns about financial market fragility.

policy rule, but also the effects of model uncertainty, so that a policymaker knows how the form of robust rule is affected by specific characteristics of divergent models taken into account. I disclose degrees of outcome dispersion - how losses associated with optimal policy depend on models - and action dispersion - how optimal policy differs across alternative models.

Another extension of the model averaging approach adopted here is the fault tolerance methodology suggested by Levin and Williams (2003). The aim here is to use fault tolerance approach to ascertain whether robust policy could be attained by appropriate amendment of non-robust monetary policy rule and whether under robust policy rule welfare could be improved across the models by deviating from optimal policy. I propose an extension to this approach here and evaluate how tolerant are model economies in welfare sense to deviations from all the optimal policy rules, what enables me to establish whether and how a policymaker could promote welfare in alternative economy representations by amending a particular policy rule she chooses to follow. I find that modified policy rule optimal for the basic New Keynesian model is robust when output coefficient is sufficiently increased. Though, this modified policy rule is not optimal for any of the models (it does not deliver the highest level of welfare in any of the models), it yields acceptable welfare outcomes in all model economies.

This paper is organized as follows. Section 2 presents three models analyzed for robustness of monetary policy. Section 3 presents the monetary policy setup, welfare measure and discusses the results of robustness analysis. Section 4 investigates fault tolerance of the models. Section 5 concludes.

2 The models

To analyse the impact of different amplification mechanisms on monetary policy robustness the models studied here are similar in many respects but financial frictions. The suite of models includes a basic New Keynesian (BNK) model, a financial accelerator (FA) model and a model with housing and collateral constraints (HCC) model. All the models are forward-looking, contain no inflation persistence and account for nominal stickiness and monopolistic competition. In all the models monetary policy plays an active role in stabilizing economy because of short-term nominal inertia. All the models incorporate monetary policy and technology shocks. In what follows I briefly introduce main characteristics of the models. Detailed exposition of the models is given in Walsh (2010), Christensen and Dib (2008) and Iacoviello (2005). Equilibrium conditions and parameters calibration used for simulations are given in the Appendices A-C.

2.1 Basic New Keynesian model

The basic New Keynesian model is a benchmark model for monetary policy analysis. It has practically become a consensus between empirical relevance, theoretical foundations and oractical usefulness. BNK does not incorporate any financial factors and is a useful benchmark. The BNK model (Clarida et al., 1999) accounts for purely forward-looking output and inflation; dynamics is entirely due to exogenous force processes without endogenous persistence; outcomes depend on agents' expectations. The baseline BNK model features no investment and capital. Equilibrium conditions and calibrated parameter values for BNK model are given in Appendix A.

The version of the BNK model studied here is taken in its standard form as in Walsh (2010). Government spending is added to the model to introduce demand side (government spending) shocks that are absent in the model's formulation in Walsh. Three types of exogenous disturbances are accounted by the BNK model here: shock to government spending, productivity shock and monetary policy shock.

BNK model features a negative effect of interest rate on output. Current output depends on expectations of future consumption. Nominal prices are set based on future marginal costs; this indicates no inertia in inflation. Inflation ultimately depends on movements in marginal costs, associated with variation in excess demand. The monetary policy rule that closes the model is presented in the section 3. It has been demonstrated in the literature that efficiency is fully restored in the BNK model when policy stabilizes economy's average markup at frictionless level (Walsh, 2010; Gali, 2008).

2.2 Financial accelerator model

This model adopts financial accelerator (FA) framework developed in Bernanke et al. (1989). It incorporates credit market frictions by modeling borrowers and lenders of capital explicitly into an otherwise standard New Keynesian setup with nominal stickiness and monopolistic competition. Frictions arise from agency problem caused by informational asymmetries (profitability of borrowers is private information) and entailed agency costs between borrowers and lenders. In the costly state verification setup (Townsend, 1979) the optimal contract is a standard debt contract where entrepreneur's payment is independent of realization of her idiosyncratic productivity. When entrepreneur cannot repay, the lender pays verification cost as a share of entrepreneurs assets and takes over her entire project. So, FA model manifests the cost of external funds higher than the cost of internal funds and thus, sets out how procyclical net worth of borrowers affects demand for investments, giving rise to shocks amplification. Thus, exogenous disturbances are propagated in the FA model due to the fact that net worth depends on return to capital disproportionally due to the leverage effect.

Here the FA model specification follows Christensen and Dib (2008). Apart from monetary policy and productivity shocks, the FA model features preference shock, money demand shock and investment specific shock. As argued in Bernanke et al. (1999) and Christensen and Dib (2008), investment specific shock is an important exogenous force driving FA model economy; provided with sufficient disturbance of investment specific shock FA model explains important features of business cycle data. The role of financial accelerator mechanism in investment fluctuations depends on the nature of the shock generating them. Financial accelerator amplifies and propagates the effects on investment of demand shocks - monetary policy, money demand and preference shocks. At the same time financial accelerator pushes down the response of investment to supply side shocks - technology and investment-efficiency shocks (Christensen and Dib, 2008). Real distortions introduced to this model imply that there is a trade-off for a policymaker between inflation and output stabilization. It has been shown by Edge (2003) that lifetime utility-based welfare of the model with endogenous capital without financial accelerator could be approximated by variances of inflation, output gap and investment spending gap. Equilibrium conditions and calibrated parameter values for the FA model are given in Appendix B.

2.3 Model with collateral constraints

This New Keynesian model accounts for housing and collateral constraints (HCC) and incorporates three types of agents: entrepreneurs, impatient (liquidity-constrained) and patient (unconstrained) households. The source of friction in this model is difference in discount rates of different agents. As proposed by Iacoviello (2005), HCC model incorporates housing used by the borrowers - entrepreneurs and constrained households - as collateral.

The HCC model incorporates rich endogenous propagation mechanism that conducts exogenous disturbances to affect output: beyond workings of financial accelerator the change of asset prices affects borrowing capacity of the debtors. Assuming that constrained households have a strong preference for current consumption, growing housing prices induce more than proportional rise of borrowing and consumption, which in its turn has an influence on aggregate demand. Debt deflation also contributes to the changes in value of the borrowers net worth. Thus the demand shocks are amplified in the HCC model. At the same time inflation depresses the impact of supply shocks that induce negative correlation between output and inflation. So, the impact of supply shocks in this model is contracted in the same way as in the FA model. In addition to monetary policy and productivity shocks the HCC model accounts for cost-push shock, housing price shock and preference for housing shock. It has been shown by Andres et al. (2010) that lifetime utility-based welfare could be approximated by variances of inflation, output gap, consumption gap between constrained and unconstrained households and distribution of housing between three groups of agents. The specification of the HCC model used here is taken from Iacoviello (2005) unaltered. Equilibrium conditions and calibrated parameter values for HCC model are set in Appendix C.

3 Monetary Policy and Welfare Measure

I assume that monetary policy is conducted by means of interest rate rule - a plan for the path of interest rate that a policymaker commits to abide by forever. This rule provides a clear policy objective, but in reality there is a room for discretion. Interest rate reaction function is simple, optimal and implementable in style of Schmitt-Grohe and Uribe (2006). Their formulation is that, first, interest rate should be a function of a small number of easily observable variables. Second, this reaction function should maximize social welfare. Third, the rule should deliver a unique rational expectations equilibrium.

I assume that monetary policy is conducted by means of policy rule of the following form:

$$\ln(r_t/r) = \rho * \ln(r_{t-1}/r) + \alpha_\pi * \ln(\pi_t/\pi) + \alpha_y * \ln(y_t/y) + \epsilon_t \tag{1}$$

where r_t is the gross nominal interest rate, π_t is inflation rate and y_t is output. The variables without subscripts denote steady state values of these variables. Thus, this policy rule features deviations of each variable from its steady state value. The parameter values in the BNK and HCC models are calibrated such that the steady state value of inflation is set to zero.

I assume that policymaker commits to the rule (1) and maximizes social welfare subject to the models' equilibrium conditions and to a policy rule to find optimal parameter values ρ, α_π and α_y. Welfare in the BNK model could be approximated by a quadratic loss function, which is a weighted sum of inflation and output gap variances (see Woodford (2003), Gali (2008) and Walsh (2010)). FA and HCC models have more complex structures featuring financial distortions. Approximation of representative agent welfare in FA and HCC frameworks in the context of linear-quadratic approach has not been implemented yet to the best of our knowledge. In this paper welfare is evaluated numerically.

To draw inferences about robustness of optimal rules I run each of three model economies with all the policy rules and evaluate welfare costs of adopting suboptimal rules in them. First, I evaluate welfare in the BNK, FA and HCC models sequentially applying alternative specifications of (1), which are three simple policy rules evaluated as being optimal (i.e. maximize welfare of representative agent) for the models. Second, I compute welfare costs of adopting alternative rules relative to the equilibrium path associated with the optimal rule. In doing this I rely on second-order approximation of the model's solution. The first-order approximation is not acceptable for the purpose of welfare comparison, because the implied expected values of variables coincide with their non-stochastic steady state; as a result, the volatility effect on variables is neglected (more on this is in Kim and Kim (2003) and Schmitt-Grohe and Uribe (2006)) and all alternative policy rules yield the same level of variables in non-stochastic steady state.

The welfare associated with the optimal policy rule conditional on a particular state of the economy in period 0 is:

$$\widetilde{W_0} = E_0 \sum_{t=0}^{\infty} \beta^t U(\widetilde{C}_t, \widetilde{N_t}) \tag{2}$$

where E_0 is conditional expectation over the initial state and $\widetilde{C}_t$ and $\widetilde{N_t}$ are contingent plans for consumption and hours worked under the optimal policy rule. Analogously, the welfare associated with the alternative policy rule conditional on a particular initial state of economy is an appropriate aggregation of contingent plans for consumption and hours under an alternative rule C_t^a and N_t^a:

$$W_0^a = E_0 \sum_{t=0}^{\infty} \beta^t U(C_t^a, N_t^a) \tag{3}$$

The use of conditionally expected discounted utility of the representative agent allows to account for transitional effects from non-stochastic steady state to an equilibrium path implied by alternative policy rules.

Welfare costs λ are measured as a fraction of consumption a representative household would agree to be compensated with in order to gain the same level of welfare as under the optimal rule:

$$W_{0,\lambda} = E_0 \sum_{t=0}^{\infty} \beta^t U(C_t^a(1+\lambda), N_t^a) = \widetilde{W}_0 \tag{4}$$

The level of λ for the HCC model is obtained by solving (4) for the given specification of utility function in HCC model (Appendix C):

$$\lambda = \exp((\widetilde{W}_0 - W_0^a) * (1-\beta)) - 1 \tag{5}$$

In calculating welfare cost for the HCC model I only account for welfare of patient (unconstrained) households; welfare of entrepreneurs and constrained households is disregarded as fractions of their consumption in the total welfare in negligibly small.

Because it is impossible to derive the level of λ analytically for the BNK and FA models given complex utility functions specifications, I evaluate welfare costs for these models by numerical search for λ over the grid so that condition (4) is satisfied.

An alternative measure of optimality - policymaker's loss function minimization - is also used here. This optimality criterion is commonly used in literature on monetary policy robustness[2]. Period objective function of policymaker takes the form:

[2]Quadratic loss function minimization as an optimality criterion is used in Clarida et al. (1999), Cogley and Sargent (2005), Levin and Williams (2003), Cogley et al. (2011), etc.

$$L = var(\pi_t) + \lambda_y * var(y_t) + \lambda_{\Delta r_t} * var(\Delta r_t) \quad (6)$$

This loss function approximates representative agent welfare appropriately only for the BNK model. The use of this loss function for the other models is justified by the fact that policymaker might have preferences for inflation targeting, interest rate smoothing and output gap stabilization. Ability of loss function (6) to capture different types of policymaker's preferences makes this optimality criterion more flexible than representative agent welfare maximization. For example, setting λ_y and $\lambda_{\Delta r_t}$ to zero lets to consider the case of strict inflation targeting policy. Setting $\lambda_y = 1$ enables to analyse the case of equal preferences for inflation and output gap stabilization, whereas $\lambda_y = 2$ is the case of strong preference for output gap stabilization. Besides, not utilising the representative agent assumption could be regarded as an advantage of this approach as it could be misleading for welfare distribution/inequality analysis. As argued in Levin and Williams (2003), there is no consensus about the "correct" values of weighting λ_y and $\lambda_{\Delta r_t}$ parameters. In this paper I use loss function specification for the grid of values for λ_y and $\lambda_{\Delta r_t}$: $\lambda_y = 0, 0.5, 1$ and 2 and $\lambda_{\Delta r_t} = 0, 0.5$ and 1. Here I only report results for two sets of preferences: strict inflation targeting ($\lambda_y = 0$ and $\lambda_{\Delta r_t} = 0$) and inflation and output gap stabilization ($\lambda_y = 1$ and $\lambda_{\Delta r_t} = 0$).

For each model I search numerically for parameter values ρ, α_π and α_y that maximize households' welfare. I also search for values of ρ, α_π and α_y that minimize policymaker's loss function. These parameter values specify optimal simple rules for every model. Parameter ρ is restricted to lie on the interval [0, 0.99], α_π - on the interval [1, 3] (values below 1 result in rational expectations equilibrium indeterminacy) and α_y - on the interval [0, 3][3]. In this numerical search I solve the models to obtain second order approximation of the policy functions around non-stochastic steady state. The parameters of the optimal policy rules that maximize representative agent welfare are shown in Table 1.

[3]These intervals are conventional for the search of optimal parameter values in the literature (see, for example, Schmitt-Grohe and Uribe, 2006). Values outside of these intervals are disregarded on the ground that they don't result in non-negligible welfare improvement.

Table 1: Models' optimal rules - utility-based welfare maximization

Model	ρ	α_π	α_y
BNK	0.52	3	0
FA	0.16	3	0.78
HCC	0	3	0.86

Policy rule optimal for the BNK model features strong reaction to variations in inflation ($\alpha_\pi = 3$), no response to output gap ($\alpha_y = 0$) and a moderate degree of interest rate smoothing ($\rho = 0.52$), what is a well-known result for this type of model (see, for example, the result of optimal simple rules evaluation in Justiniano et al. (2013), Schmitt-Grohe and Uribe (2006) or in Levin and Williams (2003)). The FA optimal rule is characterized by the sizable reaction to deviations of output ($\alpha_y = 0.78$), strong responses to inflation ($\alpha_\pi = 3$) and a relatively small degree of policy rate inertia ($\rho = 0.165$). Rule optimal for the HCC model features the strongest among all the models reaction to output fluctuations ($\alpha_y = 0.86$), strong reaction to inflation ($\alpha_\pi = 3$) and no interest rate smoothing ($\rho = 0$).

All the models' optimal rules feature importance of inflation stabilization: α_π coefficient takes its highest possible value 3 in all the rules. This happens due to presence of nominal rigidities and due to inflation being forward-looking in all the models. Price dispersion is the main source of welfare costs in all the models, hence the call to minimize it. The rules differ in their ρ and α_y values. In the FA and HCC rules larger response of policy rate to deviations in output and small/no degree of interest rate smoothing characterize their aggressiveness. First, presence of real distortions in the FA and HCC models implies that "divine coincidence" does not hold in them. Thus, a policymaker faces trade-off in output and inflation stabilization. The FA and HCC optimal rules call for sizable response to output fluctuations, what makes them more aggressive comparing to the BNK rule. In the baseline NK model optimal policy replicates flexible price equilibrium allocation (Gali, 2008); strict inflation targeting is optimal in this model as policymaker does not face a meaningful policy trade-off. Second, absence or very small interest rate inertia in the FA and HCC rules features their aggressiveness, because it implies that policy rate should only react to variables' fluctuations in the current period with no backward-looking component in it. This constrasts with the sizable degree of inertia of the BNK policy rule that calls for more cautious policy in the short run[4]. Smoother changes in policy rate are welfare-improving in the baseline model, because they facilitate agents to anticipate policy and predict interest rate and thus improve short run trade-off between output and inflation stabilization in absence of real distortions.

Optimal policy rules are different not only due to different amplification mechanisms in the models, but also because of different structure of optimality criteria. Utility-based welfare measure of the BNK model can be appriximated by the weighted average of inflation and output variability[5], what is not the case for the financial frictions models. Linear quadratic approximation of welfare measure for the FA model includes investment spending gap, so that the composition of output matters in this model[6]. Welfare losses in the collateral constraints model have been shown to be approximated by variability of consumption gap between constrained and unconstrained households and distribution of housing between firms, constrained and unconstrained households[7]. Thus, it would be inappropriate to see the source of welfare losses in the FA and HCC models only in inflation and output variability.

Table 2: Conditional welfare costs

Model	BNK rule	FA rule	HCC rule
BNK	0	0.002	0.003
FA	1.16	0	0.001
HCC	7.67	0.06	0
FA no frictions	0.55	n/a	n/a
HCC no frictions	1.66	n/a	n/a
FA no frictions and model-specific shocks	0.21	n/a	n/a
HCC no frictions and model-specific shocks	0.64	n/a	n/a

Conditional welfare costs are measured by $\lambda * 100\%$.

Evaluation results of welfare costs of following suboptimal policy rules in all the model economies are shown in the Table 2. BNK rule adopted in the FA model entails welfare costs

[4]Significant interest rate smoothing as an optimal policy has also been found by Schmitt-Grohe and Uribe (2006)

[5]See Woodford (2003), Walsh (2010), Gali (2008), etc.

[6]This is demonstrated in Edge (2003).

[7]Demostrated in Andres at al. (2010).

of 1.16% of consumption, in the HCC model - 7.67% of consumption. These are unacceptable levels of welfare losses[8]. Adopting the FA and the HCC rules delivers acceptable welfare losses in all the models with the losses being the smallest on average in the case of HCC rule. Hence, the HCC rule would be the first-best to adopt in case of model uncertainty about financial factors. At the same time the HCC model is themost fragile to suboptimal policy formulations, as welfare losses in the HCC model are the highest: 7.67% under the BNK rule and 0.06% under the FA rule[9].

BNK optimal rule yields welfare detrimental outcomes in the models with financial frictions due to absence of reaction to output fluctuations in this rule[10]. High welfare costs in this case are due to real imperfections and increased variability of output. Thus, BNK rule is not robust to model uncertainty.

The parameters of the optimal policy rules that minimize loss function are shown in Tables 3 (for the case of strict inflation targeting) and 4 (for a policymaker's preference for both inflation and output gap stabilization). I include Rudebusch and Svensson (1999) macroeconometric model (RS) in the set of models here. This model does not have microfoundations, so it is impossible to analyse it together with other New Keynesian models when utility-based welfare optimality criterion is used. However, ths is a feasible exercise when the loss function minimization optimality criterion is utilized.

Table 3: Models' optimal rules - quadratic loss function minimization. Strict inflation targeting.

Model	ρ	α_π	α_y
BNK	0.85	3	0
FA	0.5	3	0
HCC	0.85	3	0
RS	0.7	2.15	1.5

Results of loss function minimization show that in the case of strict inflation targeting

[8] I am following here an informal threshold of $0.8 - 1\%$ of consumption level as being unacceptable as in Schmitt-Grohe and Uribe (2006).

[9] The same result of the most fragile model yielding the most robust policy rule has been obtained by Cogley et al. (2011)

[10] This is shown in the Section 4 of the paper, where fault tolerance of all the models is analyzed.

all New Keynesian models (BNK, FA and HCC) have similar type of optimal policy rules. In all the model economies it in not optimal to respond to deviations of output gap $\alpha_y = 0$, whereas responses to inflation are strong: $\alpha_\pi = 3$ (Table 3).

Table 4: Models' optimal rules - quadratic loss function minimization. Inflation and output gap stabilization.

Model	ρ	α_π	α_y
BNK	0.7	2.2	0.4
FA	0.35	2.9	2.6
HCC	0.9	1.4	2.7
RS	0.1	2.4	2.6

To check whether these are financial factors that are responsible for non-robustness of the baseline policy rule, the BNK rule is adopted in the FA and HCC model economies where financial frictions are inactive. Financial accelerator mechanism is "switched off" in the FA model by breaking the connection between the external finance premium and the net worth position of borrowers (details of this are in the Appendix B). This leads to the fact that external funding of entrepreneurs, and thus their demand for capital, does not depend on their leverage ratio anymore. Hence, the FA model with inactive financial accelerator becomes a NK model with capital and capital adjustment costs (so, it is still different from the baseline NK model in this). Collateral constraints mechanism is deactivated by closing asset price channel - price of housing does not affect firms' and households' abilities to borrow; housing/consumtion margin conditions are modified in the set of equilibrium conditions of the HCC model to account for that. Besides, debt is not nominal, but indexed: borrowing constraints of firms and constrained households are amended to take it into account (details are provided in the Appendix C). This experiment of running the BNK optimal rule in the FA and HCC models without frictions shows that the baseline-optimal policy performs well in these models: welfare losses in them are 0.55% and 1.66%, what is substantially smaller than the losses in the full-version FA and HCC models. A part of these welfare costs can be attributed to the workings of model-specifc shocks: investment-specifc and preference shocks in the FA model and housing and cost-push shock in the HCC model.

When model-specific shocks, included in the models in order to improve performance of frictions' amplification mechanism are also deactivated, the baseline rule is robust, what is demonstrated by acceptable level of welfare losses in the FA and the HCC models in this case. Thus, deactivating the frictions and model-specific shocks in the FA and HCC models (effectively means deactivating real imperfections in these models) removes the trade-off between inlfation and output stabilization; this observation is consistent to the results obtained by Justiniano et al. (2012). No trade-off implies that the rule, optimal for the baseline model, performes well enough in alternative models. Thereby it is shown that financial factors are the principal reason for the BNK rule being non-robust.

Welfare losses in various models under alternative policy rules are not symmetrical. The BNK model is not sensitive to suboptimal policy rules: welfare costs of adopting suboptimal rules are negligibly small: 0.002% of consumption under the FA optimal rule and 0.003% under the HCC optimal rule. Therefore, sizable response to output fluctuations (captured by positive value of output coefficient α_y) in the BNK economy does not deteriorate welfare substantially. Thus, the baseline model is tolerant to changes in policy rule[11].

Another important feature of the FA and HCC optimal rules is that the FA and HCC models are mutually tolerant to adopting suboptimal policy rules: the FA model welfare loss under the HCC rule is 0.001% and the HCC model welfare loss under the FA rule is 0.06% of consumption. This happens due to similarity of the FA and HCC optimal policies. Though the amplification mechanisms and shocks are different in the FA and HCC models, these models call for similar policy responses. As a result, both the FA and the HCC optimal rules are robust to model uncertainty about financial factors within given set of models. Adopting the FA and HCC policy rules entails acceptable welfare costs in all alternative model economies with the smallest losses entailed by following the HCC rule.

[11]this is also demonstrated by the means of fault tolerance analysis in the Section 4.

4 Fault Tolerance

The fault tolerance approach was initially proposed for analysis of monetary policy robustness by Levin and Williams (2003). This method is a test of how tolerant models are to deviations from optimal policy. In this section I argue that the original version of fault tolerance approach by Levin and Williams (2003) should be amended to enable obtain robust policy rules and to help find rules that improve welfare across the models. I use the proposed extension of fault tolerance approach to show how BNK policy rule could be modified so that it becomes robust.

Levin and Williams (2003) advocate fault tolerance as a methodology to evaluate sensitivity of models to deviations from optimal policies. Although it seems to be a natural extension, they don't propose to test particular policy rules for robustness within fault tolerance methodology. In short, Levin and Williams demonstrate that a model's tolerance is to be analysed only with respect to deviations from policy rule, which is optimal for this particular model. Deviations from suboptimal policy rules are not examined, though it is exactly what should be evaluated to find robust policy rules, because it is by changing parameters of a specific policy rule (optimal for one model and suboptimal for alternative models) how a non-robust policy could be modified to be robust.

The original proposal of Levin and Williams is to fix two out of three parameter values (for example, α_π and α_y if sensitivity to deviations in ρ are analysed) at the different levels for different models - levels that correspond to their optimal values and that are not the same for all the alternative models, - and to analyse welfare implications of the change in one paramter (in this example, ρ) for all the models. Thus, every model is tested for fault tolerance only to deviations from its own optimal policy. Levin and Williams argue that in order for a robust policy rule to be attainable, there should be acceptable welfare losses on overlapping intervals for all three policy rule parameters. They claim that if loss function is relatively insensitive to changes in all three parameters then there exists a robust policy; and for that to be the case there should be overlapping regions of high fault tolerance of all the models with respect to changes in all the parameters of the policy rule.

However, a robust rule across the set of models cannot have different parameter vales for different models. A robust rule a policymaker is interested in is a specific rule that works well in all alternative models. Hence, it is one rule for all the models; the welfare implications of following this rule are acceptable in all the model economies for the specific parameter values. Levin and Williams' method does not test for this because their approach is limited to analysing deviations only from optimal rules; suboptimal rules are disregarded. Therefore, the original fault tolerance methodology is not useful to see whether losses in alternative models are acceptable when one particular policy is adopted and when deviations from this policy are allowed for.

Thus, I suggest that the original fault tolerance methodology is to be extended. This extension consists in testing the models' tolerance to deviations from all the optimal policy rules for all the models. In the context of this paper of three models and three-parameter type of policy rule nine experiments of parameters' deviations from their optimal values are to be conducted. Then robust rule is attainable if there is at least one out of nine cases where the interval of overlapping acceptable losses is present. This amendment of fault tolerance approach allows to see if modification of any of three optimal rules could result in this rule being robust. Besides, it allows to find the values of parameters in the robust policy rule.

The results of applying the extended fault tolerance methodology are presented graphically in the Appendix D. Deviations from the optimal policies are implemented in order to search for the possible cases where changing one parameter of an optimal policy improves welfare, i.e. reduces welfare costs, in the alternative models.

Allowing for changes in the value of ρ parameter in the BNK optimal rule leads to divergent welfare outcomes. Lower values of ρ (less inertial policy rule) reduce welfare costs in the FA model. However, losses in the HCC model are not sensitive to any changes in ρ as long as other parameters take their BNK-optimal values ($\alpha_\pi = 3$ and $\alpha_y = 0$): welfare costs are at their unacceptably high level of more than 7% for all the possible values of ρ. Thus, changing the degree of interest rate smoothing in the BNK optimal rule does not help to improve welfare in the HCC model.

Instead, the situation is different when changes of output coefficient in the BNK-optimal rule are considered (Appendix D, Figure 3). Increasing α_y parameter from its optimal value of 0 to 0.6-1.2 reduces welfare losses in the models wtih frictions to acceptable levels: both FA and HCC economies generate welfare losses close to zero when α_y lies on interval [0.6, 1.2]. Hence, by modifying BNK-optimal rule policymaker could attain its robustness for a particular set of output coefficient parameter values.

Increasing the value of ρ coefficient in the FA optimal rule from its optimal value of 0.165 up to 0.6 brings about reduction of welfare losses in the BNK model economy. At the same time welfare losses on the HCC and FA models don't increase much as a result of this change. Thus, if FA optimal policy rule is adopted by a policymaker, making interest rate more inertial would result in improvement of welfare across the set of the models. (However, further increase of coefficient of interest rate inertia would result in sharp increase of welfare losses in the FA model - see Figure 4 in Appendix D.)

Changing inflation and output coefficients in the FA optimal rule don't result in welfare costs decrease (Appendix 4, Figures 5 and 6): optimal values of the FA rule generate the smallest possible welfare costs, thus, no need to modify them in order to attain an increase in welfare; changes in inflation and output coefficients α_π and α_y only lead to welfare deterioration.

Fault tolerance analysis of changes in HCC optimal policy rule gives similar results as deviations of the FA rule parameters. Interest rate inertia coefficient ρ being increased up to 0.7 results in welfare improvement throughout the models (Appendix D, Table 7). However, for the values $\rho \geqslant 0.7$ welfare costs in FA economy increase up to unacceptable high levels, thus only values of ρ less than 0.7 are welfare improving. Deviations of α_π and α_y from their optimal values in the HCC optimal policy rule don't lead to any improvement is welfare; the minimum welfare costs are achieved in all the models for the HCC rule parameter values fixed at their optimal values.

To conclude, fault tolerance analysis enables to ascertain whether changes of parameter values in optimal policy rules could lead to improvement of welfare as a result of changes in policy rules. Modifying the BNK-ooptimal rule by increasing its output coefficient to any value in the interval [0.6, 1.4] makes this rule be robust. Though, the amended BNK rule is not optimal for any of the models, applying it in all the model economies entails acceptable levels of welfare losses. Besides, applying the fault tolerance methodology enables to find out whether deviations of parameter values in robust rules could improve welfare. Greater value of interest rate inertia coefficient in the FA and HCC policy rules (up to 0.6 in the FA case and 0.7 in the HCC case) results in the welfare improvement in the BNK model.

5 Conclusion

This paper demonstrates that financial frictions matter for robustness on monetary policy rule. It is shown that strict inflation targeting could be welfare detrimental in the models with financial factors. When there is uncertainty about what financial factors are at work and thus it is not evident what type of frictions - financial accelerator or collateral constraints - should be used in a reference model for optimal policy rule derivation, basic New Keynesian model should not be used by a policymaker to infer policy robust to model uncertainty unless the rule would be appropriately modified. I establish that BNK optimal rule yields high welfare losses in alternative models because of financial frictions present in these models. I show that the model with collateral constraints is the most fragile: it suffers the highest welfare costs under the baseline NK model policy formulation. Policy rules optimal for the financial accelerator model and the model with collateral constraints deliver acceptable levels of welfare losses in all the alternative model economies and thus are robust. Hence a policymaker minimizes the risk of welfare losses by using either of the models with financial factors as a reference to obtain an optimal policy rule.

I show how by using the extended version of the fault tolerance approach (Levin and Williams, 2003) one can determine specification of policy that is robust to model uncertainty across the set of models. Sizable increase of output coefficient in the policy rule optimal for the basic New Keynesian model results in this rule being robust as it delivers satisfactory welfare outcomes in all the models.

A number of questions should be answered in order to have a strategy to address model uncertainty for the purposes of policymaking. First, it is crucial to establish, what models should be used in the set of alternative economy representations. As seen in the literature, specification of robust policy is sensitive to the set of alternative models considered (Cogley et al., 2011; Levine et al., 2008; Brock et al., 2003; Levin and Williams, 2003). Thus, it is critical to verify what models have to be accounted for in quest of robust policy. Relevance of this point increases in light of development of many variants of models with divergent financial factors aiming to capture mechanisms conductive to economic distress. It is conceivable that not all alternative models should be considered as possible representations of economy when looking for robust policy. Second, the analysis here could be extended by monetary policy rule incorporating other variables (in addition to inflation, output and interest rate). For example, policymaker could respond to changes in leverage ratio - this could improve stabilization properties of monetary policy rules in the models with financial factors. Another extention of this paper could be to analyse robustness with respect to other types of financial frictions, for example, disruptions of financial intermediation, asset prices bubbles, etc., as these factors could possibly affect the results regarding robustness obtained here. Additionally, Bayesian updating could be used, so that prior beliefs about the probabilities of each model being a true one and their updating are incorporated in the analysis (as in Cogley et al., 2011 or Brock et al., 2007).

Appendix A

Basic New Keynesian model: equilibrium conditions (Walsh, 2010). Variables without time subscripts denote steady state values of these variables.

$$c_t^{-\sigma} = \beta * E_t(r_t * \frac{c_{t+1}^{-\sigma}}{\pi_{t+1}})$$

$$\chi * \frac{n_t^{\eta}}{c_t^{-\sigma}} = w_t$$

$$mc_t = \frac{w_t}{z_t}$$

$$1 = \omega * \pi_t^{\theta-1} + (1-\omega) * p_t^{1-\theta}$$

$$x_{1,t} = c_t^{1-\sigma} * mc_t + \omega * \beta * x_{1,t+1} * \pi_{t+1}^{\theta}$$

$$x_{2,t} = c_t^{1-\sigma} + \omega * \beta * x_{2,t+1} * \pi_{t+1}^{\theta-1}$$

$$p_t = \frac{\theta}{\theta-1} * \frac{x_{1,t}}{x_{2,t}}$$

$$y_t = z_t * n_t$$

$$y_t = c_t + g_t$$

$$\ln(z_t) = \rho_z * \ln(z_{t-1}) + \epsilon_{z,t}$$

$$\ln(g_t/g) = \rho_g * \ln(g_{t-1}/g) + \epsilon_{g,t}$$

$$\ln(r_t/r) = \rho * \ln(r_{t-1}/r) + \alpha_\pi * \ln(\pi_t/\pi) + \alpha_y * \ln(y_t/y) + \epsilon_{r,t}$$

Representative agent utility function:

$$U(C_t, N_t) = \frac{c_t^{1-\sigma}}{1-\sigma} - \chi * \frac{n_t^{1+\eta}}{1+\eta}$$

Table 5: Variables and parameters

Description	Notation
Household consumption	c_t
Household labour supply	n_t
Marginal costs	mc_t
Government spending	g_t
Output	y_t
Productivity	z_t
Real aggregate price level	p_t
Inflation	π_t
Gross nominal interest rate	r_t
Real wage	w_t
Productivity shock innovation	$\epsilon_{z,t}$
Shock to government spending innovation	$\epsilon_{g,t}$
Monetary policy shock innovation	$\epsilon_{r,t}$
Auxiliary variables	$x_{1,t}, x_{2,t}$
Coefficients in the interest rate policy rule on lagged interest rate, inflation and output	$\rho, \alpha_\pi, \alpha_y$

Table 6: Calibrated parameter values

Description	Parameter	Value
Discount rate	β	0.9902
Relative risk aversion	σ	2
Weight of labour in the utility function	χ	1
Labour supply aversion	η	3
Calvo parameter	ω	0.75
Price elasticity of demand for each good variety	θ	6
Steady state share of government consumption	g	0.17
Persistence of productivity shocks	ρ_z	0.8556
Persistence of government spending shocks	ρ_g	0.87
Standard deviation of innovation to productivity shock	σ_z	0.0064
Standard deviation of innovation to government spending shock	σ_g	0.016
Standard deviation of innovation to monetary policy shock	σ_r	0.0031

Note: The driving forces g_t and z_t are calibrated based on estimations of Schmitt-Grohe and Uribe (2006). Monetary policy shock innovation is calibrated based on estimation of Ireland (2004).

Appendix B

Financial accelerator model: equilibrium conditions (Christensen and Dib, 2008). Hatted variables denote log-deviations of these variables from steady state values. Variables without time subscripts denote steady state values of these variables.

$$((1-\gamma)*\lambda*c-1)*\hat{c_t} = \gamma*\hat{\lambda} + \lambda*m*(r-1)/r*(\hat{b_t} + (\gamma-1)*\hat{m_t}) - \gamma*\hat{e_t}$$

$$\gamma*\hat{r_t}/(r-1) = \hat{b_t} + \hat{c_t} - \hat{m_t}$$

$$h*\hat{h_t} = (1-h)*(\hat{w_t} + \hat{\lambda_t})$$

$$\hat{y_t} = \alpha*\hat{k_t} + (1-\alpha)*\hat{h_t} + (1-\alpha)*\hat{A_t}$$

$$\hat{y_t}*y = c*\hat{c_t} + i*\hat{i_t}$$

$$\hat{w_t} = \hat{y_t} + \hat{\epsilon_t} - \hat{h_t}$$

$$\hat{z_t} = \hat{y_t} + \hat{\epsilon_t} - \hat{k_t}$$

$$\hat{\mu_t} = \hat{m_t} - \widehat{m_{t-1}} + \hat{\pi_t}$$

$$\hat{f_t} = z/f*\hat{z_t} + (1-\delta)/f*\hat{q_t} - \widehat{q_{t-1}}$$

$$\hat{q_t} = \chi*(\hat{i_t} - \hat{k_t}) - \hat{x_t}$$

$$\hat{\pi_t} = \beta*\pi\hat{_{t+1}} + (1-\beta*\phi)*(1-\phi)/\phi*\hat{\epsilon_t}$$

$$\widehat{\lambda_{t+1}} = \hat{\lambda_t} - \hat{r_t} + \pi\hat{_{t+1}}$$

$$\widehat{k_{t+1}} = \delta*\hat{i_t} + \delta*\hat{x_t} + (1-\delta)*\hat{k_t}$$

$$\widehat{f_{t+1}} = \hat{r_t} - \widehat{\pi_{t+1}} + \psi*(\hat{q_t} + \widehat{k_{t+1}} - \widehat{n_{t+1}})$$

$$\widehat{n_{t+1}}/(\upsilon*f) = k/n*\hat{f_t} - (k/n-1)*(\widehat{r_{t-1}} - \hat{\pi_t}) - \psi*(k/n-1)*(\hat{k_t} + \widehat{q_{t-1}}) + (\psi*(k/n-1)+1)*\hat{n_t}$$

$$\ln{(r_t/r)} = \rho * \ln{(r_{t-1}/r)} + \alpha_\pi * \ln{(\pi_t/\pi)} + \alpha_y * \ln{(y_t/y)} + \epsilon_{r,t}$$

$$\hat{e_t} = \rho_e * \widehat{e}_{t-1} + \epsilon_{e,t}$$

$$\hat{b_t} = \rho_b * \widehat{b}_{t-1} + \epsilon_{b,t}$$

$$\hat{A_t} = \rho_A * \widehat{A}_{t-1} + \epsilon_{A,t}$$

$$\hat{x_t} = \rho_x * \widehat{x}_{t-1} + \epsilon_{x,t}$$

To set financial accelerator mechanism inactive elasticity of external financial premium to firm leverage ratio is appointed to be equal to zero: $\psi = 0$.

Representative agent utility function:

$$u(.) = \gamma * e_t/(\gamma - 1) * \ln{(c_t^{(\gamma-1)/\gamma} + b_t^{(1/\gamma)} * m_t^{(\gamma-1)/\gamma})} + \eta * \ln(1 - h_t)$$

Table 7: Variables and parameters

Description	Notation
Household consumption	c_t
Household labour supply	h_t
Net worth	n_t
Government spending	g_t
Output	y_t
Productivity	A_t
Gross nominal interest rate	r_t
Real wage	w_t
Lagrange multiplier	λ_t
Real money balances	m_t
Aggregate capital	k_t
Aggregate investment	i_t
Lagrange multiplier associated with production function	ϵ_t
Real marginal productivity of capital	z_t
Money growth	μ_t
Inflation	π_t
Real interest rate on external borrowed funds	f_t
Price of capital	q_t
Weight of preference for consumption	e_t
Money demand	b_t
Investment specific productivity	x_t
Preference shock innovation	$\epsilon_{e,t}$
Money demand shock innovation	$\epsilon_{b,t}$
Investment specific shock innovation	$\epsilon_{x,t}$
Productivity shock innovation	$\epsilon_{A,t}$
Shock to government spending innovation	$\epsilon_{g,t}$
Monetary policy shock innovation	$\epsilon_{r,t}$
Coefficients in the interest rate policy rule on lagged interest rate, inflation and output	$\rho, \alpha_\pi, \alpha_y$

Table 8: Calibrated parameter values

Description	Parameter	Value
Discount rate	β	0.9902
Gross steady state risk premium	S	1.0075
Gross steady state inflation rate	π	1.0079
Intermediate goods elasticity of substitution	θ	6
Constant elasticity of substitution between consumption and real money balances	γ	0.0598
Weight of leisure in the utility function	η	1.315
Price stickiness parameter	ϕ	0.7418
Constant associated with money demand shock	b	0.062
Capital adjustment costs paramter	χ	0.5882
Capital share	α	0.3384
Depreciation rate	δ	0.025
Steady state ratio of capital to net worth	k/n	2
Probability of survival of entrepreneurs	υ	0.9728
Elasticity of external finance premium to firm leverage ratio	ψ	0.042
Persistence of productivity shocks	ρ_A	0.7625
Persistence of money demand shock	ρ_b	0.7206
Persistence of preference shock	ρ_e	0.6156
Persistence of investment efficiency shock	ρ_x	0.6562
Standard deviation of innovation to productivity shock	σ_A	0.0096
Standard deviation of innovation to money demand shock	σ_b	0.0103
Standard deviation of innovation to preference shock	σ_e	0.0073
Standard deviation of innovation to investment efficiency shock	σ_x	0.0331
Standard deviation of innovation to monetary policy shock	σ_r	0.0031

Note: Calibration is based on estimations of Chistensen and Dib (2008).

Appendix C

Collateral constraints model: equilibrium conditions (Iacoviello, 2005). Hatted variables denote log-deviations of these variables from steady state values. Variables with time subscripts denote log-deviations of the steady state values of these variables. Variables without time subscripts denote steady state values of these variables.

$$\hat{Y_t} = c/Y * \hat{c_t} + c'/Y * \hat{c'_t} + c''/Y * \widehat{c''_t} + I/Y * \hat{I_t}$$

$$\hat{c'_t} = \widehat{c'_{t+1}} - \widehat{rr_t}$$

$$\hat{I_t} - \hat{K_{t-1}} = \gamma * (\widehat{I_{t+1}} - \hat{K_t}) + (1 - \gamma * (1 - \delta))/\psi * (\widehat{Y_{t+1}} - \widehat{X_{t+1}} - \hat{K_t}) + 1/\psi * (\hat{c_t} - \widehat{c_{t+1}})$$

$$\hat{q_t} = \gamma_e * \hat{q_{t+1}} + (1-\gamma_e) * (\widehat{Y_{t+1}} - \widehat{X_{t+1}} - \hat{h_t}) - m * \beta * \widehat{rr_t} - (1 - m * \beta) * \Delta\widehat{c_{t+1}} - \phi_e * (\Delta\hat{h_t} - \gamma\Delta\widehat{h_{t+1}})$$

$$\hat{q_t} = \gamma_h * \hat{q_{t+1}} + (1-\gamma_h) * (\widehat{J_{t+1}} - \widehat{h''_t}) - m'' * \beta * \widehat{rr_t} - (1 - m'' * \beta) * (\widehat{c''_t} - \omega * \widehat{c''_{t+1}} - \phi_h * (\Delta\widehat{h''_t} - \beta''\Delta\widehat{h''_{t+1}})$$

$$\hat{q_t} = \beta * \hat{q_{t+1}} + (1-\beta) * \widehat{J_{t+1}} + i * \hat{h_t} + i'' * \widehat{h''_t} + \hat{c'_t} - \beta * \widehat{c'_{t+1}} + \phi_h/h' * (h\Delta\hat{h_t} + h''\Delta\widehat{h''_t} - \beta * h * \Delta * \widehat{h_{t+1}} - \beta h''\Delta\widehat{h''_{t+1}})$$

$$\hat{b_t} = \widehat{q_{t+1}} + \hat{h_t} - r\hat{r}_t$$

$$\hat{b''_t} = \widehat{q_{t+1}} + \widehat{h''_t} - r\hat{r}_t$$

$$\widehat{Y_t} = \frac{\eta}{\eta - (1 - \upsilon - \mu)} * (\hat{A_t} + \upsilon * \widehat{h_{t-1}} + \mu * \widehat{K_{t-1}}) - \frac{1 - \upsilon - \mu}{\eta - (1 - \upsilon - \mu)} * (\widehat{X_t} + \alpha * \hat{c'_t} + (1 - \alpha) * \hat{c''_t})$$

$$\hat{\pi_t} = \beta * \hat{\pi_{t+1}} - \kappa * \widehat{X_t} + \hat{u_t}$$

$$\widehat{K_t} = \delta * \widehat{I_t} + (1 - \delta) * \widehat{K_{t-1}}$$

$$b/Y * \hat{b_t} = c/Y * \hat{c_t} + q * h/Y\Delta\hat{h_t} + I/Y * \widehat{I - t} + Rb/Y(\widehat{R_{t-1}} + \widehat{b_{t-1}} - \hat{\pi_t}) - (1 - s' - s'')(\hat{Y_t} - \widehat{X_t})$$

$$b''/Y * \hat{b''_t} = c''/Y * \hat{c''_t} + q * h''/Y\Delta\hat{h''_t} + Rb''/Y(\widehat{R_{t-1}} + \widehat{b''_{t-1}} - \hat{\pi_t}) - s''(\hat{Y_t} - \widehat{X_t})$$

$$\ln(r_t/r) = \rho * \ln(r_{t-1}/r) + \alpha_\pi * \ln(\pi_t/\pi) + \alpha_y * \ln(y_t/y) + \epsilon_{r,t}$$

$$\hat{j}_t = \rho_j * \widehat{j_{t-1}} + \epsilon_{\hat{j},t}$$

$$\hat{u}_t = \rho_u * \widehat{u_{t-1}} + \epsilon_{\hat{u},t}$$

$$\hat{A}_t = \rho_A * \widehat{A_{t-1}} + \epsilon_{\hat{A},t}$$

$$\omega = (\beta'' - m''\beta'')/(1 - m''\beta)$$

$$i = (1-\beta)h/h'$$

$$i'' = (1-\beta)h''/h'$$

$$\gamma_h \equiv \beta'' + m''(\beta - \beta'')$$

$$\widehat{rr}_t \equiv \widehat{R_t} - E_t\widehat{\pi_{t+1}}$$

$$\gamma_e \equiv m * \beta + (1-m) * \gamma$$

$$s' \equiv (\alpha(1-\mu-\upsilon) + X - 1)/X$$

$$s'' \equiv (1-\alpha)(1-\mu-\upsilon)/X$$

To close the effects of collateral constraints, housing/consumption margin conditions of entrepreneurs and impatient households are modified. so that the asset price channel is inactive:

$$\hat{q}_t = \gamma_e * \hat{q_{t+1}} + (1-\gamma_e) * (\widehat{Y_{t+1}} - \widehat{X_{t+1}} - \hat{h}_t) - \widehat{c'_{t+1}} * (\gamma + 1 - \gamma_e) + \hat{c}_t - \phi_e * (\hat{h}_t - \widehat{h_{t-1}} - \gamma * (\widehat{h_{t+1}} - \hat{h}_t))$$

$$\hat{q}_t = \beta'' * \hat{q_{t+1}} + (1-\gamma_h) * (\hat{j}_t - \widehat{h''_t}) - \widehat{c''_{t+1}} * \beta'' + \widehat{c''_t} - \phi_h * (\widehat{h''_t} - \widehat{h''_{t-1}} - \beta'' * (\widehat{h''_{t+1}} - \widehat{h''_t}))$$

Representative agent utility function:

$$u(.) = \ln(c'_t) + j\ln(h'_t) - (L'_t)^\eta/\eta$$

Table 9: Variables and parameters

Description	**Notation**
Output	y_t
Entrepreneurs, patient and impatient households consumption	c_t, c'_t, c''_t
Patient and impatient households labour supply	L'_t, L''_t
Entrepreneurs, patient and impatient households holding of housing	h_t, h'_t, h''_t
Aggregate investment	i_t
Aggregate capital	k_t
Markup	X_t
Price of housing	q_t
Real borrowing, lending	b_t
Inflation	π_t
Gross nominal interest rate	r_t
Preference for housing	j_t
Productivity	A_t
Inflation shock	u_t
Preference for housing shock innovation	$\epsilon_{j,t}$
Cost-push shock innovation	$\epsilon_{u,t}$
Productivity shock innovation	$\epsilon_{A,t}$
Monetary policy shock innovation	$\epsilon_{r,t}$
Auxiliary variables	$\omega_t, i_t, i''_t, \gamma_h$
Ex ante real interest rate	rr_t
Income shares of patient and impatient households	s, s
Slope of Phillips curve	κ
Coefficients in the interest rate policy rule on lagged interest rate, inflation and output	$\rho, \alpha_\pi, \alpha_y$

Table 10: Calibrated parameter values

Description	Parameter	Value
Discount rate of patient households	β	0.99
Discount rate of impatient households	β''	0.98
Discount rate of entrepreneurs	γ	0.95
Weight on housing services	j	0.1
Labour supply aversion	η	1.01
Variable capital share	μ	0.03
Elasticity of output to housing	υ	0.03
Housing adjustment cost	ϕ_e, ϕ_h	0
Variable capital adjustment costs	ψ	2
Variable depreciation rate	δ	0.03
Calvo parameter	θ	0.75
Patient households wage share	α	0.64
Loan-to-value entrepreneur	m	0.89
Loan-to-value household	m''	0.55
Steady state gross markup	χ	1.05
Persistence of technology shock	ρ_A	0.03
Persistence of housing preference shock	ρ_j	0.85
Persistence of inflation shock	ρ_u	0.59
Standard deviation of innovation to technology shock	σ_A	2.24
Standard deviation of innovation to housing preference shock	σ_j	24.89
Standard deviation of innovation to inflation shock	σ_u	0.17
Standard deviation of innovation to monetary policy shock	σ_r	0.29

Note: Calibration is based on estimations of Iacoviello (2005).

Appendix D

Fault tolerance analysis

Figure 1: Fault tolerance to deviations of ρ parameter in the BNK optimal rule

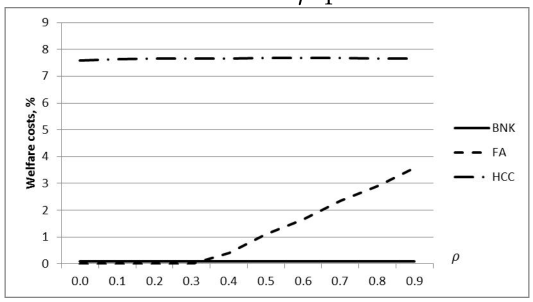


Figure 2: Fault tolerance to deviations of α_π parameter in the BNK optimal rule

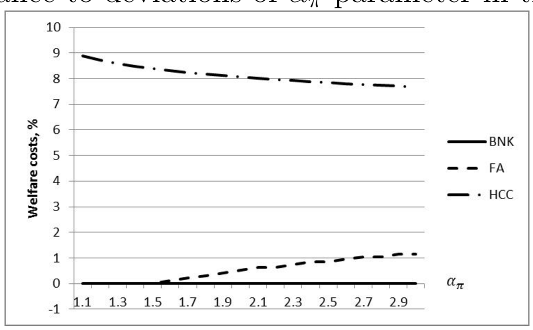


Figure 3: Fault tolerance to deviations of α_y parameter in the BNK optimal rule

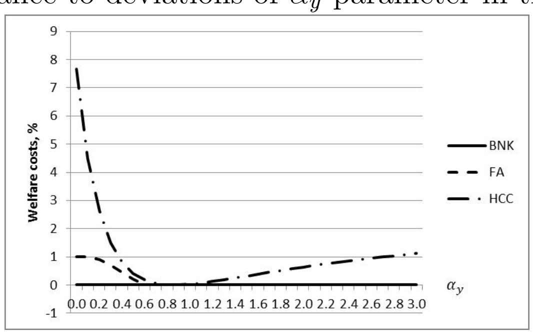


Figure 4: Fault tolerance to deviations of ρ parameter in the FA optimal rule

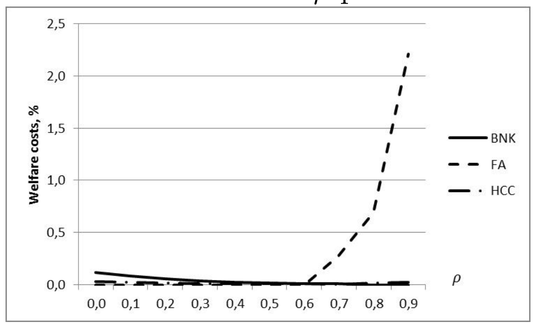


Figure 5: Fault tolerance to deviations of α_π parameter in the FA optimal rule

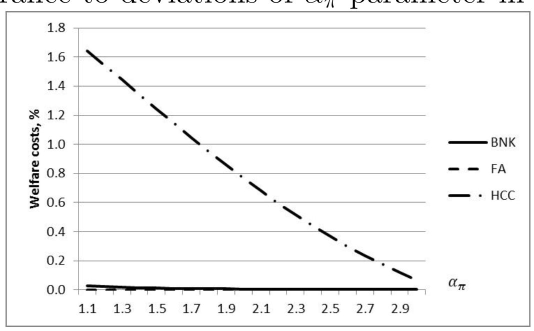


Figure 6: Fault tolerance to deviations of α_y parameter in the FA optimal rule

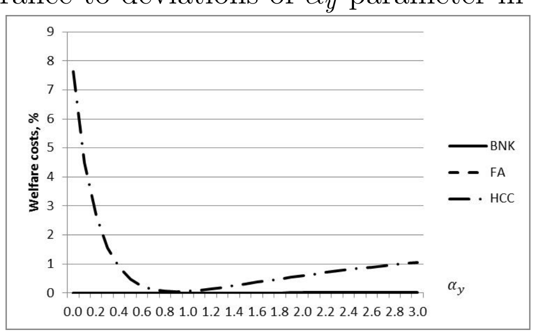


Figure 7: Fault tolerance to deviations of ρ parameter in the HCC optimal rule

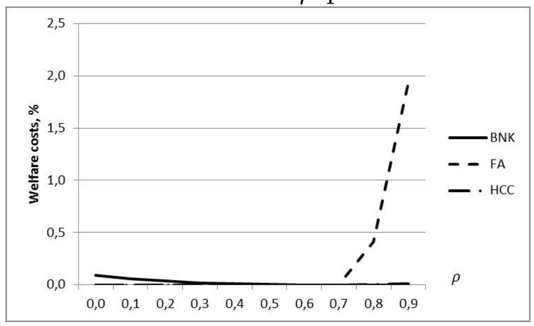


Figure 8: Fault tolerance to deviations of α_π parameter in the HCC optimal rule

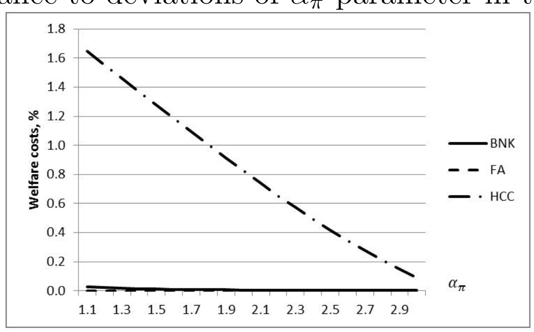
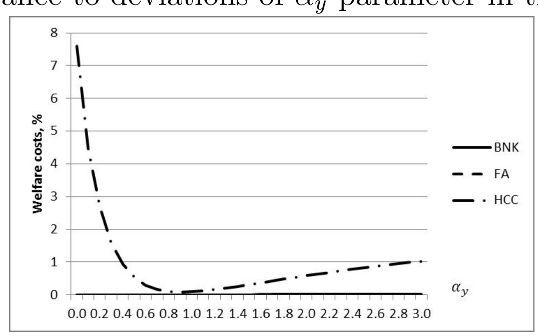


Figure 9: Fault tolerance to deviations of α_y parameter in the HCC optimal rule



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