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Stress Testing: A Review of key Concepts

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Abstract

The note is a review of the literature on the quantitative methods used to assess the vulnerabilities of financial systems to risks. In particular, the author focuses on the role of system-wide stress testing. He summarizes the recent developments in the literature, highlighting topics relevant for the Czech case. He presents the key concepts relating to system-wide stress tests, overviews the stress tests performed by central banks and international financial institutions, and discusses conceptual issues relating to modeling of individual risk factors.

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Introduction

In response to the increased financial instability in many countries in the 1990s, policy makers have become interested in better understanding the vulnerabilities in financial systems and measures that could help prevent financial crises. One of the key techniques for quantifying financial sector vulnerabilities is stress testing.

The purpose of this note is to review the literature on the quantitative methods used to assess the vulnerabilities of financial systems to risks, focusing on the role of system-wide stress testing. The note summarizes the recent developments in the literature, focusing on topics that could be interesting in the Czech case. The first section introduces macroprudential analysis, which encompasses stress testing as one of the main methods. The second section discusses the concept of a stress test. The third section gives an overview of the stress tests performed by central banks and international financial institutions. The fourth section describes the implementation of stress tests as a multi-step process. Finally, the fifth section discusses specific issues relating to individual shock factors.

To keep the presentation concise, the text focuses on issues that could be of more interest in the Czech context. Where a topic is well covered elsewhere and the relevant literature is easily available, only a short summary and a reference to the original source is included. An extensive list of references is provided in Appendix I. A follow-up technical note describes practical issues involved in implementing stress tests for the Czech banking system which could be conducted on a regular basis (Čihák, 2004).

1. Macroprudential Analysis

The assessment and monitoring of the strengths and vulnerabilities of financial systems is called *macroprudential analysis*.[1] Macroprudential analysis uses quantitative information on the financial system as well as qualitative information on the institutional and regulatory framework (Figure 1). It encompasses surveillance of financial market conditions and analysis of macro-financial linkages. It is, in turn, part of a broader framework for macroeconomic vulnerability assessment, which includes the balance sheet approach, debt sustainability analysis, and monitoring of macroeconomic conditions. One of the key elements of the quantitative analysis is stress tests.

Measuring financial system soundness requires good quantitative inputs: information on the structure of the system, general macroeconomic indicators, and "financial soundness indicators" (FSIs). FSIs are compiled to monitor the soundness of financial institutions and markets, and of their corporate and household counterparts. Financial market data and macroeconomic data are useful because they provide forward-looking information that can help in assessing the likelihood of shocks affecting the financial system.

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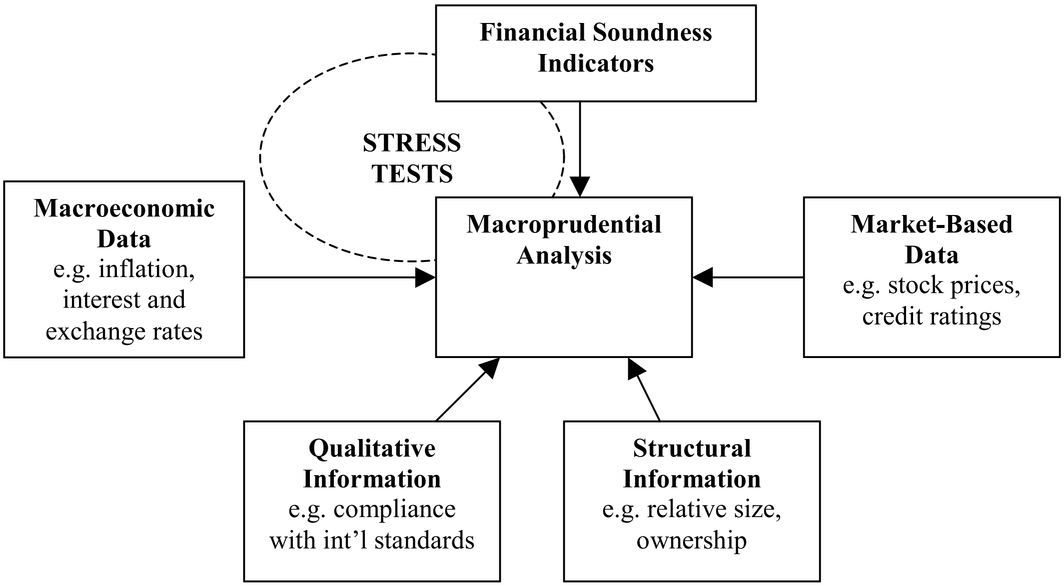
[1] For more on macroprudential analysis, see in particular Evans et al. (2000), Sundararajan et al. (2002), International Monetary Fund (2003 a,b), and IMF–World Bank (2003).

Figure 1: Framework for Macroprudential Analysis



***Source**:* Sundararajan et al. (2002).

FSIs include both aggregated information on financial institutions and indicators that are representative of markets in which financial institutions operate. To facilitate the compilation of these indicators, the IMF has defined sets of "core" and "encouraged" FSIs. A list of the core FSIs is presented in Table 1. All core FSIs relate to the banking sector, reflecting its dominance in most countries' financial systems. The encouraged FSIs include additional indicators for banks, data on financial market liquidity, nonbank financial institutions, the non-financial corporate sector (e.g. total debt to equity), the household sector (e.g. household debt service and principal payments to income), and real estate markets (IMF, 2003a). There are three categories of FSIs, each with a different role: monitoring financial sector vulnerabilities arising from credit, liquidity, and market risk; assessing the condition of non-financial sectors; and assessing the capacity of the financial sector to absorb losses, as measured by capital adequacy. For guidance on the definitions and compilation of the FSIs, see the IMF's *Financial Soundness Indicators Compilation Guide* (IMF, 2003a). For the key issues involved with analyzing FSIs, their inter-relationships and their relationships to other parts of the macroprudential analysis framework, such as stress testing, see IMF (2003b). Appendix II provides more details on the framework for financial stability analysis, showing the various types of financial sector surveillance and the types of indicators used in the surveillance.

Table 1: Financial Soundness Indicators: Core Set

Capital adequacy	Regulatory capital to risk-weighted assets
	Regulatory Tier I capital to risk-weighted assets
Asset quality	Nonperforming loans to total gross loans
	Nonperforming loans net of provisions to capital
	Sectoral distribution of loans to total loans
	Large exposures to capital
Earnings and profitability	Return on assets
	Return on equity
	Interest margin to gross income
	Noninterest expenses to gross income
Liquidity	Liquid assets to total assets (liquid asset ratio)
	Liquid assets to short-term liabilities
Sensitivity to market risk	Duration of assets
	Duration of liabilities
	Net open position in foreign exchange to capital

Source: IMF (2003a).

2. The Concept of Stress Testing

In the context of macroprudential analysis, the term stress testing refers to a range of statistical techniques used to help assess the vulnerability of a financial system to exceptional but plausible events.[2] For a good general introduction to the stress testing methodology, see Blaschke et al. (2001). A detailed list of literature references is included in Appendix I.

This note focuses on *system-wide stress tests* (or macrofinancial stress tests), which measure the impact of shocks on financial system stability. Compared to stress tests for individual financial institutions, the system-wide stress tests have—as the name suggests—wider coverage (i.e. the financial system or a systemically important part of it), are used for a different purpose (financial sector surveillance rather than risk management), focus more on channels of contagion (i.e. how a risk to one institution can become a systemic risk), and often have to use more streamlined techniques (because of the ensuing complexity of the calculations). Also, system-wide stress testing is a much newer concept, and the literature on the topic is consequently much shorter than that on stress testing for individual institutions.[3]

The system-wide nature of the stress tests does not mean that they should be performed on aggregate data. Applying the tests to the financial system as a whole or to large groups of institutions can disguise substantial exposures at the level of individual institutions, which can lead to failures of these institutions and then contagion to the rest of the system. These exposures can get "netted out" in the aggregation. It is therefore important to perform the stress tests on an institution-by-institution basis to the extent possible, and to analyze not only the aggregate results,

[2] A web search shows about 175,000 occurrences of the term, more than, for instance, "banking supervision" (72,000) and "capital adequacy" (98,000). This is partly explained by the fact that stress tests are used in areas as diverse as cardiology, engineering, and software programming.

[3] For an introduction to the literature on stress testing for individual institutions, see, for instance, Laubsch (2000). For an international survey of stress testing practices in major banks, see, for instance, Committee on the Global Financial System (2000 and 2001) or Fender et al. (2001).

but also the dispersion of the results around the aggregate figure. The positive "by-product" of calculating the stress tests this way is that they can be used by bank supervisors as an additional off-site tool to identify vulnerable banks.

The key element of the definition of stress testing—and also one of the more controversial themes in the literature on the topic—is the definition of an exceptional but plausible event. While some authors view stress testing as a subgroup of risk modeling focusing on "tail" events that can and should be included in a comprehensive risk model (e.g. Berkowitz, 1999), others describe the selection of scenarios for the system-wide stress tests as "an art" rather than a science (e.g. Kupiec, 2001). The approach taken in the present paper is an intermediate one: while recognizing the difficulties involved in estimating an "exact" risk model, especially for multi-factor scenarios for a system as a whole, the selection of stress test scenarios should be—to the extent possible—based on a measure of plausibility.

Stress tests can be classified, by methodology, into three main types: (i) *sensitivity analysis*, which seeks to identify how portfolios respond to changes in relevant economic variables (such as interest rates and exchange rates); (ii) *scenario analysis*, which seeks to assess the resilience of financial institutions and the financial system to an exceptional but plausible scenario; and (iii) *contagion analysis*, which seeks to take account of the transmission of shocks from individual exposures to the financial system as a whole.

The importance of stress testing for macroprudential analysis derives from integrating a forward-looking macroeconomic perspective, a focus on the financial system as a whole, and a uniform approach to the assessment of risk exposures across banks. Unlike the stress tests conducted at large banks, which are designed to measure portfolio- and bank-specific risk exposures, system-wide stress tests apply a common set of scenarios based on an assessment of macroeconomic and market risks. This uniform approach allows for the aggregation of results, helping to identify key vulnerabilities at the level of the overall system, and providing comparable information on risk profiles across banks.

Stress testing is primarily about identifying latent exposures. There is little need to perform complicated stress test calculations if the exposures are obvious, or obviously lacking. Stress tests are needed to identify exposures that are less obvious, perhaps hidden across a wide variety of instruments, credits, and derivatives positions.

2.1 Stress Tests and Analysis of FSIs

In analyses of financial sector stability, FSIs are often used together with stress testing. There are a number of important differences between stress testing and FSIs, deriving from their different roles in macroprudential analysis. In particular, stress testing illustrates more clearly the potential cost of shocks. To serve this purpose, each stress testing exercise must be tailored to the features of a particular system. This higher flexibility means that is impossible to derive "standard" methodology comparable to that for compiling FSIs (IMF, 2003a). Stress test shocks and models are based on judgments and assumptions, so the stress test output is not comparable to FSIs measuring actual conditions in a financial system. It is not subject to the rigorous standards applied by statisticians to data.

Bearing in mind these caveats, stress testing and FSIs provide complementary approaches to analyzing similar risks. The complementarity between stress testing and FSIs is probably of greatest relevance in the area of sensitivity to market risk. The more advanced state of market risk stress testing makes it feasible to use the measure of loss from these stress tests as a soundness indicator along with market risk FSIs. This is more likely to be the case in more sophisticated financial systems where banks conduct frequent market risk stress tests as an integral part of their risk management. The results of these stress tests could be presented in a form comparable to the relevant market risk FSI (e.g. as a measure of loss relative to capital for a shock of a given size). This complementarity reflects the close relationship between the two at the analytic level. For example, the estimated direct loss from a stress test of an exchange rate shock can be approximated by the change in the exchange rate multiplied by the net open foreign exchange position FSI (see IMF, 2003b).

2.2 Stress Tests and Value-at-Risk Models

Many commercial banks use value-at-risk (VaR) models to measure their risk exposures, in particular for market risks. While the market risk VaR results may be of interest, their usefulness for the systemic stress test calculations is limited, since they apply only to trading book assets, and focus exclusively on losses. As a general matter, VaR and stress test exposure estimates are not additive. A stress test measures the *x* percent tail in an assets profit and loss distribution, while a value-at-risk measures the mark-to-market gain or loss that an asset would experience should one or more of the underlying economic factors that determine the asset's value experience a specific change in value.

Systemic stress test measures must be capable of estimating gains as well as losses in the various institutions in the financial sector if the intended purpose of the test is to assess the financial sector's net exposure to a potential macroeconomic risk. Risk exposures pose the greatest systemic threat when all or most institutions have exposures of the same sign.[4] Value-at-risk measures focus on the loss side. The use of a value-at-risk measure in the stress test setting precludes the ability to measure the net exposures in a system, and so they are an inappropriate measure of risk in many stress testing situations (Kupiec, 1998 and 2001).

3. Stress Tests by International Financial Institutions and Central Banks

The International Monetary Fund (IMF) and the World Bank (WB) have initiated the *Financial Sector Assessment Program* (FSAP), which strives to assess strengths and vulnerabilities in their member countries' financial systems. The assessments under this program have so far covered more than 50 jurisdictions and provided various recommendations for improvement in the

[4] This is particularly important for exposures generated by derivative positions. Derivatives instruments are "zero net supply" contracts, i.e. there is an agent taking a short position for every agent taking a long position. On many instruments (options being an exception), the potential gains/losses on long/short positions are symmetric. If derivative losses accrue entirely as gains to counterparties in the same financial system then, on balance, the financial system has no change in wealth. If these losses accrue entirely as gains to counterparties outside the system, the financial system has lost wealth. For an open financial system such as the Czech one, it is quite likely that the aggregate change in wealth will be non-zero. From a macroprudential perspective, the key issue will be identification of the counterparties.

financial system framework (many of the assessments are available on the IMF and WB websites). Stress testing was from the beginning a key element of the assessment of financial sector stability.

Stress testing in the FSAP has evolved. Most FSAP missions to date have included single-factor sensitivity analysis based on historical extreme values, although an increasing number have also applied scenario analyses, using multiple techniques to determine the size of shocks. While almost all stress tests relied on data provided by the authorities, the involvement of the authorities in the recent FSAP missions has gone beyond providing data, as they have also been actively involved in designing and implementing stress tests in the recent FSAP missions. Moreover, recent FSAP missions to industrialized countries have aimed to improve the effectiveness of stress tests through the use of macroeconomic models, the analysis of contagion resulting from interbank exposures, and the involvement of major financial institutions in the stress testing exercise (IMF and the World Bank, 2003).

The availability and quality of data impose major constraints on the nature of the stress tests that can be performed. Data limitations have come in three forms: (i) basic data availability, especially in countries where information on key exposures may not be available; (ii) an inability to isolate the desired exposures in a financial institution, especially in the case of complex financial institutions or institutions which are active in the derivative markets; and (iii) confidentiality issues—limitations on what the authorities are legally able to share with the mission.

The experience of the FSAP to date suggests that the types of stress tests need to be tailored to country-specific circumstances, the complexity of the financial system, and data availability. In industrialized countries, the analysis can be strengthened by using macroeconomic models (to help calibrate the scenarios and arrive at a consistent set of assumptions for the tests), the analysis of interbank contagion, and the involvement of major banks in the stress testing exercise (IMF and World Bank, 2003).

The experience also suggests that stress tests can have a number of benefits. In particular, they can help define the amount and nature of the data required for ongoing monitoring of financial stability, thereby playing an important role of "capacity building." They can also provide an independent verification of potential sources of vulnerability and broaden the understanding of linkages in the financial system (IMF and World Bank, 2003). Several central banks have started conducting a regular stress testing exercise following the FSAP, some central banks have increased regulatory attention to stress tests done by commercial banks, and some central banks have asked for follow-up technical assistance with establishing a framework for conducting stress tests on a regular basis.

There are two general uses of stress tests at central banks. The first one is supervisory stress tests designed to identify potentially weak banks. Stress testing can be used, together with the more traditional off-site analytical tools (CAEL ratings, early warning systems, and other data and qualitative information), to help identify banks that are in need of closer supervisory attention and possibly remedial action. The second use for stress tests is macrofinancial surveillance, i.e. analysis of the robustness of the financial system as a whole to external shocks. A number of central banks have started to regularly publish their analyses of financial sector stability (typically called Financial Stability Reports). The approaches to stress tests used by central banks differ widely from more mechanical approaches to approaches focusing more on sources of credit risk, as illustrated by the Financial Stability Reports of the Austrian National Bank, the National Bank of Hungary, and the Bank of Norway (see Boss, 2002, National Bank of Hungary, 2003, and Eklund et al., 2001, respectively).

4. Implementing Stress Tests

System-wide stress testing can be viewed as a *multi-step process* of examining the key vulnerabilities in the system. This involves: identifying the major risks and exposures in the system and formulating questions about those risks and exposures; defining the coverage and identifying the data required and available; calibrating the scenarios or shocks to be applied to the data; selecting and implementing the methodology; and interpreting the results.

4.1 Identifying Major Risks

To be relevant, stress tests must probe the consequences of potential shocks that are related to the macroeconomic risks that exist in the actual situation of the country. The process of designing system-wide stress tests therefore typically starts with a discussion of the potential risks faced by the economy. The discussion then suggests that certain types of shocks (e.g. a potential increase in interest rates or a depreciation of the currency) are more likely in the given economy than other types of shocks.

The fact that there are macroeconomic risks that could result in shocks to the financial system does not necessarily mean that the impact of the shocks would be large. The impact can still be small if the exposures in the system are small. It is the purpose of the stress tests to assess how the risks combine with the exposures. The design of stress tests is often an iterative process, since some originally identified risks may lead to relatively small impacts, while some risks originally assessed as small may lead to large impacts if there are substantial exposures.

Even if the exposures are large and stress tests identify a potentially large impact on the financial system, it is the purpose of the other parts of the macroprudential analysis to assess the likelihood that these impacts can be mitigated by prompt action by supervisors and banks.

4.2 Defining Coverage and Identifying Data

Another key step in designing stress tests is defining their coverage. The general rule is to include all systemically relevant institutions and exposures. The practical issues are: what types of financial institutions to include (typically banks, since they dominate most financial systems, but sometimes also other institutions, such as insurance companies) and how to include foreign-owned financial institutions (a typical solution is to include subsidiaries but exclude branches of foreign-owned financial institutions). In terms of exposures, the most frequently covered are exposures to credit risk and market risks, and sometimes also liquidity risk and interbank contagion risk. The choice of coverage then determines the data needed for the calculation.

4.3 Calibrating Shocks and Scenarios

There are two general ways of asking questions about the size of exposures in the financial system. These two ways correspond to two different approaches to formulating and presenting stress testing calculations. The first, more typical, way is to formulate an extreme scenario that has a chosen degree of plausibility and ask what would be its impact on the system. We will call this method the "worst case approach," since in effect it looks the scenarios that have the maximum impact for a given level of plausibility. The second, less common, way is to select a threshold in terms of the impact on the system and ask what are the smallest shocks that would need to occur for the system to reach that threshold. We will illustrate that these two approaches are essentially equivalent, even though they offer two different ways of presenting the vulnerabilities in the system.

The "worst case" approach

The process of scenario selection under this approach can be summarized as identification of a "worst case scenario." Roughly speaking, the worst case scenario for a given portfolio is the scenario of risk factors that minimizes the value of this portfolio, but has a certain predefined "plausibility". This approach only requires the selection of the minimum level of plausibility (e.g. 1 percent) admissible in the worst case scenario. Figure 2 illustrates the choice of the scenario in a case with two risk factors. These could be thought of as, for instance, the exchange rate and interest rate. Each of the ellipses depicts the set of combinations of the two risk factors with the same probability of occurrence. The shape of the ellipse reflects the correlation between the two factors, and its size the level of plausibility. The larger the ellipse, the smaller the plausibility. The diagonal lines depict combinations of the risk factors leading to the same overall impact in terms of the capital adequacy ratio (CAR). The impact generally increases with the size of the shocks to the risk factors, so the CAR decreases in the northeast direction. The diagonal line does not have to be straight; it is only depicted here as such for simplicity.

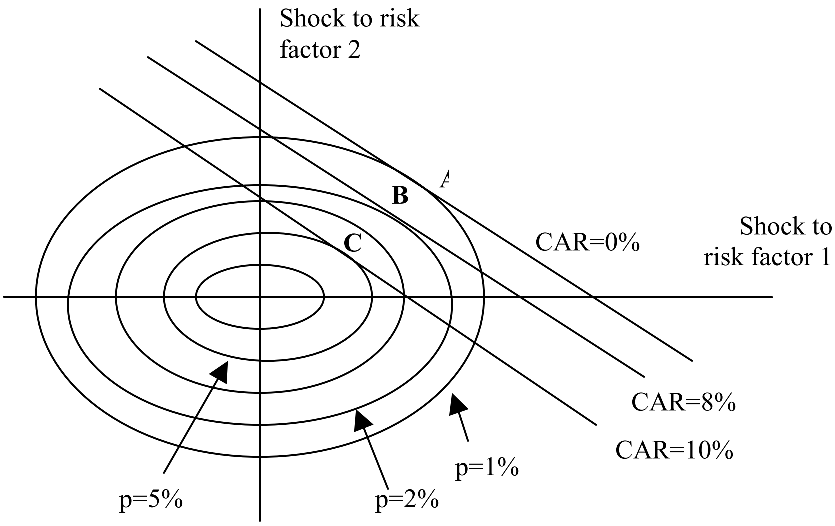
The worst case approach would start with selecting a level of plausibility, e.g. 1 percent, and searching for the combination of shocks with this level of plausibility that have the worst impact on the portfolio. In Figure 2 this means searching for the point on the largest ellipse (including all 1 percent plausibility events) that lies as far northeast as possible. This is point A.

The "threshold" approach

An alternative approach to presenting stress tests is to present the largest shocks that leave the system above a certain threshold. For instance, one can ask what is the largest increase in nonperforming loans (NPLs) that the banking sector would be able to survive with no bank becoming insolvent. An example of a tighter threshold would be that no bank's capital adequacy ratio declines below the Basel Accord minimum of 8 percent. An example of a loose threshold would be that not more than 25 percent of the banking system becomes insolvent. The advantage of this approach is that it does not require calibrating macroeconomic scenarios. Also, it provides a result that is very intuitive and straightforward to interpret. Its potential disadvantage is that it is more difficult to implement for more than one risk factor. Figure 2 shows how it could be implemented for two factors.

The threshold approach starts with selecting the threshold, i.e. the diagonal line; it then searches for the smallest shocks reaching this threshold. This is straightforward if there is only one risk factor; if there are two risk factors, one needs to take into account the correlation between the risk factors. For the specific correlation pattern in Figure 2, selecting a threshold of zero capital adequacy would lead us again to the combination of shocks corresponding to point A. The point of Figure 2 is to illustrate that even though in particular cases the two approaches can lead to different results depending on the choice of threshold or plausibility level, these are essentially equivalent approaches to the same problem.[5]

Figure 2: Worst Case Approach vs. Threshold Approach



Source: Author.

Practical approaches

In practice, establishing the exact level of plausibility of a shock or a scenario can be very difficult. Having in mind that stress testing deals with "tail events," establishing the probability of an extreme event can be problematic even for a single factor and single exposure. It is even more complicated when multiple risk factors are considered (in which case the covariance pattern comes into question). Finally, it is even more difficult to implement when there is need to map shocks from macroeconomic variables (such as GDP) into the risk factors directly influencing banks (such as interest rates). Given the difficulties involved, it is not surprising that some authors consider stress testing to be "an art" (Kupiec, 2001).

For risk factors where good historical data are available (which is more likely to be the case for market risks), the natural starting point is to base the scenarios on the patterns of volatility and covariance observed in past data. Calibrating the shocks is particularly straightforward for single-factor stress tests for market risks: an exchange rate shock can be based on 3 standard deviations

[5] From the microeconomic viewpoint, these are two dual tasks.

of past changes in the exchange rate (corresponding roughly to a 1 percent confidence level). To establish correlation patterns in models with more risk factors, one could simply look at the covariance statistics of the various variables, or use stochastic simulations based on existing macroeconomic models. Such calculations are of course subject to a number of caveats mentioned earlier (models tend to break down for large shocks). Nonetheless, the models, if used cautiously, could help in finding a first-cut approximation of the scenarios for the stress-tests.

A practical approach to addressing the difficulties involved in scenario selection is to base the stress tests on an extreme historical scenario. This approach makes it possible to specify relatively complex stress tests with a number of risk factors. For Asian countries, for example, such a scenario might be the 1997 crisis; for the Czech Republic, it might be the 1997 exchange rate turbulence and the 1997–1999 recession.[6] The advantage of this approach is that it is quite illustrative and plausible. Its disadvantage is that the plausibility level of such a scenario may not be clear; at the same time, it is not clear whether the past crisis is a useful model for possible future crises.

There has been some controversy in the literature about whether stress tests should or should not include hypothetical scenarios that go beyond the historical experience (Berkowitz, 1999). At the same time, virtually all authors seem to agree that there can be plausible scenarios that have not yet happened. Examples of extreme market movements or crises confirm that it is inadequate to supervise and manage risks only on the basis of business conditions prevailing in the past. New crises may include, for example, new concentrations of risk emerging through cross-market linkages not present in the past.

Specifying a hypothetical scenario means simulating shocks that (i) are suspected to be more likely to occur than historical observation suggests (or that have never occurred); or (ii) reflect a structural break that could occur in the future (Berkowitz, 1999). Simulating such shocks is consistent with the general approach to stress testing presented in Figure 2, i.e. the design of the scenarios is still based on some (at least implicit) probability measure. However, in hypothetical scenarios, the probability distribution used for scenario selection is different from the one that we could obtain from past observations.

The easiest case in this context is if the hypothetical scenarios indicate that the exposures are small. In this case, the "threshold" approach is a useful presentation tool: for example, if we ask what shocks are needed to make a significant impact on the financial system and find that the shocks would have to be several times larger than the largest shocks observed so far, the stress testing scenario provides an important conclusion, namely that the financial system is not very exposed to the risks considered in the scenario. In this case, the extremely low plausibility of the stress testing scenario is actually an advantage, because it helps to make the case that the system is very robust.

One practical possibility for presenting hypothetical scenarios is to combine a scenario justified by historical data (e.g. a large crisis that happened in the past) with sensitivity analysis (i.e. alternative assumptions about the sizes of the individual shocks). This approach is still open to the criticism that the level of plausibility of these scenarios may not be clear, but it at least provides

[6] The design of suitable stress tests for the Czech Republic is discussed in more detail in Čihák (2004).

some anchor to the shocks (i.e. the main scenario, based on historical experience), while providing some assessment of the robustness of the scenario's results with respect to changes in the model assumptions.

4.4 Selecting and Implementing Methodology[7]

The methodologies for individual shocks are discussed in more detail in Section V. As a general point, when attempting to identify measurement techniques, it is important to understand where exposures may generate losses in the financial system. This requires estimating where these exposures are recorded as positions either on or off the balance sheets of the institutions. In particular in more developed financial systems, finding the exposures may require understanding the details of the risk transfers that have occurred through derivatives and securitization activities.

Isolating the exposures that generate stress loss estimates often requires that institutions "slice and dice" their on- and off-balance sheet positions into sector specific decompositions that they may not typically monitor. Exposure estimates that relate to shocks to a specific economic sector may be obtained by aggregating the exposures from a customized decomposition of a financial institution's alternative activities (e.g. credit, equities, derivatives, credit derivatives, structured products, strategic long-term investments, and insurance). For example, the correction in the output of an important economic sector of the economy may be reflected in the stress test by direct loan and bond related losses on credits extended to this industry, by an equity market price shock to investments in firms in this industry, by a rise in consumer credit and mortgage related losses to the extent that wages and employment are adversely affected by the shock, and by losses on the banking and insurance industries' off-balance sheet positions, as counterparties default on their obligations in response to the shock.

Is there any unified approach to accurately and consistently estimate the magnitude of these potential losses even after the positions are isolated? According to Kupiec (2001), the answer is no. In many situations, the use of formal risk management models may add little in the way of measurement rigor to the stress test process. For example, the construction of a reasonably accurate estimate of the potential importance of an overall economic downturn and an increase in problem bank loans need not require the use of some complicated formal credit risk measurement model. Rather, historically informed judgmental estimates of the increase in NPLs and their corresponding provisions may, in many cases, give a more accurate picture of potential exposures. Depending on the interpretation attached to the stress test exposure estimate, it may be more important to identify merely that the losses are likely to be significant rather than to attempt to identify the "exact" magnitude of the losses.

Once the individual positions and portfolios that are likely to be the source of stress test losses are identified, even after recognizing the underlying imprecision involved, the stress test must have a way of revaluing these positions to reflect the effects of the stress scenario.

[7] This sub-section builds on Kupiec (2001).

4.5 Interpreting and Using Results

Stress test estimates, no matter how technical the model used to arrive at an estimate, are at best only first order approximations to the true potential loss exposure. Stress testing is only a starting point for analyzing the vulnerability of a financial system. Stress tests provide information complementing the insights gathered using other analytical tools, in particular assessment of the legal, institutional, regulatory, and supervisory framework; analysis of the financial system structure and key vulnerabilities; and empirical analysis of financial soundness indicators.

When interpreting stress tests, one needs to bear in mind their limits and the assumptions on which they are built. Typical stress tests view banks as static portfolios rather than actively behaving units. A thorough examination of vulnerability, however, must take into account the fact that banks adapt dynamically to shocks in the environment. Depending on the kinds of incentives that banks face, these adaptations may exaggerate or mute the vulnerabilities created by the initial shock. To understand the structure of incentives that banks may face in particular circumstances, it is necessary to look at the institutional environment, such as the corporate governance arrangements in banks; the legal, accounting, tax, and regulatory conditions; and how claim holders on banks may react in the bond and equity markets to actions that banks take.

Stress tests should be interpreted as indicators of exposures rather than as forecasts of bank failures. Exposures could appear large relative to an institution's regulatory capital, and yet the institution may well be able to survive the shock. One important reason is that a stress test considers only a part of a bank's income-generating operations. The bank may have significant positions in assets that are unaffected in performance or value under the specific stress scenarios analyzed. In particular, given their focus on financial asset and derivative value changes, stress testing calculations tend to ignore the importance of fee income and other bank income sources that are not formally "capitalized" on a bank's balance sheet or recognized in off-balance sheet position reports. The income from these operations might offset the losses that would arise in the stress scenario envisioned.

Another caveat against interpreting stress tests simply as predictors of default is their mark-to-market nature. Banks can often remain open and avoid default as long as regulators allow them to continue operating, even if they are insolvent on a mark-to-market basis. Regulatory capital requirements rely on book values and banks may suffer substantial mark-to-market losses on their banking book assets without recording any adverse effect on their regulatory capital position. Large mark-to-market losses on banking book assets are not reflected in regulatory capital calculations, and not only do most rated credits that are downgraded continue to pay interest and remain performing assets, but also many of them recover value as transitory market stresses subside. Therefore, while mark-to-market loss estimates are informative as to an institution's financial risk exposures, they are not nearly as informative about the ability of a bank to sustain losses and remain a going concern.

5. Specific Methodological Issues

We will now turn to specific methodological issues relating to the individual risk factors, namely exchange rate risk, interest rate risk, credit risk, equity price and real estate price risk, and liquidity risk. We will then discuss the modeling of interbank contagion of these shocks. With the significant exception of interbank contagion risk, a good introduction to modeling these risk factors is provided in Blaschke et al. (2001), and it is assumed in the following text that the reader is familiar with this basic paper.

5.1 Exchange Rate Risk: "Stress Testing 101"

Exchange rate risk is the risk that exchange rate changes affect the local currency value of institutions' (and the sector's) assets and liabilities as well as off-balance sheet items. Exchange rate risk can arise from positions in foreign currency as well as those in local currency that are indexed to foreign exchange rates. Furthermore, exchange rate risk can be *direct* when financial institutions have positions in foreign currency, or *indirect* when the foreign exchange positions taken by the financial institutions' borrowers may affect their creditworthiness.

The *direct exchange rate risk* can be assessed using the net open position in foreign exchange, which is one of the core FSIs (Table 1). The direct exchange rate risk is perhaps the simplest of the individual stress tests. To illustrate this stress test, let F denote the net open position in foreign exchange, C the capital, A_{RW} the risk-weighted assets (all in domestic currency units), and e the exchange rate in units of foreign currency per unit of domestic currency. A depreciation (decline) in the exchange rate leads to a proportional decline in the domestic currency value of the foreign exchange exposure, i.e. $\Delta e/e=\Delta F/F$ (for $F\neq 0$). Let us assume, for simplicity, that this translates directly into a decline in capital, i.e. $\Delta C/\Delta F=1$.[8] The impact of the exchange rate shock on the ratio of capital to risk-weighted assets would then be

$$\frac{\Delta[C(e)/A_{RW}(e)]}{\Delta e} \cong \frac{\frac{F}{e}A_{RW} - C\frac{\Delta A_{RW}}{\Delta C}\frac{F}{e}}{A_{RW}{}^{2}} \cong \frac{1}{e}\frac{F}{C}\frac{C}{A_{RW}}\left(1-\frac{\Delta A_{RW}}{\Delta C}\frac{C}{A_{RW}}\right), \qquad (1)$$

where we have used the fact that $\Delta C/\Delta e=\Delta F/\Delta e=F/e$. The symbol "$\cong$" means that the equation is only approximate for larger than infinitesimal changes. Equation (1) can be rewritten as

$$\Delta[C(e)/A_{RW}(e)] \cong \frac{\Delta e}{e}\frac{F}{C}\frac{C}{A_{RW}}\left(1-\frac{\Delta A_{RW}}{\Delta C}\frac{C}{A_{RW}}\right). \qquad (2)$$

The term $\Delta A_{RW}/\Delta C$ can have values from 0 to 1, reflecting the degree of co-movement of capital and the risk weighted assets.[9] In the special case of $\Delta A_{RW}/\Delta C=0$, i.e. if the risk-weighted assets do not change, the change in the capital adequacy ratio equals simply the exchange rate shock times the exposure, measured as a product of the two core FSIs (F/C and C/A_{RW}). This is sometimes used as a short-hand calculation of the direct exchange rate stress test. It should be noted that (2)

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[8] More realistically, we could deduct the impact first from profits, and then from capital—see Čihák (2004) for a discussion of the treatment of profits in stress tests.

[9] Empirically, $\Delta A_{RW}/\Delta C$ could be estimated by a regression.

holds only as a linear approximation, which works well if foreign exchange portfolios are essentially linear. However, if banks have large positions in foreign exchange options, the relationship between the exchange rate change and the impact on capital can become highly non-linear. In such cases, stress tests based on detailed decomposition of banks' open positions are a superior analytical tool.[10]

It is important to incorporate *indirect foreign exchange risk* into the stability assessment. The indirect risk is often more significant than the direct one, given that the direct exposure is relatively easy to measure and therefore to manage and regulate, while it is typically much more difficult to monitor the foreign exchange vulnerabilities of banks' counterparties. Especially in countries with fixed or heavily managed exchange rates, firms and households can be lulled by the perceived absence of foreign exchange risk and enter into large open positions in foreign exchange. In some of these countries, regulators either have started to ask, or are contemplating asking, banks to report!on their largest borrowers' foreign exchange exposures. (The information gathered in this way is undoubtedly useful; at the same time, it would not cover, for example, foreign exchange exposures in the household sector, credit to which has been growing rapidly in some countries.)

To illustrate the significance of the indirect risk, let us denote the corporate sector's debt, equity, and open foreign exchange position as $D_c(e)$, $E_c(e)$, and $F_c(e)$ respectively. (For simplicity, we will refer only to the corporate sector, even though the analysis would be essentially the same even if we included the household sector.) Let us assume that, similarly to the case of the bank's net open position, a percentage change in the exchange rate will translate into the same percentage change in the domestic currency value of the corporate sector's net open position, which will in turn lead to an equivalent change in the corporate sector's equity, i.e. $\Delta E_c/\Delta e = \Delta F_c/\Delta e = F/e$. The impact of the exchange rate on corporate leverage (D_c/E_c) is then given by

$$\frac{\Delta[D_c(e)/E_c(e)]}{\Delta e} \cong \frac{\frac{\Delta D_c}{\Delta E_c}\frac{F_c}{e}E_c - D_c\frac{F_c}{e}}{E_c^{\,2}} \cong -\frac{1}{e}\frac{F_c}{E_c}\left(\frac{D_c}{E_c}-\frac{\Delta D_c}{\Delta E_c}\right). \tag{3}$$

Thus, if the corporate sector is short in foreign exchange, a depreciation (decline) in the exchange rate would lead to an increase in its leverage. Corporate leverage is typically positively correlated with the share of banks' NPLs in total loans (denoted as NPL/TL), i.e. $\Delta(NPL/TL)/\Delta(D_c/E_c)=a>0$.[11] The impact of a change in the exchange rate on the NPL/TL ratio can then be expressed as

$$\Delta(NPL/TL) \cong a\,\Delta[D_c(e)/E_c(e)] \cong -\frac{\Delta e}{e}\frac{F_c}{E_c}a\left(\frac{D_c}{E_c}-\frac{\Delta D_c}{\Delta E_c}\right). \tag{4}$$

In the special case when $\Delta D_c/\Delta E_c=0$, the change in the NPL/TL ratio would equal the exchange rate change times the respective FSI (the net open position), times the parameter a, which can be

[10] As a general point, stress tests need to include not only balance sheet positions, but also off-balance sheet items.

[11] For a panel of 47 countries, a 10 percentage point rise in corporate leverage was associated with a 1.1 percentage point rise in *NPL*/*TL* after a one year lag (see IMF, 2003).

estimated empirically. To find the impact on capital adequacy, we can assume that the credit shock has the form of a transition of performing loans into the nonperforming category. By differentiating C/A_{RW} with respect to NPL/TL, and substituting for NPL/TL from (4), we obtain

$$\Delta(C/A_{RW}) \cong \frac{\Delta e}{e}\frac{TL}{A_{RW}}\left(1-\frac{C}{A_{RW}}\frac{\Delta A_{RW}}{\Delta C}\right)\pi\frac{F_c}{E_c}a\left(\frac{D_c}{E_c}-\frac{\Delta D_c}{\Delta E_c}\right), \quad (5)$$

where provisions are assumed to be a fixed percentage (π) of NPLs, and are deducted directly from capital.

The incorporation of the indirect effect makes the analysis more complex and dependent on additional assumptions or regression analysis. While the presentation of the direct effect in (2) and the indirect effect in (5) may appear similar (in both cases, the change in the capital adequacy is expressed as the shock times the net open position), the calculation of the indirect effect is generally much more complex, given that it needs to include the impacts on stocks as well as on flows. It must reflect the impact of exchange rate changes on the net present value of the corporate sector, which means taking into account changes in the net present value of future earnings. For example, in export-oriented companies, a depreciation can be expected to increase their future earnings. In terms of the net present value, the effect would be essentially equivalent to the impact of a long position in foreign currency. However, it may be more practical to calculate the impact on flows, by estimating the elasticity of earnings to interest and principal expenses (an encouraged FSI) with respect to the exchange rate, and then to estimate the relationship between this FSI and the NPL/TL ratio. Alternatively, one can look at an indicator measuring the corporate sector's flow exposure, e.g. the ratio of earnings in foreign exchange to interest and principal expenses in foreign exchange.

Exchange rate risk was analyzed in almost all FSAP missions. Half of them calculated the impact on the net open foreign exchange position for individual institutions or for groups of banks, which in turn was calibrated in terms of impact on capital. Regressions and Monte Carlo simulations to determine the effect of exchange rate changes on credit quality (NPLs) were applied in about 40 percent of the FSAP missions (IMF and the World Bank, 2003).

5.2 Interest Rate Risk

Interest rate risk is the exposure of a bank's financial condition to adverse movements in interest rates. Interest rate changes affect interest income and interest expenses as well as the balance sheet through changes in market prices of financial instruments. Sources of interest rate risk are discussed in Basel Committee (2001).

The impact of changes in the interest rate on net interest income is typically measured using the "repricing gap" model. The model allocates interest-bearing assets and liabilities into buckets according to their time to repricing, and the gap between assets and liabilities in each bucket is used to estimate the net interest income exposure to interest rate changes (see Blaschke, 2001, for practical examples). The position in interest-based financial derivatives can be incorporated into this analysis by recalculating the expected future receipts and payments as interest rates change.

There are two commonly used approaches to measuring the effect of interest rate changes on market prices of financial instruments: the duration model and the "gap" model. Duration, defined as the weighted average term to maturity of assets/liabilities, is a direct measure of the interest rate elasticity of an asset or liability.[12] The higher the duration, the more sensitive the price of an asset or liability to changes in interest rates,

$$\frac{\Delta A(r_A)}{A(r_A)} \cong \frac{-D_A \Delta r_A}{(1+r_A)}, \quad \frac{\Delta L(r_L)}{L(r_L)} \cong \frac{-D_L \Delta r_L}{(1+r_L)}. \tag{6}$$

where $A(r_A)$ and $L(r_L)$ are the market values of assets and liabilities of a banking system, and r_A and r_L are annual interest rates on assets and liabilities (see, e.g., Bierwag, 1987). This feature of duration can be used to summarize the impact of changes in interest rates on banks' capital. In particular, we can define capital as $A(r_A)$–$L(r_L)$, and express it as a ratio to risk weighted assets.[13] Differentiating capital with respect to the interest rate on assets, and substituting from (6), the sensitivity of the C/A_{RW} ratio to interest rate changes can be expressed as

$$\begin{aligned}\frac{\Delta[C(r_A,r_L)/A_{RW}(r_A)]}{\Delta r_A} &\cong -\frac{(L/A_{RW})}{1+r_A}\left(D_A - D_L \frac{1+r_A}{1+r_L}\frac{\Delta r_L}{\Delta r_A}\right)\frac{1-\frac{\Delta A_{RW}}{A_{RW}}\frac{C}{\Delta C}}{1-\frac{\Delta A}{A}\frac{C}{\Delta C}} \\ &\cong -\frac{(L/A_{RW})}{1+r_A} GAP_D\end{aligned} \tag{7}$$

where the approximation on the second line assumed that the risk-weighted assets move proportionately to total assets, i.e. $\Delta A_{RW}/A_{RW}=\Delta A/A$. GAP_D is the duration gap, defined as

$$GAP_D = D_A - D_L \frac{1+r_A}{1+r_L}\frac{\Delta r_L}{\Delta r_A}. \tag{9}$$

The formulas (6) and (7) hold exactly for small changes in interest rates. For large changes in interest rates, they are only linear approximations. For large changes in interest rates (which are typically assumed in stress tests), it is necessary to take into account nonlinearity, since duration can change with large changes in interest rates. Given that the price-yield relationship is convex rather than linear, as assumed by the basic duration model, duration typically overpredicts the fall in prices for large interest rate increases and underpredicts the increases in prices for large interest rate declines. A new parameter (named CX for "convexity") can be specified and estimated which increases the precision of the estimates of the changes in the value of assets and liabilities:[14]

[12] For the formula defining duration and practical examples of its calculation, see IMF (2003a).

[13] The impacts can also be expressed in terms of banks' profitability, which may be useful when branches of foreign banks, which typically do not have own capital, play an important role. Bierwag (1987) derives the impact on profits in the case of a single bank.

[14] For more details, see, e.g., Saunders (2000).

$$\frac{\Delta A(r_A)}{A(r_A)} \cong \frac{-D_A \Delta r_A}{(1+r_A)} + \frac{CX_A}{2}(\Delta r_A)^2, \quad \frac{\Delta L(r_L)}{L(r_L)} \cong \frac{-D_L \Delta r_L}{(1+r_L)} + \frac{CX_L}{2}(\Delta r_L)^2 \tag{10}$$

An alternative approach to assessing the price revaluation effect of an interest rate shock is to use "gap" analysis. Under this approach, expected payments on assets and liabilities are sorted into time "buckets" according to the time to repricing for floating-rate instruments, and the time until payments are due on fixed-rate instruments. The net present value of assets and liabilities can be derived by discounting the net cash flows in each time bucket, and the effect of an interest rate shock estimated by rediscounting the net cash flows using the changed interest rates. IMF (2003a) provides a template for conducting such a gap analysis.

Interest rate risk was analyzed in the majority of the FSAP missions. Reflecting data constraints, most FSAPs used maturity buckets and gap analysis. Some used more advanced techniques based on duration or value at risk (VaR). About 25 percent of FSAP missions did not obtain data on maturity buckets or duration and used income statement data instead to calculate simple earnings at risk (IMF and the World Bank, 2003).

5.3 Credit Risk

Credit risk can be defined as the loss associated with unexpected changes in credit quality. Despite many innovations in banking, credit risk is typically the most significant source of risk. The largest source of credit risk is loans; however, it also takes the form of positions in corporate bonds or transactions on over-the-counter markets, which involve the risk of a default of the counterparty.

Measuring credit risk involves estimation of a number of different parameters: the likelihood of default on each instrument both on average and under extreme conditions; the extent of the losses in the event of default (or loss given default), which may involve estimating the value of collateral; and the likelihood that other counterparties will default at the same time.

There are two general approaches to system-wide stress tests for credit risk. First, there are approaches based on loan performance data. These can be either purely mechanical (assuming certain shocks to performance of loans) or based on a regression analysis between loan performance and macroeconomic variables. Second, there are approaches based on data on borrowers (financial leverage, interest coverage).

More than half of the FSAP missions used NPL-based approaches to modeling credit risk. About 60 percent of the missions used ad-hoc NPL migration. Only about 30 percent of the missions found it useful to apply regression analyses to examine the impact of future potential macroeconomic shocks on the behavior of non-performing loans (IMF and the World Bank, 2003).

Approaches based on loan performance data

The advantage of this approach is that loan performance data are relatively easily available to supervisors. Also, they are available for all sectors, including the household sector (for which it is difficult or impossible to obtain reliable balance sheet or income statement information). The key disadvantage of this approach is that NPLs are lagging indicators of asset quality.

The first subgroup of approaches in this group are those based on asset reclassification. Under this approach, loans (and other assets) are moved one or more classification categories down. The potential effect of the loan reclassification on the capital ratio is calculated after deducting the additional provisions from both the reported capital data and the reported asset data.

There are various types of asset reclassification. It can be purely mechanical (e.g. a certain percentage of loans in each category is moved down by a category) or it can be based on experience with past crisis episodes (e.g. the percentage of loans reclassified is the same as the percentage of loans migrating down during the last banking sector crisis). Alternatively, if sufficiently detailed information is available, it can be based on "peer reviews" whereby loans to the same borrower from different institutions are reclassified according to the lowest grade assigned by an institution (this could be a very laborious approach, though). Another approach is based on "supervisory reviews": for example, if recent on-site examinations in some banks have uncovered significant discrepancies between the reported and "true" classification of loans, a stress test could assess what would happen if similar discrepancies were found in other banks.

The second subgroup of approaches in this group are those based on a regression or a VAR model including NPLs and a number of macroeconomic factors, such as real interest rates, GDP growth, and terms of trade changes.[15] The regressions can be run at sectoral level (if there are data on NPLs by economic sectors) or even on the individual bank level to capture the banks' different sensitivities to macroeconomic developments (this approach can, however, be too resource intensive; it is therefore more common to use regressions for aggregated data). The parameters estimated in the regression of aggregate NPLs and other variables can be fed into the bank-by-bank calculations based on the individual banks' positions. This is sometimes referred to as combining a "top-down approach" (i.e. one starting from aggregate relationships) with a "bottom-up approach" (i.e. one starting from individual bank data and proceeding to an aggregation).

Problems with the regression approach include the lack of long and consistent time series data on NPLs. Even where the data are available for a sufficiently long time period, they may exhibit structural breaks due to financial and economic reforms which may have changed the behavioral patterns of lenders and borrowers. Moreover, considerable caution is needed when drawing conclusions from models that may be subject to several sources of error. They should be thoroughly cross-checked where possible with conclusions derived from other approaches or sources of information, such as the FSIs for the nonfinancial corporate sector.

Approaches based on data on borrowers

Approaches based on data on borrowers have the potential advantage that they can provide more "substance" to the credit risk stress test by explicitly modeling linkages between the health of the real sector and the financial sector. Another advantage of borrowers data is that they can help to indicate problems in the loan portfolio earlier than the loan classification, which is by definition a lagging indicator. A potential disadvantage of this approach is that data on borrowers (in particular households and small and medium-sized enterprises) are often difficult to obtain and are typically available only with long lags.

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[15] See Blaschke et al. (2001) for an illustration.

Cross-country calculations do indeed suggest that leverage is a good early warning indicator for higher NPLs. IMF (2003b) includes an estimate of a model of the following type:

$$npls = \alpha_0 + \alpha_1 lev + \alpha_2 reer + \alpha_3 \hat{y} + \alpha_4 \hat{p} + \alpha_4 \hat{m} + \alpha_5 rcc$$
$$lev = \beta_0 + \beta_1 npl + \beta_2 rcc + \beta_3 \hat{y} + \beta_4 \hat{p} + \beta_5 \hat{d} + \beta_6 roe + \beta_7 reer$$
$$rcc = \gamma_0 + \gamma_1 lev + \gamma_2 \hat{y} + \gamma_3 \hat{m}$$

where *npls* is the ratio of non-performing loans to total loans, *lev* is the leverage ratio, *rcc* is the real cost of capital, *reer* is the real effective exchange rate, $\hat{y}$ is the growth rate of real GDP, $\hat{p}$ is the inflation rate, $\hat{m}$ is the growth rate of M1, $\hat{d}$ is the growth rate of domestic credit, and *roe* is corporate sector return on equity. IMF (2003b) includes a detailed economic justification of these three equations and estimates, using the panel data approach, that, on average, (i) a 10 percentage point increase in corporate leverage is associated with a 1.8 percentage point rise in NPLs relative to total loans after one year; and (ii) a 1 percentage point rise in GDP growth results, on average, in a 2.6 percentage point decline in the NPLs to loans ratio, reflecting the fact that during periods of rapid growth fewer corporations are likely to experience problems repaying loans, or to default.

There is a wide range of possible approaches to modeling credit risk, depending on the availability of data. A relatively elaborate approach used in some countries is to estimate a logit model predicting individual bankruptcy probabilities as a function of age, size, industry characteristics, and corporate soundness indicators (leverage, earnings, liquidity, financial strength). The model would include interest and exchange rates on the right hand side (to capture the indirect risk). Individual banks would be linked to the exercise through their exposures to the various groups of companies. This could then be used to predict banks' potential losses, taking into account collateral as well. Eklund et al. (2001) is an example of a model of this type, used by the Bank of Norway.

A simpler approach would be based on exposure variables. The basic idea of this approach is that if an exposure variable exceeds an estimated (or assumed) threshold, the default rate becomes higher. Similarly to the previous approach, this would be translated to banks' losses, taking into account collateral held by banks. An example of an exposure variable is the net open position in foreign exchange and the ratio of foreign exchange income to foreign exchange costs (for indirect foreign exchange risk). To measure indirect interest risk, the exposure variable to use would be interest coverage.

5.4 Equity and Real Estate Price Risk

Equity price risk is modeled in a similar way to foreign exchange risk. The calculation is based on the net open position in equities, which is defined in a similar fashion to the net open position in foreign exchange.[16] Similarly to foreign exchange risk, it is necessary to include the off-balance sheet position.

Banks' exposure to real estate price risk consists of (i) the direct exposure (investment in real estate); (ii) credit exposures (e.g. lending to real estate developers); and (iii) risk resulting from the degree of real estate collateralization. The risk arising from real estate collateral should be

[16] See the *Financial Soundness Indicators Compilation Guide*, IMF (2003a).

seen in relation to the credit risk; it increases with the loan-to-value ratio (i.e. the ratio of the outstanding loan to the value of the collateral) and with the default probability.

In the case of the direct exposure to real estate price risk, the difference between the mark-to-market approach and book value approach, mentioned earlier (Section IV.E.), is particularly important when interpreting stress test results. The impact on banks' reported data resulting from changes in real estate prices is going to be much smaller than suggested by a stress test when banks (as is often the case) do not mark to market their real estate investments.

Equity or real estate price risk was examined in about half of the FSAP missions. In most cases, equity price risk stress tests were included in general market risk, i.e. risk related to a major change in the overall stock market, usually a market crash scenario (IMF and the World Bank, 2003).

5.5 Liquidity Risk and Other Risks

Liquidity risk is the risk that assets are not readily available to meet a demand for cash. Stress testing the liquidity of the banking sector involves assessing the impact on the liquidity gap of a shock such as large-scale deposit withdrawals, a large fall in the price of equities, or an exchange rate crisis. Modeling liquidity risk is often considered to be much more difficult than modeling interest rate or exchange rate risk. Many central banks therefore rely on the liquidity stress tests conducted by the banks themselves. The results of these stress tests are reported off-site, which is followed-up by integrity checks during on-site visits.

The most challenging step in designing a liquidity stress test is identifying which assets that are normally considered liquid may become illiquid in periods of financial stress. IMF (2003a) provides operational guidelines for defining liquid assets and liquid liabilities which could be used as the starting point for conducting stress tests. Similarly to the other stress tests, off-balance sheet positions (e.g. derivatives or loan commitments extended by banks) can have a significant impact on liquidity and should not be neglected in the stress tests.

A straightforward approach to stress testing for liquidity risk is to shock the value of liquid resources by a certain percentage or amount. The percentage or amount could be determined based on past bank runs or on a rule of thumb, and it should generally be different for different maturities. A rule of thumb used by some supervisors is that a bank should be able to survive at least five days of a moderate liquidity run without outside support. The reason behind this choice of threshold is that this would make it possible for the bank to survive till the weekend, when banks are closed. This "cooling-off" period would enable the bank and supervisors to better assess the situation and, where appropriate, take necessary actions.

A version of liquidity risk is concentration risk on banks' liabilities. This is typically modeled as the risk of sudden withdrawals by the banks' largest depositors. Another version of liquidity risk is the risk of bank-to-bank contagion of liquidity stress. An example of such contagion would be a liquidity run on a bank perceived as "weak," triggered by liquidity problems (either genuine ones, or also caused by a liquidity run) in another bank. Subsection F below provides a discussion of interbank contagion risk, focusing on contagion through uncollateralized interbank exposures. The modeling of contagion through reputational effects would be conceptually the same, but practically more difficult, since there are no good data on bank-by-bank exposures in terms of reputational effects. Čihák (2004) includes a discussion of possible ways to model such reputational effects.

Other shocks included in some of the FSAP missions are likely to be less relevant to stress tests for the Czech banking system. These shocks generally reflected the specific circumstances of a given country. For instance, several FSAP missions included stress tests for commodity price risk, notably in developing countries, where trade in commodities is important (IMF and the World Bank, 2003).

5.6 Interbank Contagion Stress Test

Interbank stress testing complements the standard set of stress tests by measuring the risk that the failure of a bank or a group of banks will trigger the failure of other banks within the system. There are a number of interbank contagion channels. The most direct one is contagion through uncollateralized interbank lending, which was an important transmission channel during the Asian crisis. Other plausible channels of contagion include reputational effects, whereby a perceived stability problem in a bank could make it difficult for other banks in the system to borrow liquidity in international markets. Such a lack of confidence would either entirely prevent the banks from accessing international markets for liquidity or raise the funding costs substantially, exacerbating any liquidity problem the bank faces. The reputational effect of a failure of a bank can also lead to liquidity runs on other banks that are perceived as weak. Conceptually, modeling reputational effects would be similar to modeling contagion through lending exposures. Empirically, however, it is much more difficult to define the "exposures" for reputational risk. Čihák (2004) offers some discussion of proxy variables to characterize such contagion.

We will now focus on the risk of contagion through banks' uncollateralized interbank loans. There are two basic types of interbank stress tests: (i) *the pure interbank stress test*, where the shock is the failure of one bank, triggered for example by fraud, and where the impact on other banks in the system is through the interbank exposures; (ii) *the integrated interbank stress test*, where the banking system is first subjected to macro shocks or scenarios and if these shocks or scenarios trigger a failure of a bank or a group of banks, the interbank stress test is run to assess the impact of additional failures through interbank exposures, as in the pure interbank stress test.

The key element of interbank contagion stress test calculations is a matrix of bilateral interbank exposures (Table 2). The cells of the matrix contain the gross bilateral interbank exposures between banks, defined as all uncollateralized lending from one bank to another, covering all on- and off-balance sheet exposures. Each row in the matrix corresponds to a bank and the cells in the row give its gross interbank exposure with respect to every other bank in the interbank market.

The *"pure" interbank contagion stress test* aims to answer the question of whether the failure of any bank (or group of banks) would bring down other banks in the system. It can also be used to show to what extent other banks are weakened (even if no bank fails) because of the potential for this to trigger a liquidity crisis (as banks have imperfect information about the solvency of their counterparties). This stress test could be useful in identifying which banks are a potential source of systemic risk.

Table 2: Matrix of Bank-to-Bank Exposures

	Bank 1	**Bank 2**	**. . .**	**Bank n**
Bank 1	-- --	Exposure of bank 1 to bank 2	. . .	Exposure of bank 1 to bank *n*
Bank 2	Exposure of bank 2 to bank 1	-- --	. . .	Exposure of bank 2 to bank *n*
. . .	. . .	. . .	-- --	. . .
Bank n	Exposure of bank *n* to bank 1	Exposure of bank *n* to bank 2	. . .	-- --

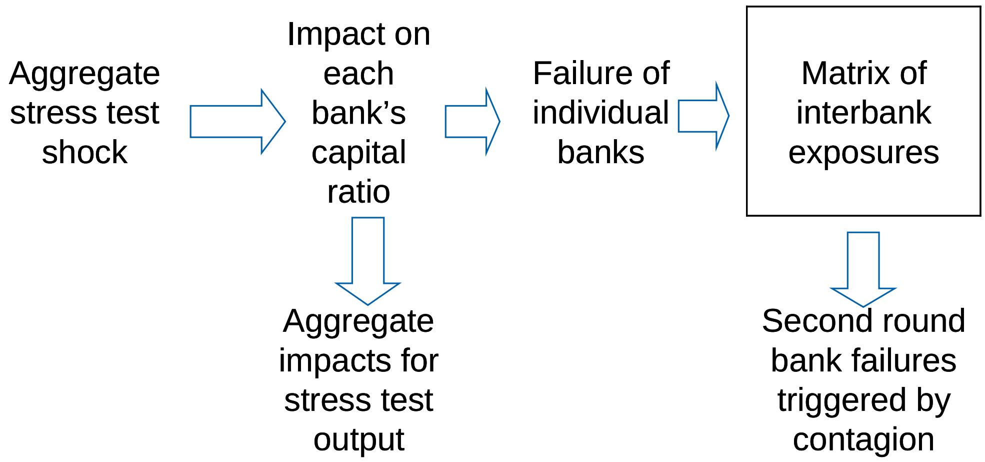
The pure contagion test assumes that there is a failure in a bank (say, Bank 1). The failure can occur for any reason, for instance due to a fraud. The first round of the contagion calculation would than calculate the direct impact of Bank 1's failure on each of the other banks, assuming Bank 1 would not repay its uncollateralized interbank exposures (or a portion of the exposures). If some banks fail as a result of Bank 1's failure, the second round of the calculation would calculate the impact on each of the remaining banks of these newly failed banks not repaying their uncollateralized interbank exposures. The process can be repeated in a third run if there are new failures after the second run, and so on.

Two indicators of systemic risk can be calculated from the output of the pure interbank stress test: (i) a frequency of bank failure indicator, which is the ratio of the cumulative number of failures to the number of banks in the system; (ii) statistical measures of the impact on bank system capital (e.g. mean, distribution, and quartiles). Specifically, one can define a "systemic risk index", the average reduction in the capital ratios of banks in the system triggered by the failure of the systemically most important bank (or banks). Such a measure could be computed for all banks in the system and used to rank them by their systemic importance.

The *"macro" contagion test* differs from the pure contagion test in that it focuses on interbank contagion triggered by a macroeconomic stress (Figure 3). It first exposes the banking system to a stressful macroeconomic scenario. If the scenario triggers failures of some banks, the interbank contagion is then run as in the pure contagion test. The key difference is that the contagion takes place in a system that has already been weakened by the macroeconomic scenario or shock, so it is more likely that it will spread in further bank failures. If the scenario does not trigger any bank failures, one possible conclusion is that there is no interbank contagion for this particular scenario (there might still be liquidity problems, given that banks have imperfect information about their counterparties). Alternatively, one could ask what is the largest shock that does not trigger a "chain reaction" in the system. To answer this question, one needs to "gross up" the macroeconomic shocks until the weakest institution (or group of weakest institutions) fails, and calculate the interbank contagion effects as in the pure contagion test.

Similarly to the pure interbank contagion stress test, quantitative measures of systemic risk can be produced. Exactly the same frequency of bank failures statistics as described above can be used. However, the index of systemic risk will be different and needs to be decomposed into two components: (i) the average reduction in capital ratios due to the grossed-up shock; and (ii) the further reduction in the average of these ratios triggered by the failure of the bank due to the shock, which causes it to default on its loans. This latter index is identical to the one in the pure stress test.

Figure 3: Aggregate ST vs. Interbank Contagion ST



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Appendix I: Selected Additional References

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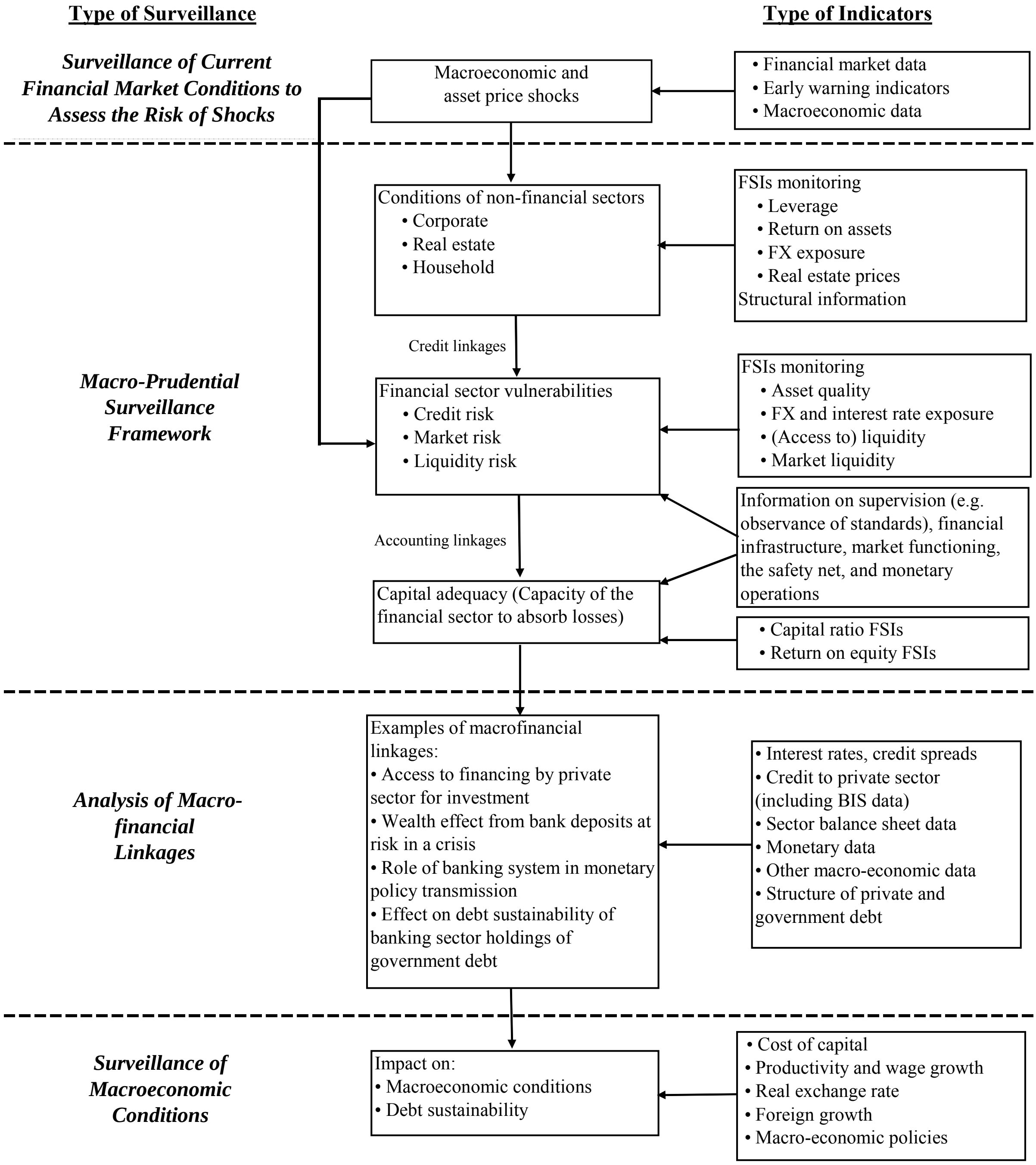
Appendix II: Framework for Financial Stability Analysis

The figure below provides more details on the framework for financial stability analysis and supplements Figure 1 in the main text.



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