DOCTORAL (PHD) THESIS

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SUPPORTING BANK MANAGEMENT DECISION-MAKING BY DEVELOPING AN ASSET COMPOSITION OPTIMIZATION MODEL

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1. BACKGROUND AND GOALS OF THE THESIS

1.1. Background of the research

Maintaining the stability of the financial system is also a fundamental issue at the macroeconomic level, directly affecting a country's growth trajectory, financial resilience and social well-being. Banks play a key role in this environment, as their complex activities expose them to credit, market, counterparty and operational risks. The 2008 global financial crisis made it clear that capital inadequacies can result in systemic vulnerabilities, the effects of which go beyond the level of individual institutions and can destabilize the entire economy. Following the crisis, international regulatory frameworks, in particular Basel III/IV and its European implementation, the CRR Regulation, have set prudential requirements aimed at strengthening banks' capital adequacy and mitigating systemic risks.

However, regulatory compliance has created a new dilemma. Strict capital adequacy requirements have encouraged banks to maintain significant capital buffers, which, while enhancing stability, also tie up available resources, reducing profitability and capital efficiency. In many cases, there is a discrepancy between the risk-weighted asset values (RWA) determined by prudential ratios and the actual economic risk profile, as the regulatory calculation logic does not fully cover the real exposures reflected by market models, such as Value-at-Risk. This difference is not only of theoretical but also of practical importance, so ensuring capital-efficient operation has become an increasingly strategic task for bank management.

The relevance of the research is that banks today have to meet both prudential requirements and shareholder return expectations, while the uncertainties of global financial markets and macroeconomic volatility put continuous pressure on them. The literature has so far approached the issue primarily from two directions: on the one hand, it examined the institutional-legal aspects of regulatory compliance, and on the other hand, it focused on the quantitative modeling of capital requirements. However, these two approaches have rarely been combined in a framework that would be able to handle regulatory requirements and market logic together and provide direct decision support for banking practice. The novelty of the research and the scientific gap can be captured in this contradiction: an integrated model that simultaneously internalizes prudential constraints, takes into account the economic significance of risk dimensions, and fits the goals of strategic capital management is missing. The aim of my research is therefore to develop a deterministic, linear optimization model that treats own funds allocation not only as regulatory compliance, but also as strategic resource optimization. My further goal is to demonstrate that empirical testing of the model can demonstrate how the optimum between prudential compliance and capital efficiency can be achieved, which can ensure the stability and competitiveness of institutions in the long term in banking practice.

1.2. Research objective

Under what conditions can an integrated bank capital optimization model be developed that, while meeting prudential requirements, is able to handle the differences between risk weights derived from regulatory standards and market risks?

Can an empirically based quantitative optimization approach be identified that provides a generally applicable framework for handling portfolio optimization problems in bank capital allocation?

Methodologically, how can a mathematical model be constructed that uniformly addresses the CRR requirements and the challenges arising from the difference in actual risks?

Can it be proven that the developed optimization model is able to release regulatory excess capital without increasing the bank's risk level?

How can an empirically supported objective function be defined that ensures the minimization of own funds by taking into account the differences between market and regulatory asset risks, so that the actual risk profile of the bank portfolio remains unchanged, thereby strengthening efficiency and profitability?

2. MATERIAL AND METHOD

As a result of the experiences of financial crises and the resulting tightening of prudential regulations, the issue of capital management has increasingly become the focus of the operations of financial institutions. The aim of regulators is to improve the risk profile of banks and other financial actors, strengthen financial stability, and increase resilience to system-level shocks. However, this process has encouraged institutions to maintain a significant amount of excess capital, i.e., a capital buffer, which excessively ties up the available resources of banks, thereby having a negative impact on their economic performance and profitability. As a result, a serious professional dilemma arises. How can one find the optimal balance under which the capital adequacy criteria required by the regulations are fully met, risk levels remain sufficiently low, and at the same time the strategic business goals of financial institutions are not harmed?

The fundamental objective of this research is to resolve this dilemma. To create a mathematical optimization framework that is able to reconcile the different, often conflicting aspects of regulatory requirements, risk management requirements and bank strategic goals. The focus of the research is therefore to create a new model that not only examines these three dimensions separately, but is also able to interpret and optimize them simultaneously, in an integrated manner.

From a scientific research methodological perspective, the research used qualitative interviews, document analysis and a single case study methodology. Thus, the linear optimization model is built from information and relationships derived from qualitative interviews and document analysis, as well as explicit mathematical tools, during which the problem is formalized in a structured, precisely defined set of conditions. This research can be interpreted as a deductive, mathematical-logical, theoretical model-building method. Subsequently, the model is validated using a specific, real banking case study, which allows the practical relevance of the model to be verified in a real business environment. The application of the study methodology serves to strengthen the practical validity of the model and provides an opportunity to place the model in an empirical context. The combination of methodologies therefore constitutes a mixed-method research approach that, on the one hand, ensures the integration of empirical results and the rigorous mathematical-logical consistency of the model, and on the other hand, supports its practical relevance and validity.

In terms of practical applicability, the research has significant added value for financial institutions. The model directly helps banks to use their available own funds more efficiently, minimizing unnecessary buffers, thereby improving the competitiveness and profitability of banks. Through the strategically directed reallocation of capital released by the model, banks can also better exploit the business opportunities offered by the market, thereby strengthening their market position. From a scientific perspective, the model represents a clear novelty in the literature, as no methodology has integrated regulatory compliance, risk management and strategic management aspects into a single optimization framework with such depth and complexity. This not only represents a methodological innovation, but also an empirical contribution, as I successfully tested and validated the model in a real institutional environment during the research. The empirical results obtained thus support both the practical relevance and scientific significance of the model. Thus, this research represents the development of the first comprehensive model that enables optimized capital structure by simultaneously integrating regulation, risk, portfolio construction and fundamental strategies, thereby filling an important methodological gap and creating direct practical value for financial institutions. In this way, the research not only provides results that can be used in current professional practice, but also points the way for the further development of sustainable capital optimization strategies of financial institutions in the long term.

2.1. Theoretical foundations of the model

The challenges of financial institutions' own funds management arise from the combined consideration of regulatory frameworks and economic rationality. Own funds, which financial institutions are required to hold to cover their risks, play a key role in prudential regulation. They basically serve three purposes. On the one hand, they ensure coverage of bank losses, on the other hand, they protect the interests of depositors and investors, and thirdly, they contribute to the stability of the financial system. At the same time, own funds are not only a security issue, but also an economic issue, since excessively or unnecessarily high capital means a cost, which reduces the profitability and capital efficiency of banks. In addressing this issue, determining the optimal amount and structure of own funds becomes crucial, which represents a complex optimization problem for bank management. During the literature review, several optimization methodologies can be identified, which are able to handle different aspects of this complex decision-making situation. Classically, the Markowitz approach, based on portfolio theory, focuses on the risk-return balance, however, this model was primarily developed for investment decisions and does not explicitly address the rigid and numerical constraints arising from the regulatory environment of financial institutions.

In the banking environment, prudential regulatory compliance is particularly important, which defines the minimum capital levels to be maintained in the form of explicit limits (e.g. CET1, TCR, leverage ratio). Accordingly, regulatory optimization models that directly integrate regulatory limits and numerical conditions aimed at their fulfillment have gained a prominent role in the literature. These models allow optimization results to be immediately auditable and transparent for both regulators and bank managers. Among the alternative approaches, stochastic optimization models attempt to handle the uncertainties of the market environment on a probabilistic basis. Although they may be able to take into account changes over time and risk uncertainties, they have the serious disadvantage of being data-intensive, computationally complex, and therefore more difficult to implement in banking practice. Similarly, genetic algorithms (GA) and neural networks could also be used, as they are capable of handling complex nonlinear relationships, but these methods have limited auditability and are difficult to interpret in the banking environment, making them less suitable for direct consideration of prudential regulations.

The deterministic, static linear optimization methodology (Linear Programming – LP), which I implemented using the PuLP Python-based framework, is in many ways an outstanding fit for the specific environment and goals of bank capital management. This methodological choice was justified by the specific objectives of the research, the characteristics of the regulatory environment, and the practical applicability of the results. The operation of financial institutions is fundamentally determined by prudential regulation, which sets precise numerical limits on the minimum level of capital (e.g. CET1, TCR, leverage ratio) and enforces these limits with binding force. This environment can be characterized mathematically by linear inequalities, simple and explicit numerical conditions, which fit exactly the characteristics of the linear optimization framework. One of the main features of linear programming is precisely that it is able to incorporate these explicit regulatory limits in a simple and precise manner, directly into the model structure, thereby directly guaranteeing regulatory compliance in the optimized solution. Another important element for the purpose of the research is the deterministic approach. Deterministic modeling means that the parameters and data of the model are given in advance, fixed, audited, and do not contain random variables or uncertainties. This deterministic nature is particularly important in the banking environment, as both regulatory authorities and the management of financial institutions expect results that are accurately reproducible, easily verified and auditable. Deterministic optimization results are fully transparent, thus suitable for creating a precisely documented, auditable decision support system that meets the requirements of both internal and external controls. The only non-deterministic constraint is the assessment of real market risks.

The use of static optimization offers additional advantages that also fit the practical objectives of the research. A static model means that the optimization is based on data and information relating to a given point in time and does not take into account changes over time or dynamic elements. This feature is particularly advantageous, since prudential regulatory requirements typically define capital requirements in relation to a given point in time. A dynamic or stochastic model would entail significant additional complexity and computational demands, which would not necessarily provide a proportionally greater practical value, while increasing the model's difficulty in handling and interpretation. In contrast, static optimization allows for the production of fast, clear, and directly interpretable results. From a methodological point of view, the use of linear programming fits the research environment perfectly precisely because the conditions and objectives used during the optimization can be well described in linear form, with numerical constraints and weights. This mathematical description corresponds exactly to the structure of regulatory and practical requirements. Linear programming allows explicit incorporation of regulatory constraints, enabling immediate control and auditability, which is crucial for a financial institution. Furthermore, PuLP -based linear optimization efficiently handles data, enables simple and fast model execution, which supports rapid decision-making by bank managers. This methodology does not require a large computational infrastructure and quickly provides clear, precise, auditable answers. The model developed during the research therefore fully meets the practical requirements of bank capital optimization and the auditability, controllability and communicability expectations imposed by prudential regulations. At the same time, the application of linear optimization provides a solid foundation for subsequent developments, such as sensitivity analyses, scenario analyses, or even the addition of additional, more complex analysis layers. The choice of the linear programming method was therefore a decision that is fully consistent with the objectives of the research and the regulatory requirements of the banking environment. The PuLP -based LP methodology provides banks with fast, easy-to-implement and auditable optimization solutions that directly integrate prudential regulatory requirements, support strategic decision-making, and ensure the economic efficiency of capital management. This methodology not only brings direct practical benefits, but also forms a solid foundation for further developments, such as sensitivity analyses or scenario tests, thereby enriching the scientific and practical areas of own funds management.

2.2. Description of input data and parameters

The practical applicability of the capital adequacy optimization model for financial institutions depends significantly on how accurately it can map the

real business and regulatory environment of banks. Consequently, the separate but joint management of the input data and parameter groups used in the research, the regulatory parameters, the market risk data, and the institutional strategic targets plays a particularly important role in the optimization process.
One of the fundamental conditions for the operation of financial institutions is the full compliance with the own funds levels set by prudential regulations. One of the cornerstones of the own funds optimization model used in this research is therefore the integration of regulatory parameters, which ensures that the model accurately reflects the strict regulatory environment in which banks and other financial service institutions actually operate.

The most important starting point for regulatory parameters is the European Union Capital Requirements Regulation (CRR) is a regulation that contains binding and clear numerical requirements for financial institutions in all Member States. The CRR primarily determines the minimum amount of own funds that banks are required to maintain. This minimum capital requirement is typically a percentage of the bank's risk-weighted assets (RWA). Weighted Assets – RWA) is defined as a certain, predetermined percentage; according to the currently generally accepted regulatory standard, this rate is 8%. The 8% capital requirement is therefore an explicit numerical limit, ignoring which is not only unacceptable from a regulatory perspective for the bank, but may also have significant legal consequences, either in the form of financial penalties or other sanctions. This parameter therefore appears in the model as a condition that must be fully met in every optimized solution, thus ensuring regulatory compliance. The minimum capital requirement applied in the developed model consists of several parts and is derived not only from the CRR regulation, but also from additional regulatory regulations, such as local regulations set by the Hungarian National Bank (MNB).

The second, particularly important group of parameters, which is integrated into the capital optimization model used in this research, comes from the data related to market risks. One of the fundamental characteristics of the operation of financial institutions is that capital allocation decisions always have a significant impact on the institution's market risk exposure. Accordingly, for the model to be realistic and practical, it is essential that these risks are explicitly, numerically and in detail taken into account in the decision-making process. Market risk parameters primarily include the risk weights of various investment instruments. These weights show to what extent the capital allocated to a given investment instrument burdens the bank's capital requirement. The precise determination of the risk weights of the instruments is of critical importance because it determines to what extent capital allocation decisions increase the bank's risk-weighted assets (Risk Weighted Assets (RWA) and thus the additional capital required to maintain regulatory compliance. The risk weights used in the model therefore directly and explicitly determine the level of risk exposure of a given investment, thus directly linking the market risk environment to the bank's regulatory capital requirements, as described in the legislation. Market risk parameters include not only risk weights, but also the expected return on investment assets and their volatility, i.e. the fluctuation of returns. This is crucial because financial institutions not only have to meet regulatory requirements, but also strive for economic efficiency. The model therefore explicitly takes into account returns and their volatility, allowing it to integrate market conditions into capital optimization in a realistic and economically sound manner.

To determine the strategic parameters used in the model, I chose a qualitative research methodology, which strengthens the practical validity of the linear optimization model. With this research step, I aimed to explore the real characteristics, aspects and preferences of the decision-making processes related to the bank's asset portfolio, as well as the real market risk of the assets, which differs from those specified in the regulation. Given that the strategies, portfolio construction methods and real market risk calculation methods of banking institutions are unique, it was necessary to develop a general, yet conceptually well-structured framework that can effectively integrate the strategic specificities of any bank into the model. To this end, I conducted eight in-depth interviews with bank managers, experts and directors who have relevant and direct experience in the strategic and business aspects of own funds management and portfolio construction. The interviews were conducted in a semi-structured format: I followed a predetermined set of questions, but I also gave the interviewees the opportunity to elaborate on their thoughts in more detail and to add new perspectives. The questions were based on the literature background (e.g. Saunders this al., 2014; Hull, 2018) and my own professional experience, thus ensuring their relevance and professional soundness.

2.3. Mathematical structure of the model

Linear programming (LP) is an important optimization tool in mathematics and economics that was born during World War II. In 1947, the American mathematician George Dantzig published the so-called simplex algorithm, which was able to efficiently maximize or minimize linear functions in problems with multiple linear constraints. LP quickly spread from wartime planning to logistics to financial portfolios; its essence is to optimally distribute given resources (raw materials, capital, time) between conflicting goals.

General form of a linear programming problem

Objective function: a linear function (such as income or utility) must be maximized or minimized:

$$max\{c^T x\}\ or\ min\{c^T x\}$$

where c is the weight vector of the objective function and x is the vector of decision variables .

Constraints: decision variables are subject to linear inequalities and equalities (e.g. resource constraints, technological constraints):

$$Ax \leq b, Gx = h$$

Non-negativity condition: variables cannot be negative in general (According to $x \geq 0$).the standard form of the model, all constraints are equalities (equations) and all variables are non-negative. LP can be solved analytically using the simplex method or numerical optimization software (e.g. Gurobi, CPLEX, PuLP). Modern software also allows for mixed integer linear programming (MILP), where some variables are restricted to integer values.

Applied Method: The present work uses linear programming for portfolio optimization. The objective function is a weighted combination (return-variance difference, Sharpe ratio, sigmoid quality indicator), which is a linear function of the variable exposures. The constraints are linear equations and inequalities: budget constraint ($\sum x_i = B$), credit risk RWA target ($\sum r_i x_i = RWA_{target}$), return and VaR constraints ($\sum x_i \mu_i \geq H_0, \sum x_i v_i \leq V_0(1+\gamma)$), and diversification minimum and maximum constraints ($m_i \leq x_i/B \leq M_i$). The variables are all non-negative amounts. The iteration should be performed until all constraints can be satisfied at the desired level of capital adequacy ratio (CAR).

2.4. Software implementation and technical background

For the software implementation of the equity capital optimization model developed during the research, I used the Python programming language, which is a widely used mathematical modeling environment. The main reason for this was that the Python language offers excellent opportunities for simple and structured handling of large amounts of numerical data, as well as for the transparent and precise implementation of linear optimization tasks. Python also offers well-documented, open-source libraries that support the simple auditable and easy-to-verify implementation of linear optimization. I implemented the mathematical implementation of the model using the PuLP linear programming library, which is a Python-based framework specifically developed for linear optimization. This framework provides the opportunity for each step of the optimization problem to be defined clearly, in explicit numerical form, with algebraic definitions. The advantage of PuLP is that it is compatible with several optimization solvers, of which the CBC (Coin-or Branch and Cut) solver was used. This solver provided numerical stability, speed and reliability in solving the problem, thus guaranteeing the stability and reproducibility of the model results.

2.5. Logical-mathematical examination of the internal coherence of the model

In validating the model, I conducted a theoretical and logical-mathematical analysis in order to ensure the internal coherence of the model and to examine whether its mathematical structure meets the methodological criteria of linear programming. To this end, I applied the general modeling principles formulated by Hillier and Lieberman (2015) and Winston (2003), which are widely accepted in the linear programming literature. I conducted the internal coherence analysis of the model along three main aspects: the economic and mathematical interpretability of the decision variables, the logical and numerical relevance of the objective function, and the consistency and coherence of the linear constraint conditions. When examining the interpretation of the decision variables, I first checked that all variables were clearly defined and economically relevant in the real banking environment. I paid special attention to the fact that the variables were interpreted in a non-negative range, since negative values cannot be interpreted in the case of own funds allocation. As a result, I determined that the decision variables of the model clearly meet the standard requirements of linear programming, and their economic and financial relevance is supported. This was followed by a detailed examination of the structure of the objective function. Here, I checked whether the objective function adequately reflects the optimization goal defined by the research, in this case the minimization of the solvency buffer. During my examination, I checked step by step the parameters included in the linear combination of the objective function and their numerical relevance. During the check, I determined that the elements of the objective function are indeed suitable for the precise formulation of the set optimization goal, so the objective function proved to be correct in both logical and numerical terms.

Finally, I analyzed the mathematical consistency and logical coherence of the linear constraint conditions. Here, I examined whether the constraint conditions were explicitly defined in a clear linear algebraic form, whether they truly form a closed solution space, and whether they did not contain redundancy or contradiction. In doing so, I systematically reviewed each constraint condition and verified that they had clear numerical parameters, that the condition system was coherent, logically followable, and directly aligned with the regulatory requirements. I summarized the results of these three analysis aspects in the form of a summary matrix, in which I evaluated each criterion binary (yes/no), and documented in detail the extent to which the individual components of the model met the general methodological requirements of linear optimization (Hillier & Lieberman , 2015; Winston, 2003).

2.6. Methodological description of the model sensitivity analysis

One of the most important testing procedures during the validation process of optimization models is sensitivity analysis, which I also applied in this research to evaluate the reliability and robustness of the developed linear optimization model. The sensitivity analysis is intended to reveal to what extent the model output results, especially the optimized decision values and the result of the objective function, depend on minor or major changes in the input parameters (Saltelli this al., 2008; Hillier & Lieberman, 2015).

The methodological process of the sensitivity analysis consisted of structured steps. As a first step, I determined the critical input parameters that could significantly influence the results of the model. These included explicit parameters derived from prudential regulations, such as the minimum CET1 ratio, as well as market risk indicators used by the institution (Sharpe ratio, sigmoid indicator), as well as strategic targets (such as return on equity - ROE). The selection of these parameters was based on a literature review (e.g. Saunders this al., 2014; Berger & Bouwman, 2013), as well as the results of the previous qualitative interviews, ensuring methodological soundness. In the next step, I systematically modified the selected parameters, one by one, by three different degrees (±5%, ±10% and ±15%), while keeping the values of all other parameters unchanged. After each modification, I re-ran the optimization model and then examined how and to what extent these changes affected the model outcomes. This systematic procedure provided an opportunity to get a comprehensive picture of which parameters the model responds more sensitively to changes, and which parameters have a lower level of sensitivity.

During the numerical and statistical evaluation of the sensitivity analysis, I used the following key indicators, which are widely accepted in sensitivity studies of linear optimization (Saltelli this al., 2008; Winston, 2003):

- Absolute and relative change in objective function: I examined how the value of the model's objective function changes in absolute value and relative percentage to the initial state when modifying the parameters. This indicator is essential for evaluating how sensitive or stable the model is in terms of optimizing the objective function.

- Standard deviation of decision variables: I measured the sensitivity of decision variables by calculating the standard deviation of the optimal values of the variables after changing each input parameter. A low standard deviation indicates that the model is robust, while a high standard deviation indicates a significant sensitivity of the variable value to the given parameter change.
- Percentage of changes in optimal capital structure: I examined the effect of modifying the input parameters on the percentage change in the optimal capital allocation determined by the model compared to the original optimal solution. This indicator directly shows the extent to which each parameter influences the banking institution's proposed decisions.

I documented the results of the sensitivity analysis in a matrix format, where I assigned the above indicators to each analyzed parameter. This matrix allowed for a comprehensive assessment of the sensitivity and robustness of the model.

2.7. Case study based (single case study) model validation

As the third validation step of the model, an empirical case study (single case study) method was used in order to verify the practical relevance, applicability and validity of the developed linear optimization model in a real environment. In doing so, I used real banking data provided by a Belgian financial institution, which the institution concerned treats as a trade secret. Accordingly, neither the name of the institution nor the specific details of the data will be made public, they can only be used in summarized form for the validation of the model. The purpose of applying the case study was to test the results of the developed model in a specific institutional environment, on real financial data, thereby examining whether the model is relevant in a practical situation, valid from a regulatory perspective, and provides results that can be interpreted in economic and strategic terms. During the model test carried out with real banking data, I used the institution's current capital structure parameters, regulatory requirements, market risk data, and strategic target values that I had previously explored during qualitative research. These input data came directly from the bank's real business environment, thus ensuring the empirical relevance of the model's results.

In conducting the case study, I first processed the bank’s data in a structured manner and integrated it into the optimization model. I then ran the optimization calculations and analyzed the results in detail, with particular attention to whether the optimal capital allocation decisions proposed by the model actually met the CRR regulatory requirements, especially the minimum capital requirements, and were consistent with the economic and strategic targets set by the institution, such as the ROE targets. During the analysis, I also assessed how the solution proposed by the model compared to the bank's previous, actually applied capital structure decisions, and what improvements or changes the model's results would represent for the bank in regulatory, economic or strategic terms. The results of the case study clearly confirmed the practical relevance of the model: the optimized solution met all regulatory requirements and provided results that were economically relevant and strategically beneficial for the bank.

The methodological application of the empirical case study, which was based on the research methodology works of Yin (2014) and Eisenhardt (1989), gave me the opportunity to validate the results of the model in a real economic and institutional environment. This ensured that the developed linear optimization model would become a decision support tool that was truly applicable, relevant and directly usable for banking practice.

3. RESULTS AND DISCUSSION

During the research, I apply three main methodological steps in order to optimize the own funds. As a first step, I conduct a document analysis, during which I review the CRR 575/2013/EU Regulation in detail. After that, I conduct qualitative interviews with industry experts and managers in order to obtain more detailed information about operational challenges, regulatory compliance, and risk management preferences. Finally, based on the information obtained, I create a mathematical optimization model that allows for the optimization of the own funds rate in accordance with the law.

3.1. Document analysis of the CRR regulation

The CRR (Capital Requirements Regulation) Regulation 575/2013/EU aims to define prudential requirements for credit institutions and investment firms in the European Union. The regulation was prepared based on the Basel III framework and aims to maintain the stability of the financial system and to appropriately manage the risks of institutions. In the following, I will process the parts of the regulation related to own funds, which are significant for my model creation, through document analysis.

The regulation covers the following main areas:

- Solvency capital and capital requirements
- Risk weighting and capital requirement calculation methods
- Liquidity requirements
- Leverage ratio and other prudential rules

According to the interpretation of the regulation, the own funds (own capital) of credit institutions consist of two major components: core capital (Tier 1) and additional capital (Tier 2). Core capital consists of two sub-totals: common equity tier 1 (CET1) and additional core capital (Additional Tier 1).

- Common Equity Tier 1 (CET1): this includes shares, premiums, retained earnings and other reserves and has an unlimited capacity to absorb losses.
- Additional Tier 1 capital (Additional Tier 1, AT1): these are the -instruments that can be written down first in the event of a loss or converted to CET1, which constitute the second tier of core capital.
- Tier 2 capital: this is treated separately by the regulation, the total own funds are the sum of core capital (CET1 + AT1) and tier 2 capital.

The CRR and CRD (Capital Requirements Directive) in addition to capital calculation, the regulation also standardizes the measurement of risks. The CRR includes two main methods for determining the credit risk capital requirement of credit institutions: the standardized approach (SA) and the internal ratings-based approach (IRB).

In addition to defining the three main categories of own funds, the regulation provides a detailed description of their composition:

Common Equity Tier 1 (CET1):

- CET 1 eligible instruments and related premium
- Retained earnings and audited interim result less expected dividend
- Accumulated other comprehensive income
- Other reserves
- Reserves for general banking risks

Additional Tier 1 capital (AT1):

- AT1 qualifying instruments (hybrid capital items) and related premium
- Deductions, corrections

Tier 2 capital (T2):

- T2 qualifying instruments (subordinated debt) and related premium
- up to 1.25% of the credit risk-weighted exposure amount (RWA) net of tax effects
- Specific, general credit risk impairment, provisions Expected loss calculated using IRB method Credit risk RWA up to 0.6%
- Deductions, corrections

The methodology set out in the regulation can be divided into four main parts, depending on the type of risks covered by the regulatory capital requirement. These are as follows:

Credit Risk: The standardised credit risk approach, as set out in Articles 116-134 of the Regulation (CRR), classifies exposures into categories and assigns risk weights to each category reflecting the relative level of risk. The weights of individual exposure classes (e.g. sovereigns, public sector entities, credit institutions, corporates, retail, real estate-backed exposures, covered bonds, etc.) are typically fixed or determined by external credit ratings. Sovereign exposures with the best credit ratings (high creditworthiness) may receive a risk weight of up to 0% (especially if they are claims in the country's own currency within the EU), while lower-rated or unrated exposures are assigned a higher risk weight proportional to the level of risk. The essence of the standardised approach is that capital requirements are determined in a uniform and risk-adjusted manner across exposure categories. The most commonly used instruments are: hedging the credit risk of bank placements, corporate and retail loans, securities and other exposures.

Counterparty Credit Risk: The management of counterparty credit risk exposures has also been comprehensively regulated. The regulation requires credit institutions to calculate their exposures arising from derivative transactions, repo and securities lending operations using one of the specified methods, such as the Standardised Counterparty Credit Risk Method (SA-CCR) or, if they have the appropriate authorisation, an Internal Model (IMM). In line with this, Articles 381-384 introduce the concept and capital requirement of credit valuation adjustment (CVA) risk for OTC derivative transactions, which measures the risk of market value loss due to a deterioration in the creditworthiness of the counterparty. Two calculation methods can be used for CVA risk, depending on the size and authorisation of the banks. Larger institutions with appropriate internal modeling (IMM) and VaR licenses must use the advanced CVA model, and in all other cases the standardized CVA method, which assigns weights to the exposure based on the external credit rating of the counterparty.

Market Risk: Articles 325-361 of the Regulation regulate the capital requirements for market risks, i.e. the risks associated with positions in the trading book. The regulation aims to ensure that banks hold sufficient capital to cover losses arising from adverse changes in market prices, interest rates, foreign exchange rates, equity prices, commodity prices and option values. The Regulation distinguishes between general and specific interest rate risk in the case of government securities, corporate bonds and other interest-bearing instruments in the trading book, and also takes into account the risks of equity positions, foreign exchange and commodity positions and options. It allows for two main methods for calculating capital requirements. The standardised approach (STA), which is based on the application of pre-defined risk weights and aggregation rules, and the internal model-based approach (IMA), which is based on the bank's own risk models (e.g. VaR or sensitivity-based approaches), which is subject to supervisory approval. The regulation requires that trading book and banking book positions must be clearly separated and only positions in the trading book with active market pricing are subject to the market risk capital requirement. The regulatory objective is that institutions manage the market risks inherent in their portfolios in a conservative and transparent manner and establish appropriate capital reserves for this purpose.

Operational risk Risk: According to Articles 315-317 of the CRR, banks must set aside capital for risks arising from options, taking into account risks arising from fundamental price movements (delta risk) and additional factors such as market volatility or the passage of time (gamma and vega risks).

Options must always be treated on the basis of their underlying product, according to their sensitivity to price changes, for which the delta value is used. The regulation also provides the possibility to reduce the risk of option positions with opposite positions that serve as hedges. In addition, the regulation pays attention to the management of risks caused by internal processes, human errors, technical failures and legal problems. This means that banks must set aside capital for losses that may arise, for example, from faulty internal operations, technical problems or legal disputes. The aim of the regulation is therefore to provide comprehensive and adequate coverage for managing both financial market risks (e.g. from options) and risks arising from internal operations.

According to the regulation, the capital adequacy ratio can be considered one of the indicators to be achieved, which is the percentage ratio of own funds to total risk exposure, which can be written with the following formula:

$$CAR = \frac{\text{Solvency capital}}{\text{Total risk exposure}} \times 100$$

In order to decompose this indicator into factors, we must first identify the components that influence its value, as well as the calculation methods with which we can evaluate the contribution of each component.

The risk-weighted exposure amount in the denominator (Risk-Weighted When calculating the Risk Weighted Assets (RWA), specific risk weights must be applied to each asset and exposure. According to the regulations, each exposure must be assigned to a specific risk class, which determines the weight assigned to it. This classification takes into account the type of asset, the credit risk, the quality of the counterparty, and any collateral.

3.2. Analysis of qualitative interviews

Qualitative interviews highlighted that all four fundamental risk dimensions (credit, counterparty, market and operational risk) are important in bank capital allocation decisions, but appear with different weights. Credit risk dominates capital requirements, which is why the first two components of the model's objective function are based on it. Counterparty risk and market risk are more restrictive: although they are strategically important (for example, netting of derivative transactions reduces capital requirements, and the VaR limit system and stress tests indicate potential losses), they are less important in daily capital allocation. Accordingly, the model considers them as exogenous constraints (it incorporates counterparty risk capital requirements as an external parameter and market risk with a pre-estimated percentage correction). All experts considered operational risk to be an external factor that cannot be optimized, so the model treats its capital burden as a fixed cost element.

The interviewees unanimously emphasized that return on equity (ROE) is one of the most important indicators for bank management, as it reflects both profitability and the efficiency of capital use. ROE is of strategic importance: it influences dividend policy, reinvestment and allocation decisions, and also has an impact on shareholder expectations and the assessment of management performance. At the same time, ROE is always assessed taking into account the risk profile - an exceptionally high ROE may be due to excessive leverage or underregulation. In the model's objective function, ROE therefore appears not as a separate goal in itself, but as an implicit preference that orients the formation of decision weights. Opinions were divided regarding growth goals: some Western European managers highlighted the maintenance of the capital buffer as a condition for sustainable growth, while Hungarian experts believed that growth in itself is only a means to maintain market positions. However, there was agreement that the model should integrate not only regulatory constraints but also the bank's strategic expansion intentions. Accordingly, the developed model supports future-oriented, strategic capital allocation rather than static compliance.

The expert interviews also established the weightings of the model's objective function. According to the respondents, the stability aspect measuring the volatility of returns deserves a weight of approximately 30%: although it is not the dominant factor, it is important due to the predictability of portfolios and the ability to meet capital requirements. There was complete agreement that risk-adjusted performance (a Sharpe ratio-type measure) receives the highest weight, approximately 40%, because it helps in ranking the efficiency of assets. As a third element, a difficult-to-quantify but important qualitative factor (e.g. reputational risk, customer relationships, ESG aspects) appeared in the decision logic; the model takes this into account with a normalized “soft” indicator with a weight of 30%. Since this quality factor does not have a uniform scale, the model normalizes this component between 0 and 1 using a sigmoid transformation, ensuring that non-financial preferences have a balanced impact on the decision. Finally, the interviews also highlighted the risk of asset concentration: in order to avoid excessive exposures, the model limits the share of any one asset group to a maximum of 35% in the portfolio. This guarantees a diversified, balanced portfolio, adapting to the strategic profile of the given bank.

3.3. Risk areas and capital structure calculations

In my thesis, I calculate the value of the risk areas based on the methods specified in the CRR regulation, using data collected from the bank. In order to demonstrate the efficiency of the optimized portfolio, the current state described as the starting situation and the optimized state will be compared. Based on the bank data, I compiled the bank's asset and liability structure, which is illustrated in Table 1.

Table 1: Bank details

Tools	**Amount (HUF billion)**	**Resources and equity**	**Amount (HUF billion)**
Cash and Central Bank Reserves	2097	Government and interbank claims	1250
Cash in the accounts	454	Deposits	11530
Reserves deposited with the central bank	1339	Demand deposits	4692
Deposits placed with banks	304	Term deposits	6838
Consumer Loans	4991	Interbank liabilities	1600
Housing loans	3243	Securities issued	400
Personal and consumer loans	1748	Derivatives	1109
Corporate Loans	4435	Shares	439
Working capital loans	4435	Other obligations	1450
Investments and Securities	3638	Deferred taxes	250
Government securities	2167	Other debts	1200
Other bonds	1471	Provisions	1500
Derivatives	1790	Equity	2050
Shares	2008	Subscribed capital	1400
Tangible assets	1134	Reserves and retained earnings	650
Intangible assets and goodwill	232		
Other tools	1003		
All Devices	21328	Total Liabilities and Equity	21328

Source: Case study based on bank data

In accordance with the provisions of the regulation, I have determined the risk-weighted asset values separately for each significant risk area. However, in addition to credit risk, I only have partial data available for the other three risk areas, counterparty, market and operational risk, and therefore the value of the bank's own capital cannot be determined separately for these.

Therefore, I have determined the necessary capital requirement for the entire risk portfolio. In the case of the analyzed bank, the risk-weighted asset value of the four risk areas calculated together is 15,198.81 HUF billion , which corresponds to a 14.59% own capital ratio according to the own capital calculation method. Based on this, the analyzed bank maintains a total capital buffer of 2,218 HUF billion (Table 2).

Table 2: Summary of risk exposures

Exposure	Risk-weighted asset value (RWA, HUF billion)	Solvency capital (14.59%)
Credit risk exposure	12311.30	
Counterparty risk exposure	270.01	
Market risk exposure	1875.00	
Operational risk exposure	742.50	
Total RWA	15198.81	2218

Source: based on the requirements of EU Regulation 575/2013

3.4. Logical framework of the equity optimization model

Banks are required by law to maintain a minimum capital adequacy ratio of 8%, calculated in relation to the amount of risk-weighted assets (RWA). The value of RWA is determined based on different risk types, some of which are associated with direct and others with indirect calculation rules. The actually available, freely allocable capital, which exceeds the mandatory minimum, can be optimized, so that the freed up extra capital can be allocated to other, income-generating purposes. Based on the calculation of capital, the following objective function can be defined:

$$min\ (RWA_{loan} + RWA_{\ partner} + RWA_{market} + RWA_{operational})$$

provided that:

$$(T1 + T2 - D) \,/\, (RWA_{loan} + RWA_{\ partner} + RWA_{market} + RWA_{operational}) \geq 8\%$$

- T1 = Tier 1 capital (subscribed capital + retained earnings)
- T2 = Tier 2 capital (subordinated bonds)
- D = deductions (intangible assets, etc.)
- RWA_{loan} = credit risk RWA
- $RWA_{\ partner}$ = partner risk RWA

- RWA_{market} = market risk RWA
- $RWA_{operational}$ = operational risk RWA

I do not consider possible additional requirements (operational risk buffer, systemic risk buffer, etc.) due to the general nature of the model. When modeling capital requirements and risks, it must be taken into account that they are intertwined through numerous variables (e.g. product type, currency, counterparty rating category) and can affect multiple risk categories at the same time.

Optimization function

The developed model optimizes the portfolio composition using linear programming, while simultaneously ensuring regulatory compliance, risk management requirements, and the fulfillment of return and solvency capital goals. Below, I describe in detail the composition of the objective function, the constraints considered, and the main steps of the solution procedure.

The mathematical description of the portfolio optimization problem consists of the following elements. Let a portfolio consisting of N asset classes be given, where

- $x_i \geq 0$the i-th asset class (in HUF);
- μ_i expected return of the -th asset class; i
- σ_i its volatility ;
- r_i Basel credit risk weight;
- v_i the VaR ratio (e.g. 1-day 99% VaR per unit);
- q_i the sigmoid quality indicator, which evaluates quality on a scale between 0 and 1.

The bank's total risk-weighted assets consist R_{tot} of a credit risk component and an additional component (counterparty, market and operational risk, denoted by R_{oth}). The credit risk component consists of decision variables and fixed items:

$$R_{credit} = \sum_{i-1}^{N} r_i x_i + R_{fix}$$

where is R_{fix} the risk contribution of tangible and other assets and the central bank deposit. According to Basel rules, Tier 2 is 1.25% of the credit risk RWA, therefore the bank's regulatory capital is:

$$C(R_{credit}) = T_1 + 0.0125 \times R_{credit}$$

where T1 is Tier 1 capital. The capital adequacy ratio

$$CAR = \frac{C(R_{credit})}{R_{credit} + R_{oth}}$$

If we want $c$to adjust the CAR to a specific value (for example, 8%), we can rearrange the above formula to obtain the credit risk RWA target:

$$R_{credit,target}(c) = \frac{T_1 - c\, R_{oth}}{c - 0.0125} - R_{fix}$$

This is the value that must be generated from the decision variables in order for the CAR $c$to be just right with the full RWA.

Objective function

We maximize a multi-factor utility function for the decision variables, which takes into account return, volatility and capital adequacy ratio. In the uploaded research material, this is stated as the following weighted sum:

$$Z(x) = w_1 \sum_{i-1}^{N} x_i(\mu_i - \sigma_i) + w_2 \sum_{i-1}^{N} x_i \frac{\mu_i}{\sigma_i} + w_3 \sum_{i-1}^{N} x_i q_i$$

where w_1=0.30, w_2=0.40, w_3=0.30. The first term is the return-variance difference (rewards high returns and penalizes volatility), the second is the normalized Sharpe ratio, and the third is the weighted average of the sigmoid quality indicator.

Limits

We impose the following linear constraints on the variables:

1. Budget: $\sum_{i-1}^{N} x_i = B$, where is $B$the amount to be invested
2. RWA target: $\sum_{i-1}^{N} r_i x_i = R_{credit,target}(c)$This ensures that the credit risk portion is exactly what $c$is required for the CAR.
3. Return limit: $\sum_{i-1}^{N} x_i q_i \geq H_0$, where is $H_0$the expected return of the initial portfolio (or its value not less than a target).
4. Var limit: $\sum_{i-1}^{N} x_i v_i \leq V_0(1+\gamma)$, where $V_0$is the VaR of the initial portfolio and $\gamma$is the allowed relative increase (for example, 0.05 to allow a maximum increase of 5%).
5. Diversification ceiling and minimum: $i$for all

$$m_i \leq \frac{x_i}{B} \leq M_i$$

   where m_i=5% is the minimum and M_i=40% is the maximum portfolio ratio.

6. Other structural constraints: fixed exposures, incorporation of tangible and other assets

7. 25% limit per partner , based on the regulation

$$\sum_{i \in P_j} x_i \leq 0.25 \times \sum_{i=1}^{n} x_i \times \omega_i \qquad \forall j \in \{1, \dots, m\}$$

where:

x_i: amount invested in the i-th asset (decision variable)
ω_i: risk weight of the i-th asset
m: number of partners
n: number of devices

Solution procedure

Since the credit risk RWA needs to be set depending on the CAR target, it is worth solving the problem in steps:

1. Target value determination: start with the 8% capital adequacy threshold ($c = 0.08$). Calculate it using $R_{credit,target}(c)$the above formula and then solve the above optimization problem. If a solution exists (i.e. the model is "feasible"), then this is the smallest CAR that still satisfies the VaR, return and diversification constraints.
2. Iteration: if $c =$ the task cannot be solved at 0.08, we increase the target to 8.1%, 8.2%, and so on in 0.1 percentage point steps. At each step, we recalculate the RWA target and then solve the optimization model. The first $c$value for which there is a solution will be the "smallest" feasible capital adequacy ratio. If we do not find a solution between 8-9% or around 9%, we should increase the target to 10% or even higher.
3. Optimization of the objective function: for each $c$value, if there is a solution based on the linear constraints, we select the most favorable portfolio by maximizing the multi-factor objective function. According to the lexicographic approach, we first focus on meeting the capital adequacy (CAR) and VaR limits; if this is achieved, we maximize the weighted objective function.

Counterparty risk limit: Counterparty risk exposure (can be interpreted as the sum of the portfolio's weighted risk values per counterparty. The limit required to achieve the target level of CAR (capital adequacy $R_{partner}$)ratio (c) through the counterparty risk considered in the model can be written as follows:

$$R_{credit} + R_{partner} + R_{oth} \leq \frac{T_1 + 0.0125 \times (R_{credit} + R_{partner})}{c}$$

Rearranged, we obtain a linear form that can be used directly for model optimization:

$$(1 - 0.0125/c) \times (R_{credit} + R_{partner}) + R_{oth} \leq \frac{T_1}{c}$$

3.5. Optimized portfolio

Using the developed optimization model, I created a portfolio composition that meets the main goal set in the research: the portfolio meets the minimum 8% regulatory capital requirement, while minimizing the amount of capital tied up in capital. The goal was for the bank to use the released capital for further investments or placements, thereby improving the profitability of the portfolio. During the model building, I treated as a determining criterion that the market risk of the optimized portfolio, which I measured with the 95% VaR indicator based on the bank's data, should not change significantly compared to the original value. To this end, I allowed a maximum deviation of ±5% from the initial risk level during the optimization. The reason for allowing this deviation was that market risks are typically estimated using internal models, the results of which can differ significantly from each other, and the calculation with the annual average can distort the actual risk changes that appear on a daily basis. The optimized portfolio showed changes in two of the four risk areas examined, credit risk and market risk. Partner and operational risk remained unchanged in my example.

Table 3 summarizes the risk-weighted asset values (RWA) of the four risk areas. The capital adequacy ratio can be calculated based on the data in the table. The calculation process is as follows: first, I determined the bank's primary (Tier 1) capital, which is the sum of equity and retained earnings (2,050 billion HUF), but according to regulatory requirements, goodwill and other intangible assets had to be deducted from this. Thus, Tier 1 capital amounted to 1,818 billion HUF. The elements of the additional (Tier 2) capital are provided by subordinated bonds, of which 400 billion HUF is available. Then, I summed up the risk-weighted asset values belonging to credit, counterparty, market and operational exposures, which together amounted to 27,714.51 billion HUF. In contrast, the 2,218 billion HUF own funds (1,818 billion Tier 1 + 400 billion Tier 2), which results in a capital adequacy ratio of just 8% compared to the RWA value. This means that our optimized portfolio meets the mandatory minimum set out in the Basel -rules.

Table 3: Summary of optimized portfolio risk exposures

Exposure	Risk-weighted asset value (RWA, HUF billion)	Solvency capital (8%)
Credit risk exposure	24 401.00	

Counterparty risk exposure	270.01	
Market risk exposure	2 301.00	
Operational risk exposure	742.50	
Total RWA	27 714.51	2 218.00

Source: Own editing, 2025

3.6. Comparison of current and optimized portfolio

In Table 4, I have summarized the main financial indicators of the current and optimized portfolios. The data in the table clearly shows that in both cases the total amount of credit, cash, investment and other exposures was unchanged, 18,605 HUF billion. This value did not change during the optimization, the model only modified the composition of the assets. At the same time, the risk-weighted asset value (RWA) increased significantly, from 15,198.81 HUF billion to 27,714.51 HUF billion as a result of the optimization. This absolute increase of 12,515.7 HUF billion (approximately 82.3% relative increase) reflects that during the portfolio restructuring, assets with a higher risk weight were included in the portfolio. The absolute value of the own funds remained unchanged at 2,218 HUF billion in both portfolios. On the other hand, as the risk-weighted asset value increased significantly, the solvency ratio (capital adequacy ratio) decreased significantly. It fell from 14.59% in the initial state to exactly the 8% specified as the minimum by regulation in the optimized portfolio. This freed up a significant amount of capital buffer, providing the bank with the opportunity to make further placements and investments. A favorable change can be observed in terms of the average annual return, with the expected return increasing from the initial level of 788.20 HUF billion to 1,084.872 HUF billion in the optimized portfolio. This absolute increase of 296.672 HUF billion represents a relative increase of approximately 37.6%. Finally, examining the development of market risk, it can be seen that the VaR value estimated at a 95% confidence level over a 1-year period increased moderately, from 1,370 HUF billion to 1,434 HUF billion. This absolute increase of 64 billion HUF represents a relative increase of only 0.33 percentage points in the total exposure ratio (from 7.37% to 7.70 %), which thus remained within the previously defined maximum permissible growth ceiling of 5%. This shows that during the optimization the model deviated only slightly from the market risk of the original portfolio, in line with the set risk management criteria.

Table 4: Comparison of current and optimized portfolio

Indicators	Current portfolio	Optimized portfolio
Balance sheet value (HUF billion)	21 328	21 328
Risk-weighted asset value (RWA, HUF billion)	15 198.81	27 714.51
Solvency capital value (BFT)	2 218	2 218
Solvency capital percentage	14.59%	8%
Average yield	788.20	1084.872
VaR 95% (1 year) (BFT)	1 370	1 434

Source: Own editing, 2025

4.CONCLUSIONS AND RECOMMENDATIONS

In the next chapter, I summarize the most important results of the dissertation, assess the extent to which the originally raised research questions were answered, and point out the areas where the research contributes most to expanding existing scientific and methodological knowledge. In separate subsections, I discuss the practical suggestions offered by the dissertation, which provide directly applicable guidelines for banking decision-makers, as well as the recommendations formulated for financial regulators, which can help make prudential regulation more effective. After that, I present in detail the limitations encountered during the research, which may have affected the generalizability of the results, and taking these into account, I outline further research directions through which the topic can be explored even more deeply. To conclude the chapter, I briefly summarize the most important lessons of the research, highlighting their significance for both the scientific community and practitioners.

4.1. Answering research questions in research

The goal of the research was to develop and empirically validate a capital optimization model that supports banks' capital management through deterministic linear programming. The model did not focus on minimizing risk-weighted assets (RWA), but specifically on minimizing the excess capital resulting from regulatory compliance, while leaving the bank's actual economic risk profile unchanged. The model ensures that the bank meets the prudential requirements of the CRR and adequately covers its credit, market, counterparty and operational risk exposures in its capital allocation. The model was validated using a synthetic data-based case study of a medium-sized bank based in Belgium, which used a unique case analysis approach based on qualitative interviews.

According to the results of the case study, the bank can release a significant part of its capital buffer above the current regulatory minimum with the help of the developed model. The prudential indicators of the institution under study already met the minimum regulatory requirements, but there was an unreasonably high excess capital available. Based on the optimal solution of the linear programming model, it can be stated that the excess capital resulting from regulatory compliance can be significantly reduced by approximately HUF 12.5157 billion. This release reduced the bank's capital adequacy ratio from the original level of 14.59% to the minimum level of 8% required by the regulation, while at the same time not jeopardizing the fulfillment of any prudential indicator. The excess capital released through the optimized portfolio creates an opportunity for the bank to make new placements and investments, thus improving its profitability without significantly increasing its market risk.

A key finding is that the capital optimization achieved by the model does not increase the actual economic risks and does not worsen the bank's risk profile. The optimal solution of the model complied with all relevant prudential requirements, ensuring regulatory compliance with respect to credit, market, counterparty and operational risks. In particular, it can be emphasized that the market risk coverage remained unchanged, thus the bank's trading book and other market exposures did not become more vulnerable. Based on the results, capital allocation efficiency can be improved by exploiting the scope provided by the regulatory framework without jeopardizing financial stability.

Based on the above, the updated research questions were answered:

- An integrated capital optimization model has been developed, which, in addition to prudential requirements, is able to take into account differences between regulatory and real risks.
- The developed empirically based quantitative model provides a generally valid portfolio optimization framework that can be applied in bank capital allocation.
- The mathematical structure of the model uniformly addresses CRR requirements and challenges arising from real economic risks, providing a transparent, auditable methodological framework.
- According to the case study, the model can significantly reduce the level of regulatory capital without increasing the bank's actual risk level.
- The developed objective function ensures the minimization of own funds in an empirically based manner, taking into account the differences between regulatory and real market risks, thus increasing bank capital efficiency and profitability.

The results support the main hypothesis that deterministic modeling can reveal the rationalization potential of bank capital buffers. It is important to emphasize that the optimization potential revealed by the model is valid for the specific situation of the given bank, but the methodology can also be adapted to the specificities of other institutions.

Qualitative feedback received during the interviews also confirmed that by consciously restructuring the bank portfolio, for example by modifying the collateral policy or fine-tuning internal risk parameters (PD, LGD), the regulatory excess capital can be significantly reduced, which is directly reflected in the development of RWA.

4.2. Scientific and methodological contributions

The dissertation makes several important scientific and methodological contributions to the literature on bank capital management and financial optimization.

The research developed an innovative deterministic linear programming model that addresses bank risk exposures and prudential capital requirements in an integrated manner. The significant novelty of the model is that it minimizes the excess capital resulting from regulatory compliance while leaving the bank's actual economic risk profile unchanged. This holistic approach offers a novel perspective to the scientific discourse, demonstrating that classical capital allocation challenges can be addressed using exact optimization methods.

The empirical case study of the thesis provides evidence that significant capital release can be achieved for a typical European medium-sized bank without causing any deterioration in prudential indicators. My results highlight that part of the excessive capital buffer held by the bank can be rationally reallocated, thereby simultaneously meeting prudential requirements and improving the bank's profitability.

From a methodological perspective, the dissertation combines quantitative modeling and qualitative case studies. The precision of linear programming is complemented by practical experience gained through expert interviews, a rare and innovative combination in the field of financial modeling. This methodological contribution demonstrates how expert opinions can be integrated into the model design and the interpretation of results. In this way, the research bridges the gap between theoretical optimization approaches and banking practice.

The developed model also has practical relevance, as it offers a transparent, auditable decision support tool for bank management. The model outputs clearly identify excessively capital-intensive portfolio elements and provide concrete guidelines for improving capital efficiency. The simplicity and computational efficiency of the model allow for its wider application, even in the case of smaller financial institutions.

The research findings also contribute to the discussions on prudential regulation, emphasizing that the flexibility provided by regulatory frameworks can be used to increase banks' resilience. The optimized capital allocation proposed by the model can also facilitate more efficient macroeconomic resource allocation. Through this approach, the paper can offer new perspectives for regulators to fine-tune capital requirements, encouraging banks to adopt risk-proportionate capital allocation and more effective risk management practices.

4.3. Practical recommendations for bank management

Based on the results of the research, several specific financial and strategic recommendations can be formulated for the bank management, which support the more efficient management of the own funds, thereby significantly increasing the profitability of the bank. First of all, it should be emphasized that it is advisable to establish a continuous, regular capital allocation review process, in which the logic of the optimization model developed during the research is regularly applied. According to the results of the model, the bank can achieve significant capital release, as a result of which it can realize up to several billion forints of additional income annually without violating the prudential capital requirements.

The model can be used to specifically identify those asset portfolio elements that operate with lower efficiency or require excessively high capital, so that by rearranging them, the institution can reduce its risk-weighted asset value (RWA). At a strategic level, it is recommended to increase the proportion of lower risk-weighted, adequately collateralized assets, such as housing loans and government securities, and to reduce the proportion of high-capital-demanding, unsecured corporate loans and other risky assets. The additional capital released through the optimized asset structure can be used for productive investments, which directly contributes to the increase in the bank's profitability.

In addition, an active and targeted review of the bank's collateral policy is also a strong recommendation. The research results clearly show that the use of higher quality or higher value collateral can reduce the risk weight, thereby improving capital adequacy ratios and increasing the rate of return on capital. In parallel, the development of professional competencies and technological infrastructure is also an important priority, including expert training and the introduction of modern fintech solutions into the bank's daily operations.

Although the model technically minimizes solvency capital, caution should be exercised in its practical application. It is not recommended to liquidate the entire capital buffer, but rather to maintain an optimized reserve validated by stress tests. This allows the bank to minimize capital tie-ups during normal operations, while maintaining its flexibility and financial stability in the event of unexpected market shocks.

By consistently applying the recommendations, the more efficient capital allocation achieved according to the model enables the realization of additional profits of up to several billion forints per year, improving the bank's operational efficiency and long-term financial performance as a strategic competitive advantage.

4.4. Research limitations

The main empirical basis of the paper is a single case study based on data from a medium-sized Belgian bank. This focus allowed for a detailed presentation of the model and an in-depth examination of the concept, but at the same time limits the generalizability of the results. It is not certain that the conclusions drawn can be applied one-to-one to all banks, for example, in the case of a large global bank or a specialized financial institution (e.g. mortgage bank), the capital structure and scope may be different. The research is therefore rather demonstrative in nature and the performance of the presented model needs to be tested in other environments in order to draw general conclusions. Furthermore, the data used were available to a limited extent and were anonymized. Although I tried to calibrate the dataset realistically, there may be real anomalies or correlations that could not be adequately revealed. This circumstance limits the validation of the model, the presented results primarily demonstrate the correctness of the internal logic of the model, but further testing is needed to see if the same effect would occur on real, other bank data. The accuracy and practical reliability of the model should be verified with additional data in the future.

Both deterministic and static approaches have several limitations. I have used a deterministic, static framework in the modeling. This means that the model does not take into account future uncertainties, macroeconomic variables, or the dynamics of bank behavior. Linear programming optimizes the capital structure at a given point in time, assuming that all input parameters are fixed. However, in reality, risk parameters (e.g., loan portfolio quality, market volatility) change over time, and planning bank capital levels is a dynamic problem. The deterministic model cannot directly handle, for example, stress situations or cyclical effects, the operation of the countercyclical capital buffer, and the increase in losses during recessions are outside the scope of the model. This limitation suggests that the current model is more suitable for short-term, tactical optimization and does not replace long-term strategic planning or the need for stress tests. In addition, I have used several simplifications in the model construction. In constructing the linear programming model, certain simplifying assumptions had to be made. For example, I assumed linear additivity of the various risk factors in terms of capital requirements, and that portfolio rebalancing can be implemented directly and cost-free. In reality, there may be nonlinear effects (e.g. economies of scale, marginal benefits of portfolio diversification) and transaction costs or market effects (a large asset sale may depress prices), which the model does not handle. Furthermore, the model focused on regulatory capital requirements and did not explicitly integrate profitability aspects (although the return/risk ratio appeared indirectly). These simplifications increased the clarity and computational manageability of the model, but at the same time they limit its realism. This should be kept in mind when interpreting the results.

One of the strengths of the research was the inclusion of qualitative interviews, however, these interviews were mainly used to understand the background and support the development of the model, rather than to test formal hypotheses. The comparison of qualitative findings and quantitative results was descriptive, not statistically supported. As a result, the different weightings are not statistically proven, but are acceptable for model building. The paper did not examine, for example, how management would likely react to the model's suggestions, or what organizational factors influence the practical implementation of capital optimization. This limitation means that there may be additional challenges between the theoretical potential shown by the model and the practical implementation (e.g. risk culture, IT systems, regulatory approval), which were not explored in this research. The developed optimization model is suitable for taking into account banking strategic aspects, however, further consideration and fine-tuning of the model's conditions and limiting factors is necessary to fully integrate these aspects. I have not yet incorporated the strategic aspects in the current development phase, but by testing them, the model can be further refined and its practical applicability could be significantly improved. In addition, in addition to the RWA calculation, several other financial-mathematical indicators measuring market risk could be included, and even the refinement of RWA from a methodological point of view would reduce the subjective effect of the indicator. One of the main limitations of my research is the incorporation of individual bank strategies into the system, but this incorporation only represents a simple theoretical mathematical challenge.

5. NEW SCIENTIFIC RESULTS

In the framework of this dissertation, I have achieved four outstanding, new scientific results in the field of optimizing bank capital allocation. These results contribute in a coherent way to the development of capital management in financial institutions, integrating regulatory, risk and strategic aspects. Below, I present each of the four main results in detail, emphasizing their novel contribution and practical significance.

5.1. I created a generally applicable deterministic linear programming model for the purpose of optimizing solvency capital

A key innovation of the developed deterministic linear programming model is its ability to effectively address the return maximization problem arising from the difference between VaR -based measures reflecting real market risks and RWA-based risk weights calculated according to Basel rules. This approach allows banks to optimally exploit the differences between their actual market risks and regulatory risk values, thereby significantly increasing their profitability without compromising prudential compliance. The model framework treats the four main risk types – credit, market, counterparty and operational risk – in an integrated manner, ensuring that the bank's corporate-level capital allocation optimally reflects its actual risk profile. The model's explicit linear constraint conditions directly incorporate CRR regulatory requirements, such as the minimum required CET1 ratio, total capital ratio, leverage ratio, and other prudential limits, ensuring that all optimized solutions automatically comply with regulatory requirements.

The objective function is specifically designed to maximize the return-risk balance, which takes into account the bank's financial performance indicators (e.g. expected return, standard deviation, Sharpe ratio), regulatory compliance obligations (e.g. implicit costs of non-compliance with capital requirements), and the bank's strategic priorities. The capital requirements of each risk type can be estimated numerically according to the methodologies prescribed by the CRR, and these are explicitly incorporated into the model's constraints. The developed model represents a significant scientific advance, as previously there was no comprehensive linear optimization tool available that would address the various risk elements of banks in a complex manner and that would be able to exploit the profitability potential inherent in the differences between VaR and RWA-based approaches. The presented methodological framework is therefore not only a new scientific result, but also has direct practical applicability in improving the efficiency of bank capital allocation, ensuring prudential regulatory compliance and maximum utilization of available capital.

5.2. Sigmoid model of leadership and risk assessment preferences and integration into the objective function

To mathematically model the managerial preferences and qualitative risk assessment aspects revealed during the research, I used a normalized sigmoid function, which allows for an accurate mapping of the nonlinear evaluation mechanisms of decision-makers. The information collected during the qualitative interviews showed that certain qualitative criteria – such as the strategic fit of investment decisions, reputational risks, or the reliability of partners – significantly influence banking decisions, but these factors can be characterized not linearly, but by certain sensitivity thresholds and saturation points.

Since these aspects do not have a clear numerical scale, their traditional linear weighting would result in biases or loss of information. To address this problem, I normalized these quality criteria using the sigmoid transformation, squeezing their scale between 0 and 1, which allowed for fine differentiation of values, especially in the range of median values. The slope of the sigmoid function reflects how a given criterion drastically modifies decision-maker preferences above or below certain threshold values.

I integrated this nonlinear element into the objective function of the model, which thus became a multi-component evaluation function. The qualitative sigmoid transformed indicator is included in the objective function with a weight of about 30%, reflecting its importance determined during the interviews, while the remaining part is made up of traditional financial indicators (such as return and risk measures). This allows the model to combine qualitative expert judgments with quantitative optimization in a novel way, effectively handling the nonlinear characteristics of decision preferences.

The sigmoid function, the model accurately represents the change in preferences, thus more authentically depicting the decision-making behavior. I integrated the decision-makers' evaluation thresholds and saturation points in a structured form into the objective function, creating a connection between linear optimization and qualitative aspects. This solution is a significant scientific and methodological contribution, since traditional capital allocation models do not apply qualitative elements in a similar, mathematically grounded form. The sigmoid -based objective function thus helps bank capital allocation to reflect real managerial decision-making more accurately and sensitively in practice.

5.3. Proof of the linear modelability of prudential constraints

In the course of the research, I have shown in detail that the strict requirements of banking prudential regulation, including the capital requirements defined by the CRR and the Basel III/IV framework, create a narrow and well-defined decision space that can be handled accurately and comprehensively within the framework of a deterministic linear programming model. Requirements such as minimum capital adequacy ratios, various capital level limits, liquidity requirements and large exposure limits can all be expressed mathematically as linear inequalities, which allows us to solve the optimization of bank capital allocation in a simple but highly efficient methodological framework.

The objective function in this model summarizes the measurable components of the bank's performance, so it can be written as a linear combination of returns, risk indicators and capital requirements. This approach ensures that the result of the optimization is well interpreted not only at a theoretical level, but also in practice. There is no need for complex stochastic or nonlinear optimization procedures to make the model meet the expectations of real banking operations. As a scientific novelty, it has been demonstrated that deterministic linear frameworks are fully sufficient to ensure prudential compliance, while providing the opportunity to systematically explore optimal solutions. This recognition represents an important step in the mathematical foundation of bank capital allocation, as it shows that the narrow margin of maneuver created by regulatory requirements is not a limitation, but also an opportunity to make modeling more accurate.

5.4. Demonstrating the practical benefits of the deterministic linear approach

Deterministic linear programming is not just a tool for simplification, but a consciously chosen and expedient methodology that brings many practical advantages. One of the greatest values of the application of linear models lies in the fact that they are transparent, auditable and easy to interpret. In this way, they provide a decision-support framework that can be directly utilized by the bank's internal audit, supervisory authorities and senior management. The results produced by the linear model can be quickly run, reproduced and stably incorporated into the management decision-making process, which provides a significant advantage in banking operations. The results of the optimization are transparent, traceable and clearly communicated to all stakeholders, thereby strengthening the credibility and controllability of the bank's operations. The results of the research clearly highlight that in the case of financial optimization problems, it is often not the most complex, but rather the simpler, deterministic frameworks that lead to more reliable, more interpretable and more practically applicable results. This insight represents a significant methodological and practical contribution to bank capital allocation modeling. Deterministic linear optimization enables banking decision-making to be based on fast, accurate, and regulatory-compliant results. It provides scientific evidence that linear programming, applied within prudential regulatory constraints, can provide sufficiently precise and decision-supporting solutions, while strengthening the transparency and reliability of banking practice. This makes the model not only a theoretical tool, but also a real management support system that can contribute to maintaining financial stability and increasing banking competitiveness in the long term.

5.5. Through a case study, I demonstrated that the model is capable of significantly releasing capital buffers while the bank fully complies with strict regulatory requirements and does not increase its risk

During the dissertation, I empirically validated the developed model using a case study based on data from a Belgian bank, demonstrating its practical applicability and efficiency. During the case study, I demonstrated that the model is capable of releasing a significant amount of capital buffer while the bank fully complies with the strict regulatory requirements and does not increase its real risk. According to the specific calculations presented during the case study, with the portfolio optimized by the model, the bank's capital adequacy ratios improved or remained above regulatory requirements, while a significant amount of capital was released compared to the initial state. In practice, this resulted in two important advantages: on the one hand, the bank's profitability improved due to the reallocation of the released capital into more efficient, profitable business activities, and on the other hand, the bank's risk profile became more balanced, as the model created an optimized risk distribution between the different business lines.

It is important to highlight that the optimization is fully compliant with Basel III/IV and CRR regulations, thus not only ensuring regulatory compliance but also fully meeting supervisory expectations. This fourth main result clearly demonstrates that the developed method is workable and can create significant value for real financial institutions. The capital structure optimized by applying the model increases the efficiency of the bank without compromising its stability.

6. SUMMARY

The operation of the banking system today depends both on the regulatory frameworks ensuring global financial stability and on the efficiency requirements determining market competitiveness. The prudential regulations, consolidated in the wake of the experiences of the crises, in particular the capital adequacy norms specified in the CRR regulation, set mandatory minimum safety conditions for operation for all credit institutions. At the same time, however, the globalization of financial markets and the continuous increase in return expectations exert pressure that requires the more efficient use of capital resources. Due to this dual challenge, I considered it necessary to carry out research that treats own funds not only as a regulatory obligation, but also as a strategic resource. In order to solve this issue, I developed a deterministic, linear optimization model that is able to simultaneously take into account the aspects of regulatory compliance, risk exposures and bank strategic goals. To establish the model, I analyzed the prudential regulation in detail and conducted eight semi-structured interviews with bank managers and risk managers. I incorporated the experiences gained in this way into the model's objective function and constraint system so that the aspects designated by regulatory norms and market logic are integrated in a coherent manner.

To examine the practical applicability, I chose to test the model on the data of a medium-sized European bank. In the initial state, the total risk-weighted asset value was HUF 15,198.81 billion, which resulted in a capital adequacy ratio of 14.59 percent with a solvency capital of HUF 2,218 billion. This level was above the regulatory minimum, indicating an oversized capital buffer. With the help of the model, I identified an optimal portfolio composition that brought the capital adequacy ratio exactly close to the regulatory minimum, while the risk-weighted asset value increased to HUF 27,714.51 billion. At the same time, the annual expected return increased from HUF 788.20 billion to HUF 1,084.87 billion, while the VaR95% changed only moderately, from HUF 1,370 billion to HUF 1,434 billion. These results showed that it is possible to achieve significant return growth through a more capital-efficient portfolio composition while maintaining the safety thresholds set by the regulation.

I verified the validity of the model with a multi-stage test. The mathematical consistency of the limit system ensured internal coherence, sensitivity tests demonstrated the robustness of the key parameters, and the case study empirically confirmed that there are actual financial processes behind the decision variables. All this confirmed that the model is stable, reproducible and applicable in practice.

Finally, I concluded that own funds are not only a guarantee of regulatory compliance, but also a strategic resource whose appropriate allocation is a guarantee of the long-term stability and competitiveness of the bank. The contribution of my research can be seen in that it creates a bridge between prudential regulation and market performance requirements, while offering a practical decision-support framework for banking practice. I believe that the most important direction for further development of the model may be dynamic, stress-scenario-based validation, which could further strengthen the adaptability of financial institutions to future challenges.

7. PUBLICATIONS RELATED TO THE TOPIC OF THE THESIS

Journal Article

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