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A Review on the History and Development Direction of Quantitative Finance

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Abstract: This paper aims to systematically study and discuss the history of quantitative finance based on the literature review of various important theories in the field of quantitative finance and their review articles. Each theory's advantages, disadvantages, and historical significance are meticulously expounded upon. Following a comparative analysis of quantitative finance theories across different periods, the paper categorizes the historical development into the budding period, the axis period, and the differentiation period. The subsequent section synthesizes common false assumptions within quantitative finance theory, overlooking issues such as extreme cases and over-fitting, and proffers pertinent suggestions for refinement. Looking ahead, the paper anticipates the future trajectory of quantitative finance, asserting that artificial intelligence technology is poised to catalyze breakthroughs in quantitative finance methodologies. Furthermore, it concludes by emphasizing the burgeoning importance of sustainable development strategies within the quantitative finance domain, foreseeing increased attention and integration of these strategies for the field's enduring prosperity.

Keywords: Quantitative Finance, Portfolio Theory, Asset Pricing Model.

1. Introduction

Quantitative finance, also known as digital finance, is the study of quantitative modeling of financial markets. It is a branch of finance and a branch of applied mathematics. Therefore, quantitative finance is often considered as the intersection of finance, applied mathematics, and computer science. In this case, thanks to the rapid progress of mathematical tools and financial theory in the past 100 years, quantitative finance has also developed and iterated rapidly since the 20th century. Due to the rise of machine learning and artificial intelligence technology in the 21st century, quantitative finance has become an important subject of attention in finance and even academia. As a new discipline, the history of quantitative finance is short. In 1900, French mathematician Louis Bachelier published his book The Theory of Speculation, which is widely regarded as an important milestone in quantitative finance and the beginning of quantitative finance research. It was only a hundred years ago. Due to the short historical span, the research on the history of quantitative finance is generally less and needs to receive more attention.

The current research on the history of quantitative finance focuses on the period after 2010. It mainly appears in the relevant articles with the theme of introduction to quantitative finance and introduction to quantitative finance. P Wilmott's Frequently Asked Questions in Quantitative Finance

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is a famous popular science book on quantitative finance, in which the important development nodes of quantitative finance are summarized in a concise and clear way [1]. Due to the popular science nature of the book, the content about the history of quantitative finance is relatively simple and simple. Still, it is also an early attempt to summarize the history of quantitative finance. A Brief History of Quantitative Finance, published by Mauro Cesa in 2017, describes the development of quantitative finance and summarizes relevant papers since 2007 based on his own experience [2]. Due to the author's own experience, most of the paper introduces the history of quantitative finance after 2007 but needs to explain the whole history of quantitative finance systematically. It can be seen that the previous research on quantitative finance history has three problems: too few, too simple, and not comprehensive enough. There are some areas for improvement and gaps in the research of quantitative financial history, which need to be further summarized and studied.

Although quantitative finance is in a period of rapid development due to the introduction of many new tools and methods, the main development direction of quantitative finance is very controversial, and the development prospect needs to be clarified. Due to the rapid iteration of quantitative finance since the first century, the meta-research of quantitative finance lags far behind its theoretical development, and there are serious areas for improvement in the research history of quantitative finance. In view of this situation, quantitative finance needs meta-scientific research to reflect its past development process further and point out the direction for its future development. This paper aims to study the development history of quantitative finance, summarize the advantages, disadvantages, and historical significance of various important theories, review and reflect on the advantages and disadvantages of historical research, give suggestions, and finally look forward to the future development direction and prospect of quantitative finance.

2. Louis Bachelier's Theory of Speculation

2.1. Theoretical Basis

Louis Bachelier published The Theory of Speculation in 1900, which is regarded as the beginning of quantitative finance in mainstream academia. Bachelier's first mathematical model of price changes, however, was based on Brownian motion.

Brownian motion, a physical concept defined as the random and irregular movement of tiny particles in a fluid, was discovered as early as 1827 by British botanist Robert Brown, who observed the movement of pollen in water. In stochastic analysis, Brownian motion is an independent incremental continuous random process with normal distribution. The random motion of particles in a fluid can be likened to the random change of asset prices in the financial market. The emergence of Brownian motion inadvertently laid the foundation for the birth of quantitative finance.

Louis Bachelier first introduced Brownian motion into finance as a mathematical model to describe the changes of asset prices in the market, which brought financial activities into the quantitative mathematical framework for the first time. It was determined that the market price in the financial market was a random walk, subject to a variety of unknowable factors, so it could not be accurately predicted [3].

As Louis Bachelier's doctoral thesis, the Theory of Speculation is basically accurate in formula, calculation and derivation process. At the same time, it is also very original. It combines mathematics and finance for the first time, which is a rare interdisciplinary work. As the originator of quantitative finance, Louis Bachelier himself is a mathematician, rather than a professional financial scientist. His professional mathematical skills have laid a solid mathematical theoretical foundation for quantitative finance. However, due to the interdisciplinary nature of "Theory of Speculation", the paper was not found and valued by the mathematical judges, because "Theory of Speculation" introduced mathematics into the field of finance that mathematicians are not familiar with, resulting in the value

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of the paper was not immediately explored and utilized, which objectively delayed the development process of quantitative finance theory.

2.2. Criticism

As an early work of quantitative finance, Louis Bachelier's "Theory of Speculation" has some unavoidable shortcomings due to the limitations of its time.

(1) The Theory of Speculation is based on the basic assumption of a continuous-time model, which, although seemingly self-evident then, could be more rigorous as modern quantitative finance has shown that economic variables such as market prices change discretely over time.

(2) The Theory of Speculation assumes that asset price changes always follow a lognormal distribution, making large price changes difficult to occur. However, due to the influence of dividend payments, interest rate changes, and other factors, asset prices often have large and extreme price changes, and the lognormal distribution of price changes only sometimes holds.

(3) Bachelier's reasoning is based on the premise that markets are always efficient and players are always rational. This premise is too idealistic to fit the reality. First of all, markets are not always perfect, and unexpected events, such as financial crises, natural disasters, wars, etc., can cause markets to fall into a state of abnormal operation. Market participants could be more perfectly efficient. Modern praxeology emphasizes that human behavior is not necessarily rational and that speculation in unusual circumstances and impulse trading need to be considered [4].

Overall, Louis Bachelier's theory suffers from overly simplistic and idealistic assumptions. This is limited by his time's outdated theoretical level and research methods. However, as a pioneer, The Theory of Speculation has laid a profound theoretical foundation for quantitative finance and has had a great influence on subsequent research. The stochastic analysis method he introduced has greatly influenced the subsequent research in quantitative finance. For example, the Black-Scholes-Merton model uses stochastic differential equations, which is similar to the Theory of Speculation. Fama's Market Efficiency hypothesis in 1970 is also regarded as the continuation and development of Speculation Theory.

3. Harry Markowitz's Modern Portfolio Theory (MPT)

3.1. Theoretical Basis

In 1952, economist Harry Markowitz published the paper "Portfolio selection", which proposed the Modern Portfolio Theory (MPT). MPT is a mathematical framework for seeking risk minimization. Based on the assumption that investors are usually extremely risk averse, MPT proposes that investors should choose a number of assets with low correlation to invest, and maximize the expected rate of return under a certain level of risk through diversified investment choices [5].

The innovation of MPT is that it abandons the single idea of measuring the risk and return of assets in isolation, and instead evaluates the risk and return under the framework of multi-asset portfolio. It is the first time to give an innovative method of investing the asset portfolio as a portfolio, so that investors can balance the risk and return more scientifically. In addition, MPT introduces the concept of efficient frontier to provide a method to match investors with different risk preferences with appropriate investment strategies. Until now, the idea of portfolio is still adopted. Most modern investors will use the portfolio as the guiding idea, and use the portfolio of low correlation assets to invest.

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3.2. Criticism

(1) Like Louis Bachelier's theory of speculation, MPT is based on a random walk model that assumes a normal distribution of asset returns. However, this assumption is inaccurate and lacks theoretical verification. Modern investment theory has proved that asset returns vary greatly from the normal distribution.

(2) MPT uses covariance to evaluate portfolios, which requires a large number of parameter estimates and cannot be strictly used as a single factor to measure risk. While index models use market exposure to greatly simplify this calculation, postmodern portfolio theory also adds downside risk, possibility of loss, and other dimensions to evaluate portfolios more comprehensively [6].

(3) Similar to Louis Bachelier's theory of speculation, MPT also overestimates the degree of rationality of investors by simply assuming that investors are risk averse. In reality, however, at a given time, investors often exhibit a gambler's mentality of following popular investments in pursuit of high returns and ignoring risks. In these cases, MPT cannot be applied.

(4) MPT does not propose a solution to systemic risk. Although MPT proposes methods to use portfolio management to manage special risks, at the macro level, MPT does not offer any help to the systemic problems of the market as a whole, such as ESG and allocation mechanism, and does not propose relevant solutions to help investors solve related problems. In fact, the environmental, social, and governance issues in the macro environment have greatly affected the investment market.

In general, MPT is also in the framework of the random walk model, and with its over-idealized assumptions, MPT has many of the same similarities and flaws as Louis Bachelier's theory of speculation. However, MPT is partially inherited from Louis Bachelier's speculation theory. Unlike Louis Bachelier's speculation theory, which focuses on the price change of a single asset, MPT focuses on the risk-return allocation of a multi-asset portfolio. MPT is the second revolutionary theory in the field of quantitative finance after Louis Bachelier's speculation theory. It provides the framework for many subsequent investment theories, which can use more advanced algorithms and conceptual improvements based on MPT. For example, Sharpe's Capital Asset Pricing Model (CAPM) is developed from MPT. It introduces two concepts of market risk premium and systemic risk of assets, further enriching the connotation of the risk concept.

4. William Sharpe's Capital Asset Pricing Model (CAPM)

4.1. Theoretical Basis

In 1964, William Sharpe published the paper "CAPITAL ASSET PRICES: A THEORY OF MARKET EQUILIBRIUM UNDER CONDITIONS OF RISK, in which the Capital Asset Pricing Model (CAPM) was proposed, which was based on some assumptions and inferences of MPT. It is used to determine and calculate the required rate of return of assets corresponding to systemic risk, and to help investors make reasonable diversified portfolio allocation [7]. CAPM also introduces the concept of Sharpe ratio, which is used to measure the extra return brought by investors for each unit of extra risk. This index simply and intuitively describes the ability of investment risk to compensate for the rate of return.

4.2. Criticism

(1) The beta calculated through the traditional CAPM is a constant value. However, subsequent studies have successfully tested that beta values can change over time, so the output results often deviate from reality.

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(2) Too single. CAPM only takes the market portfolio factor as the factor affecting the change of asset return, which makes CAPM difficult to explain and effectively predict the complex multi-factor market.

(3) Like MPT, CAPM is based on the idealized assumptions of a stable market and rational participants but ignores the irrational behavior of participants and the impact of short-term market fluctuations.

(4) It is in conflict with the efficient market hypothesis. CAPM believes that expected returns can be estimated, but efficient markets believe that all information has been reflected in the price. The expected return of assets is difficult to predict. Empirically, the CAPM's forecast data often contradict the efficient market hypothesis, such as the unusually high returns of low-beta stocks [8].

4.3. Supplement of the CAPM by the Fama-French Three Factor Model

In 1992, Eugene Fama and Kenneth French proposed the Fama-French Three Factor Model. This model calculates returns based on three factors: market risk, the performance gap between high-value and low-value stocks, and the performance gap between large and small companies. Unlike the CAPM, which applies a single factor, market, the three-factor model takes into account both size and price risk [9]. As a supplement to CAPM, this model can explain more portfolios and further improve CAPM.

CAPM further expounds the rational allocation method of investment portfolio under the framework of MPT theory, which is the development and supplement of MPT theory. CAPM is also the first successful risk pricing model in the field of quantitative finance, which refreshed people's understanding of the relationship between risk and return. Compared with previous theories, CAPM systematically explains the impact of systemic risk on return for the first time. Although the oversimplified mathematical model is controversial, the subsequent three-factor model successfully complements the CAPM.

5. Eugene Fama's Market Efficiency Hypothesis

5.1. Theoretical Basis

Bachelier, who first developed the concept of efficient markets in his 1900 book The Theory of Speculation, argued that market prices already contain information about the past, present, and future, but that price changes are unaffected. In 1970, Eugene Fama's Efficient Capital Markets: A Review of Theoretical and Empirical Work carried on Bachelier's random walk theory and systematically refined the EMH. EMH revolves around the main idea that "markets are efficient". It holds that asset prices already contain all the effective information, all the known information has already adjusted the price to the current level, and investors have no chance to make profits in the long run by analyzing the known information [10].

5.2. Criticism

(1) The strong EMH is based on the premise that all information in the market is open and transparent. But in fact , information asymmetry is common in the market, and some market participants tend to have more information, and thus obtain more investment returns. In this case, market prices often do not reflect such information differences.

(2) Many value investors use experience to criticize EMH. They argue that some successful investors use past market data statistics, business changes, industry outlook analysis, etc., to successfully predict the direction of prices and obtain long-term returns. These counterexamples

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prove that EMH is not valid. The representative example is investor Warren Buffett, who refutes the EMH with the example that most of the world's top performing fund managers are value investors.

(3) The EMH holds that investors earn above-average returns because they are temporarily lucky. However, this conclusion is difficult to justify because it is hard to test and falsify.

(4) Behavioral finance holds that market participants tend to behave irrationally, while EMH is too general and inaccurate to assume that participants behave rationally. For example, the herding behavior of investors during the 2008 financial crisis proves this point.

(5) The efficient market hypothesis ignores the risks of financial bubbles and puts too much faith in the market's ability to adjust itself. For example, the efficient market hypothesis fails to provide a reasonable explanation for the 2008 financial crisis [11].

Fama's Market Efficiency hypothesis inherits Bachelier's random walk theory and, on this basis, brings a revolutionary understanding of markets, negates market speculation, and enables investors to have a deeper understanding of the nature of investment markets. And made a large number of investors turn to passive index funds. Inevitably, the EMH is controversial because its overly radical theory and concise mathematical expression have triggered criticism from financial theories such as value investing theory and behavioral finance, which has also promoted the development of these two theories to some extent.

6. Black-Scholes Options Pricing Model

6.1. Theoretical Basis

In 1973, Fisher Black and Myron Scholes published their famous paper, The Pricing of Options and Corporate Liabilities. Constructed the Black-Scholes model, which ushered in the modern era of derivative securities. The Black-Scholes model aims to find a new way to determine the value of derivatives, in which the Black-Scholes equation is able to help the option seller find the unique correct option pricing [12].

The Black-Scholes model has been widely used since its introduction, not only because the output values are accurate and easy to calculate but also because the calculations are reversible and can be used to calculate other variables.

6.2. Criticism

(1) The Black-Scholes model needs to be more innovative. In essence, it uses the way of hedging options by constantly buying and selling the underlying assets to replace the risk to reconstruct the previous model.

(2) The Black-Scholes model cannot be used for the early exercise of American options. The Black-Scholes model is only applicable to European options that can only be exercised at the expiration date. The exercise time of American options is not fixed, so the Black-Scholes model cannot be used [13].

(3) The Black-Scholes model neglects the factor of stock dividend, which is a common and important factor in reality, which makes the Black-Scholes model prone to output error results.

(4) The Black-Scholes model is based on a large number of assumptions, such as risk-free interest rate, lognormal distribution of price, frictionless market, etc., and the application conditions are too many and strict, which affects the practicability to some extent.

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6.3. The Supplement of the Binomial Tree Model to the Black-Scholes Model

In 1979, Rose, Rubinstein and Sharpe et al. published the binomial tree model, designed to compute American options. The model uses a binary tree-like data structure, splits the maturity of the security, and then calculates the value of the option at each node from the historical volatility [14].

The binomial tree model not only takes stock dividends into account, which is not taken into account by the Black-Scholes model, but also can be flexibly applied to situations where the asset price changes do not conform to the normal distribution. More importantly, the assumptions of the binomial tree model are far less than those of the Black-Scholes model, which makes it easier to calculate and more general. The use of this model is complementary to the Black-Scholes model for calculating European options. It makes up for many important shortcomings of the Black-Scholes model, so it is also regarded as a supplementary model of the Black-Scholes model.

The Black-Scholes model is a major innovation in pricing theory in quantitative finance. Under the influence of Bachelier's random walk model, stochastic differential equations are successfully applied to pricing theory. The Black-Scholes model still has some defects, such as a small scope of application and inaccurate calculation results due to insufficient parameters. However, the binomial tree model further supplements and improves the Black-Scholes model through its stronger universality and simpler operation. Together, the binomial tree model established the theoretical framework of the option pricing model, made the use of mathematical models in finance reach its peak, and paved the way for the rise of financial engineering in the 1990s.

7. The Development Status of Quantitative Financial Theory Research

From 1950 to 1980, quantitative finance experienced a period of rapid development of core theories and a large number of research results in the axis period. During this period, the core theories of quantitative finance tended to be mature, and the research prospects were close to saturation. Since 1980, the development speed of quantitative finance theory has gradually slowed down, but some achievements have still been made in the collision and integration of other fields.

7.1. Financial Engineering

Financial engineering is the intersection of finance, mathematics, and computer science. It is one of the subfields of quantitative finance. This field focuses on the engineering of finance, the design and implementation of financial products to meet the needs of financial market participants.

The real systematic study of financial engineering began with the publication of the Black-Scholes model. The Black-Scholes model provided financial engineering with an easy way to price options, and financial engineering gained an important mathematical foundation.

Based on the Black-Scholes model and arbitrage pricing theory, financial engineering began to develop rapidly after 1980. Due to the slow progress of quantitative finance in pricing theory, financial scientists began to shift from mathematical deduction method to empirical research method to summarize and analyze financial markets. The representative work is Robert Engel's ARCH model, which is a model of empirical research in financial engineering.

After that, the stochastic discount factor was proposed, which made the understanding of market risk preference in financial engineering a step closer. Incomplete market general equilibrium theory has greatly improved the efficiency of resource allocation of social capital. Finally, John Finnerdy gave a general definition of financial engineering, and universities around the world began to offer financial engineering courses. Since then, financial engineering has become a prominent subject.

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7.2. Behavioral Finance

Behavioral finance is an interdisciplinary subject of finance, psychology, sociology, and other disciplines. It mainly studies the decision-making rules of financial market participants.

After 1980, the abnormal situation in the financial market gradually increased, such as the 2008 financial crisis, the classical financial theory was greatly affected, which directly led to the rise of behavioral psychology to explain the abnormal market behavior and gradually formed a mature theoretical system through the criticism of the classical financial theory.

Around 2000, behavioral portfolio theory and behavioral asset pricing model were put forward. They correspond to modern portfolio theory and modern asset pricing model, respectively, and they are supplemented by behavioral psychology. According to behavioral portfolio theory, expected wealth and prob are the key parameters to measure the asset allocation of the portfolio. On the basis of CAPM, the behavioral asset pricing model further subdivides investors and enriches the asset pricing framework. After a long period of development, behavioral finance has become the next important sub-discipline of quantitative finance, and it is an indispensable test method for financial theory.

7.3. Machine Learning

The breakthrough of machine learning technology in the field of computer science in the 21st century has also brought an impact on the field of quantitative finance. Machine learning is based on the induction and simulation of a large amount of historical data, which is very suitable for quantitative finance disciplines that need efficient statistical tools to summarize historical data for market prediction [15].

First of all, although machine learning is still difficult to predict rising stocks, it can help screen out poor performing stocks, which can help reduce the investment risk of investors, especially stable investors, who are more likely to benefit from it. Second, portfolios can be optimized more rationally. Machine learning can more efficiently screen out the optimal asset allocation scheme in different situations,

Machine learning also has stronger information collection ability and information analysis ability, which can collect and analyze the latest industry news and industry sentiment for the first time to help investors make correct investment decisions [16].

8. Conclusion

The history of quantitative finance, emerging in 1900, unfolds in three distinct phases: the budding period (1900-1952), the axis period (1952-1973), and the differentiation period (1973 to the present). The budding period saw the birth of quantitative finance with Louis Bachelier's theory of speculation, but its recognition was delayed until the 1950s. The tumultuous backdrop of two world wars and the Great Depression contributed to a lack of influential theories during this time. The axis period marked rapid development from Harry Markowitz's Modern Portfolio Theory to the Black-Scholes options pricing model. This era witnessed the birth of financial engineering and behavioral finance, and theories like the efficient market hypothesis and the Capital Asset Pricing Model emerged, leading to conflicts and confrontations. The differentiation period, from 1973 onwards, followed the theoretical boom of the Axis era. Core theories became saturated, leading to a decrease in new models. Quantitative finance expanded into interdisciplinary fields such as financial engineering, behavioral finance, and the integration of statistics. The rise of machine learning and artificial intelligence in the 21st century brought new developments, emphasizing the discipline's divergence and extension into other realms.

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The development of quantitative finance faces several challenges. Most notably, theories often rely on idealistic assumptions, like the rational player hypothesis, leading to biased results when applied to real-world situations. The neglect of extreme financial events and over-reliance on historical data further hinder the adaptability of models to future scenarios. Moving forward, the paper suggests addressing these challenges. Researchers should critically evaluate assumptions, test theory applicability in extreme situations, and avoid overfitting models to past data. The outlook on quantitative finance foresees major technological breakthroughs with the rise of artificial intelligence, enhancing accuracy and complexity. However, the theoretical level may experience a different level of advancement. Additionally, the paper predicts a focus on sustainable strategies in quantitative finance, aligning with the growing emphasis on environmental, social, and governance (ESG) governance.

In summary, the paper provides a comprehensive analysis of the historical phases of quantitative finance, highlights major challenges, and offers suggestions for future research. The anticipated breakthroughs in artificial intelligence and the increasing focus on sustainable development strategies are identified as key trends shaping the future of quantitative finance.

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