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# REAL ESTATE MARKET, BANKING LENDING AND SYSTEMIC FINANCIAL RISKS: A NEW NONLINEAR DYNAMIC MODEL

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## ABSTRACT

Systemic risks have been the focus of economic research for several decades because they provoke dangerous consequences that cannot be mitigated with traditional macroprudential policy tools. Recently, the ESRB warned about high European banks' exposures to the real estate sector and the need to improve macroprudential regulation. The main purpose of the research paper is to develop the theoretical basis and modelling tools to clarify the nonlinear relationships between the real estate market and bank lending, thereby improving macroprudential regulation to mitigate systemic risks. We used the complex nonlinear systems methodology, mathematical theory of differential equations, the Lotka-Volterra approach for modelling nonlinear dynamics of interrelated systems, and the theory of collateral accelerator mechanism in the real estate market and banking lending. The scientific novelty of the paper is in the new theoretical and applied results: we developed a new non-linear dynamic model that sheds more light on the collateral accelerator mechanism and drivers of amplifying systemic financial risk; new insights about tipping points and structural shifts in the real estate market and banking system under specific conditions that we determined. We have found that under the collateral accelerator actions, the real estate market cannot achieve equilibrium. The real estate prices increase according to the relations we obtained, fueled by new loans. A price bubble is a dissipative structure in Prigogine's terminology, and the LTV parameter is the key driver of the rate of price increase. After reaching a threshold, the price bubble bursts, and crisis processes intensify. The paper's results are significant for deepening the understanding of the nature of systemic financial risks and assessing the drivers of crises in the banking sector and the real estate market. It can help improve banking regulation and macroprudential policy to prevent systemic crises and strengthen banks' strategic management.

**Keywords:** systemic financial risk, banking system, financial stability, CRE exposure, strategic management for banks, macroprudential policy, real estate market, self-enforced cycles, collateral accelerator

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## INTRODUCTION

Systemic risk has been the focus of macroeconomic and financial stability research for several decades because it causes dangerous, uncontrollable consequences for the whole financial system that are extremely difficult to mitigate through the traditional instruments of regulation. Since 2008, academic researchers, analysts, and regulators have done tremendous work to address systemic risk challenges and improve macroprudential policy. However, macroeconomic and financial sciences have not fully understood systemic risk's internal drivers and dynamics. It is a complex area full of puzzles, controversy, and regulatory traps, which continue to generate heated discussions and concerns about the next systemic crises.

The warnings of the ECB's Financial Stability Reviews (2023) and research of financial experts in the US banking industry, particularly data analysis of Rebel A. Cole (2024), are about high risks of future banking system losses on real estate mortgages, real estate construction loans, and properties selling at falling prices over the coming years.

In our previous paper, Unkovska T., Taruta S, and Grydzhuk D. (2022), we researched the mechanisms for "self-enforcing cycles in systemic risk accumulation and analysed the case of China's economy." This paper develops our theoretical approach and suggests a new non-linear dynamic model of the mechanisms for systemic risk arising, building up, and amplifying. This research sheds light on the non-linear nature and dynamics of systemic risk amplification through specific interactions between the real estate sector, banking system, and the whole economy that we call "collateral accelerator".

We consider two paradoxes of systemic risk increase in attempts to reduce individual credit and liquidity banks' risks through traditional instruments:

1. Securing loans by collateralising real estate.
2. Selling mortgaged real estate when borrowers default on loans (fire sales).

It is paradoxical that, under certain conditions, these conventional instruments taken together generate the emergence of the endogenous self-reinforcing collateral accelerator mechanism of increasing systemic risks. We developed a dynamic non-linear model of this mechanism that can help to predict some threats.

*The paradox of securing loans by collateralising real estate* is in the contradiction between the common-sense argument that taking real estate as collateral should lead to a reduction in individual banks' credit risks and the fact that the same strategy makes all banks similar, the banking system more homogenous, and banks' exposure to risk from real estate higher. *In a homogeneous banking system, where assets are concentrated in loans to the real estate sector, the collateral accelerator mechanism operates more intensively.* In turn, the increase in systemic risk exacerbates the vulnerability of each bank. In this paper, we consider this paradox in more detail, develop a non-linear dynamic model of the Lotka-Volterra type, and explain a structural shift mechanism that distorts a normal supply and demand adjustment in the real estate market. This structural shift is one of the root causes for the emergence of bubbles in credit, commercial, and residential real estate markets. It stimulates boom-bust cycles and increases the systemic risk that impedes the achievement of equilibrium price in the real estate market and stability of the banking system.

## LITERATURE REVIEW

Our research is based on the literature on credit cycles, housing bubbles, and their spillover effects on the economy. There is a significant body of literature connected with the real estate market, housing bubbles, and macroprudential regulation.

Particularly, in the research paper, Borio (2003), the author wrote about the necessity of a macroeconomic view on improving prudential instruments for addressing financial instability problems. The authors of the work Cerutti et al. (2015) follow these recommendations and find that an increase in LTV could positively impact the mitigation of a real estate prices bubble. They wrote that the "recent global crisis highlighted the risks stemming from real estate booms. This has generated a growing literature trying to better understand the sources and the risks associated with housing and credit booms." Their research exploited disaggregated data on credit and the characteristics of the mortgage market, including institutional factors that vary across countries. The research paper by Markus K. Brunnermeier et al. (2019) focused on the analysis of the relationship between asset price bubbles and systemic risk. The authors used bank-level data for almost thirty years and found that systemic risk of banks rises already during a bubble's build-up phase, and even more so during its bust. They approved that in a median real estate bust, systemic risk increases by almost 70 percent of the median for banks with unfavourable characteristics.

The research paper, Cristian Voicu and Michael J. Seiler (2013), devoted to relations between real estate index and bank lending in different types of cities, found some abnormal returns of banks in some cities. The authors of the paper, Adrian Alter and Zaki Dernaoui (2021), studied the dynamics of investor composition using a unique and comprehensive dataset and documented the peak of non-primary home investments in the aftermath of the global financial crisis. They found that "areas with a higher share of shadow bank lending have been associated with riskier mortgages and a more amplified house price cycle due to the presence of non-primary home transactions". They concluded the need for improvement of a macroprudential policy toolkit for non-bank financial intermediaries and provided evidence that it could limit NBFIs' risk-taking behavior and potential policy leakages.

The paper Jan Hannes Lang et al. (2019) presented a domestic cyclical systemic risk indicator (d-SRI) that captures risks stemming from domestic credit, real estate markets, asset prices, and external imbalances. The authors showed that d-SRI increased before the systemic financial crises, and "in addition, the level of the d-SRI around the start of financial crises is highly correlated with measures of subsequent crisis severity, such as GDP declines". The authors of the paper Deghi et al. (2020) predicted downside risks to future real house price growth (house-prices-at-risk or HaR) in 32 advanced


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and emerging market economies. They showed "that current house price overvaluation, excessive credit growth, and tighter financial conditions jointly forecast higher house prices at risk up to three years ahead… and a tightening of macroprudential policy is the most effective at curbing downside risks to house prices, whereas a loosening of conventional monetary policy reduces downside risks only in advanced economies and only in the short-term".

The authors of the paper, Lo Duca et al. (2019), presented the ECB framework for assessing systemic financial risks connecting with residential real estate markets (RRE). They found that "developments in the residential real estate (RRE) sector can have strong repercussions on financial stability and the real economy. The importance of the residential real estate sector for financial stability stems from its central role in the economy, the large fraction of household wealth invested in real estate assets, the primary role of the financial sector in financing real estate investments, and the important collateral role of real estate assets".

The authors of Nistor, S., Ongena, S. (2023) researched the impact of policy interventions on systemic financial risk. They analysed "a comprehensive sample that combines an original set of bank-specific bailout events with the balance sheets of key affected and non-affected European banks between 2005 and 2014. We find a positive and significant association of guarantees with systemic risk that is somewhat weaker in the long run when the regulator appoints members to the supervisory board". The paper provided an interesting conclusion that "liquidity injections are positively linked with systemic risk, but the long-run effect is mitigated for small or better capitalized banks. In the short run, injecting liquidity is associated with reduced systemic risk when the regulator imposes restrictions on supervisory board composition or on management pay or capital payouts".

Thus, the current picture of research on the real estate market in connection with banking credit and systemic risk is a rapidly evolving area. Much has been achieved in the understanding and assessment of real estate market dynamics and systemic financial risk.

## AIMS AND OBJECTIVES

The main purpose of this paper is to develop the theoretical basis and modelling tools for a clearer understanding of nonlinear interrelationships within the real estate market, banking lending, and systemic financial risks, and improve macroprudential policy to prevent systemic financial crises.

To achieve this purpose, our research addresses the following objectives, namely:

- developing a holistic approach to the real estate market, households, and banking system interactions;
- research on some blind spots that hinder the effective mitigation of systemic risk and the prevention of systemic crises. In particular, the regularities and tipping points in the endogenous mechanisms of systemic risk amplification in the real estate market and the banking system;
- working out a new nonlinear dynamic model that describes the interrelated complex processes of changes in real estate prices, bank lending secured by real estate, and households' welfare, finding analytical solutions of the differential equations system for helping to understand deeply systemic financial risk accumulation, qualitative characteristics, and key drivers of collateral accelerator tipping points;
- suggest some measures to improve macroprudential policy and banking strategic management.

## METHODS

Our research is based on fundamental macro- and microeconomic relationships, complex systems theory, and the theory of non-linear dynamic processes in the economy and finance.

We use an analytical approach to research systemic risks based on non-linear dynamic modelling of Lotka-Volterra type ("one prey – two predators" type) and the mathematical tools for providing analytical solutions of differential equations. These approaches have permitted us to find insightful conclusions about tipping points and structural shifts in the real estate market and banking system under some determined conditions.

Based on these methods, we identified the qualitative characteristics, key drivers, and critical parameters that have the biggest impact on systemic financial risks amplification.

## RESULTS

We researched the paradox of securing loans by collateralising real estate*, which* is an example of contradictions between the microlevel risk-management and macroregulation of systemic risks at the level of the banking system and the economy as a whole.

In an individual bank's risk management, the loan collateralisation mechanism seems to reduce the bank's credit risks in case of the borrower's insolvency. The mechanism of secured lending with real estate as collateral is conventional and systemically widespread in the world economy. It has been considered an acceptable and primarily necessary tool.

At the macrolevel, the real estate market, the banking system, the construction industry, development companies, commercial property owners, tenants, and the household sector are interlinked in a whole complex system, where collateral mechanisms generate self-reinforcing cycles leading to an increase in systemic risks. There is a "collateral paradox" in contradiction between the seeming positive role of collateral lending for reducing individual banks' risks and the negative role of collateral lending in generating systemic risks at the macrolevel through the collateral accelerator mechanism. After materialisation of systemic risk, individual banks suffer from unexpected consequences. In other words, it is a contradiction between the common-sense argument that taking real estate as collateral should lead to a reduction in individual banks' credit risks, and the fact that the same strategy makes all banks similar, the banking system more homogenous, and banks' exposure to risk from real estate higher. In turn, the increase in systemic risk exacerbates the vulnerability of each individual bank.

In the paper, we have developed a non-linear dynamic model of Lotka-Volterra type and explained a structural shift mechanism that distorts a normal supply and demand adjustment in the real estate market. We argue that this structural shift is one of the root causes of the emergence of bubbles in credit and real estate markets. This mechanism stimulates boom-bust cycles and increases systemic risks that impede the achievement of equilibrium price in the real estate market and stability of the banking system.

The mechanism of collateral accelerator is the primary driver of excessive concentration of the banking system's assets in mortgage lending, which increases systemic risk. The collateral accelerator acts slowly. It is a non-obvious but powerful destabiliser of the real estate market and banking system that provokes self-reinforcing cycles in the real estate market, household finance, construction industry, and the banking system with a significant spillover effect on the national and global economy. The primary source of arising collateral accelerator mechanism is the dual role of real estate:

1. On the one hand, real estate is the object of purchase, i.e., the object of demand and supply in the economy.
2. On the other hand, the real estate assets are the collateral pledges in the banks' balance sheets, stimulating the expansion of credit and further increasing demand.

*The first phase of the collateral accelerator regime* – arising and amplifying systemic risks. This phase includes the following processes:

1. The starting point is the growth of lending against property collateral and CRE and RRE banks' exposure in a low-interest rate environment in the economy, when cheap financial resources are affordable to banks.
2. As collateralisation reduces individual credit risks for banks (in the first phase), they lower customer credit standards and don't pay exceptional attention to their solvency. The credit flows from the banking system into the economy in an environment of low credit standards for customers, low interest rates (most often banks use floating mortgage interest rates) on mortgage lending, and a high Loan-to-Value (LTV) ratio triggers a surge of additional solvent demand for real estate. This demand triggers further price growth that exceeds the fundamental trend.
3. The first impulse of rising real estate prices increases the value of collateral assets in bank balance sheets and the market price of households' real estate portfolios, increasing their perception of their wealth; these two processes mutually reinforce the supply of and demand for credit and stimulate additional growth in the level of financial leverage in sectors of households, companies, and the banking system.
4. The action of the collateral accelerator, intensifying collateral lending, stimulates an increase in mortgage loans in the banking system's balance sheets.
5. Credit availability and rising real estate prices stimulate the activity of the construction industry and development companies, which increase the supply of real estate and raise their financial leverage. This strengthens the processes of banking system homogenisation and banks' exposure to risks from the real estate sector.


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The critical components of the collateral accelerator mechanism are the increasing credit growth, rising real estate prices, and growing value of collateral assets, stimulating a new round of credit expansion. This mechanism unwinds the self-reinforcing spirals of the credit cycle and the associated real estate price cycle and facilitates the building up of systemic risks. The whole structure of this complex system becomes increasingly fragile to small external shocks or endogenous fluctuations. The endogenous collateral accelerator mechanism achieves a tipping point and can shift to the second phase – materialisation of systemic risk.

*The second phase of the collateral accelerator regime*, a mature stage of systemic risk accumulation, can start from a slight rise in the mortgage interest rate or other volatility that increases the volume of non-performing loans in bank balance sheets. A phase shift occurs in a whole complex system of interconnected sectors of the real estate market, related industries, household sector, and banking system. In this case, the whole construction can start to fall apart, and a systemic crisis arises.

"Why does this mechanism transform the economy from being financially stable to structurally disproportionate and highly vulnerable to small shocks and endogenous fluctuations?

The answer is that *the collateral accelerator fundamentally changes the market environment and distorts a classical macroeconomic supply and demand adjustment in the real estate market.* A collateral accelerator pushes the real estate market into a "strange regime" where achieving market equilibrium becomes principally impossible" (Unkovska et al., 2022). Systemic crisis shifts the economy into the "bad equilibrium" state. These non-linear dynamical processes can be described by our new dynamical model of Lotka-Volterra type ("prey-predator" type).

In classical economics, "supply S(P) and demand D(P) for goods (real estate) depend on the price P in a traditional manner: when the price of goods rises, their demand falls and supply increases. An achievement of the market equilibrium real estate price $P^*$, usually described by the equation" (Unkovska et al., 2022):

$$\frac{dP}{dt} = \alpha[D(P(t)) - S(P(t))] \to 0, (P(t) \to P^*,$$

$$D(P(t)) = a - bP(t),$$

$$S(P(t)) = c + mP(t),$$

*"where a, b, c, and m are the structural parameters of the real estate market, b and m are the ratios of elasticity of demand D(P) and supply S(P) concerning price changes"* (Unkovska et al., 2022).

The equilibrium price $P^*$ in standard classical macroeconomics is expressed as follows:

$$P^* = \frac{a - c}{m + b}$$

However, this classic model is irrelevant for the real estate market with real estate collateral lending, because the "collateral accelerator mechanism comes into action. In this case, the classic budget constraints of real estate buyers, determined by their savings and income limits (mainly, the level of households' disposable income), become irrelevant in shaping the demand for real estate. Households' wealth is generated not so much by income streams from their productive activities but by increases in the prices of the houses they buy.

If real estate prices go up (as they inevitably do during the credit boom because readily available credit resources increase the demand for real estate), the wealth of property owners is constantly on the rise. They receive more and more opportunities to take collateral loans and purchase real estate. Real estate turns from a means to improve living conditions into an asset, ensuring the owner's wealth growth" (Unkovska et al., 2022).

The following formulas are derived from these logical patterns: the dynamics of supply and demand on the real estate market obey the following structural relationships:

$$D(P(t)) = a - bP(t) + K(Q, h, P(t)) - f(K)$$

$$Q = S(P(t)) = c + mP(t),$$

"where: *K (Q, h, P (t)) is the volume of loans received by the households against real estate as collateral; h is the Loan-to-Value coefficient, i.e., the ratio of the obtained loan to the volume of the market value of the collateral (real estate); Q is the volume of real estate (in square metres) offered for purchase in the economy, which can be used as collateral to obtain loans; P(t) is the market price of a square metre of real estate; f(K) is the function reflecting the volume of loan repayments by borrowers"* (Unkovska et al., 2022).

The dynamics of the volume of loans:

$$K\big(P(t)\big) = hQP(t) = h\big(c + mP(t)\big)P(t);$$

$$f(K) = kK(P(t)),$$

*"where k means the repayment ratio, which is determined by the interest rate and other terms of the loan agreements, including the bank's margin call requirements in case of falling real estate prices"* (Unkovska et al., 2022).

If the real estate market prices fall to the level where the value of the collateral in the banks' balance sheets becomes lower than the amount of the outstanding loans, banks require a margin call. Hence,

$$D(P(t)) = a - bP(t) + K\big(Q, h, P(t)\big)(1 - k),$$

$$S(P(t)) = c + mP(t).$$

Therefore, the non-classical non-linear equation for the real estate price dynamics is:

$$\frac{dP(t)}{dt} = \beta\,[D(t) - S(t)] == \beta\left[a - bP(t) + K\big(Q, h, P(t)\big)(1 - k) - c - mP(t)\right] =$$

$$= \beta\left[a - c - (b + m)P(t) + K\big(Q, h, P(t)\big)(1 - k)\right].$$

This is an *equation of an autocatalytic process in complex systems*. The autocatalytic process is an inductive process in which the final product serves as a catalyst for its production, first described by Ilya Prigozhin (1981) in his theory of dissipative structures. Dynamic models of autocatalytic processes are productively applied in the modelling of chemical and biological processes, thermodynamics, and in economic sciences.

In Nobel Prize winner Ilya Prigogine's terminology, dissipative structures arise in systems that are far from equilibrium and are maintained only by the inflow of external resources. In our case, the collateral mechanism pushes the system of 'real estate prices - bank lending - household welfare' far from equilibrium, where there is no equilibrium price for real estate. Real estate prices, lending volumes, and household welfare are growing rapidly, and a bubble is being formed in the real estate market, fuelled by more new loans. It behaves like a dissipative structure. As soon as the inflow of new loans ends due to internal or external shocks to the banking system, this bubble bursts with all the negative consequences for real estate prices, banks, and households.

We have found that *in economic complex systems, price dynamics in the real estate market under the intensive work of the collateral accelerator mechanism become autocatalytic processes*. All autocatalytic systems are non-equilibrium dissipative structures requiring permanent external inflows of energy, material, or information for fuelling.

The equation for the dynamics of the credit-backed real estate volume $K(Q, h, p)$ in the economy is:

$$\frac{dK(t)}{dt} = -kK(t) + hQP(t)\,(1 + k).$$

As is well known, the value of real estate has a direct impact on the wealth of the households that own it. Let us denote by variable W(t) the part of household wealth that represents the market value of the real estate they own. The third differential equation of household welfare (W) dynamics completes our system:

$$\frac{dW(t)}{dt} = \alpha\, W(t) + P(t)Q - K\left(Q, h, P(t)\right)(1 + k).$$

Therefore, we have the non-linear dynamic system of differential equations:


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$$\begin{cases} \dfrac{dW(t)}{dt} = \alpha\, W(t) + P(t)Q - K\,(Q,h,P(t))(1+k) \\ \dfrac{dP(t)}{dt} = \beta\,\big[\,a - c - (b+m)P(t) + K\big(Q,h,P(t)\big)(1-k)\big] \\ \dfrac{dK(t)}{dt} = -kK(t) + hQP(t)\,(1+k) \end{cases}$$

This system has some similar features and differences to the typical dynamic non-linear model of Lotka-Volterra that is widely applied in different sciences, including economics, with three species ("one prey – two predators' model"). In our findings, the processes of collateral loan volume increase and real estate price growth are analogous to the "two predators", and the wealth of households is analogous to the "prey."

We can simplify this general system by an easy transformation

$$\frac{dK}{dt} = -khQP(t) + hQP(t)(1+k) = hQP(t),$$

$$\frac{dP(t)}{dt} = \beta(a-c) + P(t)[\beta hQ(1-k) - \beta(b-m)].$$

In the case h = 0 (value-to-loan equals zero), "the collateral accelerator mechanism would be absent, and this equation turns into the standard classical macroeconomic equation" (Unkovska et al., 2022) for the dynamics of price, which tends to equilibrium $P^*$.

*In the real usual "case* $h > 0$*, the collateral accelerator works, and the economy transits to a "strange regime" when the increase in real estate market prices raises demand"* (Unkovska et al., 2022). This is the core of the self-enforcing spiral or systemic risk accumulation cycle.

Solving this system of differential equations, we obtain its analytical solutions:

$$P(t) = C_1\, e^{\beta[h(1-k)Q+m-b]\,t} + C_2 \tag{1}$$

$$\delta = \beta[h(1-k)Q + m - b]. \tag{2}$$

That is:

$$P(t) = C_1\, e^{\delta t} + C_2$$

$$K(t) = hQ\,[\,C_1\, e^{\beta[h(1-k)Q+m-b]t} + C_2] \tag{3}$$

$$W(t) = C_3\beta[1 - h(1+k)Q \cdot e^{\alpha t} + C_4 e^{-[h(1-k)Q+m-b]t} + C_5. \tag{4}$$

Under the conditions of the collateral accelerator mechanism, dynamic patterns and interdependencies can be established.

Thus, we found that the mechanism of the collateral accelerator can shift the real estate market, banking system, and the whole economy into a highly fragile and volatile dynamic regime with increasing systemic risk. "To reduce systemic financial risk and ensure financial stability without suppressing economic growth, it is seen as reasonable that macroprudential regulators considered the described non-linear processes and self-reinforcing cycles, the effect of the collateral accelerator mechanism as an endogenous destabiliser of the banking system and the whole economy" (Unkovska et al., 2022).

## DISCUSSION

The vast amount of research continues to debate systemic risk measurement and regulation. The ongoing heated debate reflects the complexity of the issue and the multifaceted nature of the problem.

There are many interesting research papers that consider practical cases of connections between the real estate market, bank lending, and the whole economy, which provide evidence of their non-linear, complex interactions.

For instance, Ren, Y., and Yuan, Y. (2014) suggested a dynamic stochastic partial equilibrium model for explaining residential investment dynamics in the United States. The authors focused on the cyclical features of residential investment,

in that it leads the whole economy, and considered news shocks, collateral constraints, and agent heterogeneity, and found that these variables are essential to dynamics in which residential investment leads consumption and GDP.

In the research paper of Kristian Blickle (2022), the author studied the effects of an increase in the supply of local mortgage credit on house prices by exploiting a natural experiment from Switzerland. The author showed that "local mortgage banks increase mortgage lending, which correlates with subsequent house price growth in their markets."

The research paper Haroon Mumtaz and Roman Sustek (2023) presented an application of a parsimonious model to house prices in 12 advanced economies since 1950. They accounted for the real estate boom and bust in Japan, the boom starting in many countries in the early 1990s, and the recurrent cycles in house prices in Switzerland. The authors "for pragmatic econometric reasons, abstracted from any dynamic interactions between the fundamentals under consideration (and the real interest rate)" and left such explorations for future work.

A vast body of practical research on the relationship between the real estate market and bank lending in different countries shows the multifactorial nature and complexity of the nonlinear connections between them. This demonstrates the need for more in-depth theoretical and methodological studies that generalise these practical cases and justify the fundamental economic laws that govern them. A great amount of work has already been done in this direction. The literature review in this paper gives an overview of part of this work. According to Sylvain Benoît, Jean-Edouard Colliard, Christophe Hurlin, and Christophe Pérignon (2015), one type of theoretical systemic risk research includes source–specific approaches, the second type of this research includes a global approach, the third family of research emphasises the network approach to assessing systemic risk, and the fourth family of papers covers the issues of measures of systemic risk. Research into theoretical foundations and modelling tools continues to develop actively at present.

In our research, Unkovska T. (2009, 2012, 2013), Unkovska, T., Taruta, S., & Grydzhuk, D. (2022), and in this paper, we develop theoretical foundations and modelling instruments into the framework of the complex nonlinear systems methodology. In our previous paper Unkovska T. et al (2022) we gave a big review of literature that cover different approach to modelling systemic risk: the network approach (The Network Approach); risk correlation analysis-based approach (Co-risk Model); the method of matrices of the interdependence of distresses (Distress Dependence Matrix); the approach based on default intensity models Intensity (Default Intensity Model) and suggested a new analytical approach based on modelling collateral accelerator mechanism that pushes the banking system and real estate market far from equilibrium.

In this paper, we continued our previous research and suggested a new non-linear model of real estate price and banking lending bubble. The growth of this bubble requires constant fuelling with new lending, the volume of which, in turn, rises due to the increase in the prices of collateral assets on bank balance sheets. Thus, an endogenous self-reinforcing spiral arises. We have built a new dynamic model of this process in the form of three Lotka-Volterra-type differential equations. Having obtained analytical solutions to this system of differential equations, we have gained insight into the behaviour of key variables. This phenomenon has the properties of an autocatalytic process. As soon as the inflow of new loans stops (sudden stop of financial flows) due to exogenous or endogenous shocks, the real estate price bubble bursts. It leads to deleveraging and a further reduction in lending. We plan to continue this research in the future.

Thus, we contributed to the study of systemic financial risk with a new approach to modelling the interrelated dynamics of real estate prices, bank lending, and household wealth, based on a modified Lotka-Volterra model for three variables. This distinguishes our paper from all the above-mentioned works. The scientific novelty of our research paper lies in the development of a new nonlinear dynamic model — a system of three differential equations describing the interrelated dynamics of household welfare, real estate prices, and the volume of bank loans secured by real estate. We found an analytical solution to the system, which revealed the autocatalytic properties of these variables' dynamics, as consequences of the action of the collateral accelerator mechanism. We found that the real estate prices bubble is a dissipative structure in the sense of Nobel Prize winner Ilya Prigozhin's sense. The growth of this bubble needs terms of determined key qualitative characteristics, drivers, and critical parameters that amplify systemic financial risks.

## CONCLUSIONS

Our paper provides a rationale for extending and deepening the macroprudential policy methodology based on the new dynamic non-linear modelling approach presented here.


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1. The dynamics of real estate prices have the character of an autocatalytic process: the increasing prices nourish further price growth through the mechanism of collateral accelerator by the exponential function described by equation (1). Real estate price growth continues as long as the parameter $\delta = \beta[h(1-k)Q + m - b]$ of the exponent function is positive. It depends on the values of the mortgage interest rate k, coefficient h (LTV), value Q, and structural parameters *m* and *b*, according to the formula (2).
2. When the delta-parameter $\delta$ changes its value from positive to negative, the phase shift occurs, and real estate price dynamics transition to the regime of falling. This, in turn, leads to the collateral lending process being reversed ("sudden stop" phenomenon).
3. We found that the real estate price growth phenomenon is a dissipative structure in Prigozhin's terminology in complex systems methodology. Its dynamics obey the equation (1) that we found. To maintain the existence of this dissipative structure, a continuing inflow of financial resources is necessary. The collateral accelerator is the mechanism that supports an expansion of this dissipative structure, and then, after a "sudden stop", leads to its collapse.
4. The exponential function (3) with the $\delta$ parameter describes the dynamics of collateral mortgage lending. When the value of $\delta$ switches from positive to negative, a phase shift occurs, and the mortgage lending volume starts declining.
5. The phenomenon of collateral lending growth is also a dissipative structure in Prigozhin's terminology. It requires continuing feeding to maintain its increase, an increase in real estate prices, and demand for collateral mortgage lending. So, we have two dissipative structures that support each other.
6. The households' welfare dynamics W(t) in the system of collateralised mortgage lending obeys the function (4), which is the sum of two exponent functions with different parameters α and δ. When the parameter δ changes from positive to negative, there is a change in the dynamic regime of W(t).
7. The most influential parameters that determine the driving forces for the spiral of interconnected dynamics of real estate prices, volume of collateral loans, and wealth of households are:

- the coefficient h = LTV – the higher the LTV ratio, the faster the increase in prices, credit volumes, and wealth of households, and then falling them;
- the structural parameters of the real estate market and elasticities of demand and supply to the changes of real estate prices (a, b, c, and m);
- the level and dynamics of the mortgage interest rate k; at this stage of research, we suppose in our basic model that k is constant; the future direction for research is widening the model by introducing dynamics for the interest rate k, LTV ratio h, and volume Q as the functions of time k(t), h(t), Q(t).

There are new directions for further research deriving from our results that could be helpful for macroprudential policy improvement. The elaborated non-linear dynamic model can be helpful for simulations with concrete parameters of different countries with various scenarios of macroprudential regulation and monetary policy.

## ADDITIONAL INFORMATION

### AUTHOR CONTRIBUTIONS

*All authors have contributed equally.*

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*The Authors declare that there is no conflict of interest.*

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## РИНОК НЕРУХОМОСТІ, БАНКІВСЬКЕ КРЕДИТУВАННЯ ТА СИСТЕМНІ ФІНАНСОВІ РИЗИКИ: НОВА НЕЛІНІЙНА ДИНАМІЧНА МОДЕЛЬ

Системні ризики вже кілька десятиліть є предметом економічних досліджень, оскільки ці ризики можуть спровокувати небезпечні наслідки, які неможливо пом'якшити за допомогою традиційних інструментів макропруденційної політики. Нещодавно Європейська Рада із Системних Ризиків (ESRB) попередила про високу вразливість європейських банків до ризиків криз у секторі нерухомості й необхідність удосконалення макропруденційного регулювання. Основною метою цього дослідження є розробка теоретичної бази та нових інструментів моделювання для поглиблення розуміння нелінійних взаємозв'язків між ринком нерухомості й банківським кредитуванням, що дозволить удосконалити макропруденційне регулювання з метою зниження системних ризиків. Ми використовували методологію складних нелінійних систем, математичну теорію диференціальних рівнянь, підхід Лотки-Вольтерра для моделювання нелінійної динаміки взаємопов'язаних систем, а також теорію механізму прискорення ціни застави (CA – collateral accelerator) на ринку нерухомості й у банківському кредитуванні. Наукова новизна полягає в отриманні нових теоретичних і прикладних результатів: ми розробили нелінійну динамічну модель, яка поглиблює розуміння дії механізму CA та основних драйверів загострення системного фінансового ризику; нові інсайти щодо точок перелому та структурних зрушень на ринку нерухомості й у банківській системі за певних умов, які ми визначили. Ми виявили, що за дії механізму CA ринок нерухомості не може досягти рівноваги. Ціни на нерухомість зростають відповідно до отриманих нами співвідношень, підживлюючись новими кредитами. Цінова бульбашка є дисипативною структурою в термінології Прігожина, а параметр LTV є ключовим чинником темпів зростання цін. Після досягнення порогового значення відбувається колапс цінової бульбашки, делевередж банківської системи та посилення кризових процесів. Результати дослідження є важливими для поглиблення розуміння природи системних фінансових ризиків та оцінки чинників криз у банківському секторі й на ринку нерухомості. Ці результати корисні для органів макрофінансового регулювання та управління банками, вони можуть сприяти вдосконаленню макропруденційної політики, банківського регулювання та зміцненню стратегічних рішень на рівні банків із метою запобігання системним фінансовим кризам.

**Ключові слова:** системний ризик у банківській системі, фінансова стабільність, експозиція CRE, стратегічне управління банками, макропруденційна політика, ринок нерухомості, цикли самозабезпечення, акселератор застави

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