



Smart Manufacturing and ESG Performance Synergy: New Engine of Competitive Advantage for Enterprises

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Abstract. This article takes manufacturing enterprises as the research object and focuses on the impact of ESG (Environmental, Social, and Governance) and intelligent manufacturing on the competitiveness of enterprises. Currently, the academic community mostly assumes a strong correlation between ESG performance and the competitiveness of enterprises, but there is a lack of in-depth verification. Through empirical analysis, this study explores how ESG performance and the level of intelligent manufacturing affect the competitiveness of enterprises and further discusses the path of their transformation into enterprise value. The study finds that companies that focus on the development of intelligent manufacturing and have good ESG performance generally have more competitive advantages. Based on this, targeted suggestions are provided for manufacturing enterprises to enhance their competitiveness and achieve value appreciation, helping enterprises to achieve a win-win situation of economic and social benefits in the wave of sustainable development and digital transformation.

Keywords: ESG performance, smart manufacturing, competitive advantage, technological integration, sustainable transformation

1 Introduction

Amidst the global transition towards sustainable development and intelligent manufacturing transformation, manufacturing enterprises are confronting unprecedented opportunities and challenges. On the one hand, the rising awareness of environmental protection, proliferation of corporate social responsibility paradigms, and continuous refinement of policy frameworks have collectively elevated Environmental, Social, and Governance (ESG) considerations as indispensable determinants in corporate development. Concurrently, the global community has reached an unprecedented prioritization of green and sustainable development principles, rendering ESG performance enhancement particularly critical for enterprises. This paradigm shift compels manufacturers to strategically align operational practices with sustainability imperatives while navigating technological advancements in intelligent production systems [22].

Existing research has extensively investigated multiple factors influencing corporate ESG performance, including CEO political orientation [3]; environmental determinants

[15]; peer effects [25]; administrative monopoly regulations [9] and business diversification [1]. However, while academia and industry conventionally equate superior ESG performance with enhanced corporate competitiveness, this presumption lacks rigorous theoretical substantiation. The intrinsic linkages and operational mechanisms between these two dimensions remain insufficiently explored, necessitating systematic investigation into how ESG excellence translates into competitive advantages through quantifiable pathways and boundary conditions.

By collecting the data which reflects the changes in the number of R&D personnel responsible for manufacturing enterprises since 2005 from CNKI [19]. It can be observed that the number of people has been increasing year by year and has shown significant fluctuations from 2010 to 2013. In addition to the aforementioned ESG performance, intelligent manufacturing, as a core driver of industrial transformation and upgrading, is profoundly reshaping production models and operational efficiency in the manufacturing sector [23]. Leveraging advanced technologies such as big data, artificial intelligence, and the Internet of Things [6], intelligent manufacturing enables automation, intelligent optimization, and precision management of production processes, thereby enhancing productivity, reducing operational costs, and improving product quality [7]. Nevertheless, significant research gaps persist regarding the synergistic impact of ESG and intelligent manufacturing on corporate competitiveness. Existing studies have yet to sufficiently address critical questions: how these two dimensions interact and mutually reinforce each other in enhancing competitive advantages, and how the resultant competitiveness can be effectively translated into tangible corporate value. A systematic exploration of their interconnected mechanisms and value-creation pathways remains imperative for both theoretical advancement and practical implementation.

Based on this, this paper takes the manufacturing industry as the starting point. By collecting and comparatively analyzing specific data such as the profits of 100 enterprises, it deeply explores three issues: how ESG performance affects corporate competitiveness; what role smart manufacturing plays in the relationship between ESG and corporate competitiveness; and how enterprises can transform the combined advantages of the two into their own sustainable corporate value. The aim of this research is to assist enterprises in achieving a win - win situation of economic and social benefits in the wave of sustainable development and digital transformation, and gaining a competitive edge in the fierce market competition.

2 Literature Review

2.1 Theoretical Basis of Intelligent Manufacturing

Intelligent manufacturing, as an emerging form of production paradigm, synergistically integrates cutting-edge information technologies, including the Internet of Things (IoT), big data analytics, cloud computing, artificial intelligence (AI), and the Industrial Internet, with advanced manufacturing techniques [6] which can be applied to intelligent factories, intelligent supply chains and intelligent services [12]. This integration enables the production process to achieve a high level of intelligence, flexibility, and

efficiency [7]. Beyond the mere application of technologies, it places a strong emphasis on the holistic collaborative optimization of the entire manufacturing ecosystem and sustainability [18], aiming to enhance overall productivity and competitiveness in the global market.

The concept of smart manufacturing originated in the United States and has now attracted the attention of more and more countries and various industries around the world. It is characterized by five features: context awareness, modularity, heterogeneity, interoperability, and composability, integrates eleven technologies and has three enabling factors [12]. One of the prominent trends in intelligent manufacturing is servitization, endowing it with the characteristics of interoperability and platform independence [17]. In the future development process of smart manufacturing, it will promote the innovation and integration of more technologies. In addition to the in-depth application of artificial intelligence, technologies such as 5G and the Tactile Internet will continue to be deeply integrated with manufacturing technologies, enabling the interconnection of devices, the intercommunication of data, and the interoperability of systems [13], so as to create an intelligent production system. Smart manufacturing provides the manufacturing industry with a series of new technologies and data, which helps to enhance efficiency and flexibility. Meanwhile, it also creates challenges to both academic and industrial sectors, namely, how to better transform theories into practices and overcome theoretical obstacles [13].

2.2 Theoretical Basis of ESG Performance

ESG performance encompasses three main dimensions: environment, society, and governance [15], and it represents the sustainable development capability of an enterprise [25].

ESG performance can comprehensively evaluate a company's management capabilities from these three dimensions, reflecting its ability and consciousness to assume social responsibilities [15]. In terms of the environmental dimension, it encompasses the response to climate change, the efficiency of resource utilization, as well as pollution and waste management, which determine whether the company has the ability to survive in the long term [24]. Regarding the social dimension, it includes aspects such as employees' rights and benefits, product liability, and community relations, etc. [14], which can demonstrate the company's responsible attitude towards employees and consumers. In the aspect of governance, it includes the structure and independence of the board of directors, the protection of shareholders' rights and interests, anti-corruption and compliance, and the prevention of behaviors such as commercial bribery [16].

There are multiple factors that can influence ESG performance, including CEO political orientation, where ideological leanings may shape corporate decisions on environmental investments and social responsibility fulfillment [3]; determinants related to the natural surroundings such as regional ecological carrying capacity and the strictness of environmental regulations, which compel operational adjustments to meet sustainability requirements [15]; peer effects driving inter-firm learning and benchmarking in ESG practices through industry competition and mimicry [25]; administrative monopoly regulations that standardize corporate conduct and shape ESG outcomes via

competitive equity frameworks [9] and business diversification that enhances sustainability performance across ESG dimensions [1].

ESG performance has an impact on a firm's financial performance and long-term competitiveness in multiple aspects. The positive impacts include, for instance, facilitating the establishment of a sustainable development strategy and model for the enterprise, enhancing corporate value, strengthening the brand image and reputation, and being conducive to attracting and retaining talents. The improvement of ESG performance can help enterprises obtain more investments, thereby promoting corporate innovation, enhancing competitiveness and corporate value [25]. However, there may also be some negative impacts, such as the backlash from "greenwashing" behaviors [8]. ESG performance may cause the enterprise to incur excessive expenditures in some less crucial aspects. For example, allocating funds to improve the external environment may lead to a decline in the enterprise's competitiveness [25].

2.3 The Synergistic Effect Between Smart Manufacturing and ESG Performance

There are various synergistic effects between intelligent manufacturing and ESG performance at the levels of environment, society, and corporate governance. At the environmental level, intelligent manufacturing, through the intelligent energy management system, can monitor and analyze energy consumption data in real time, precisely regulate the operation of equipment, and achieve energy optimization. Scholars found that by combining big data analysis, additive manufacturing, and sustainable intelligent manufacturing technologies, a sustainable intelligent additive manufacturing framework that can fully control the energy consumption and quality of products can be developed, which contributes to energy conservation and emission reduction [11]. Previous studies have proposed a technology that enables remote monitoring of raw material storage and transportation [4]. That is to say, by utilizing advanced sensor and data analysis technologies, intelligent manufacturing can accurately monitor and predict the consumption of raw materials, allowing enterprises to achieve procurement based on demand. This can reduce waste and improve the utilization rate of resources. The environmental requirements within ESG prompt intelligent manufacturing enterprises to research and develop more environmentally friendly technologies and processes, such as the development of more efficient energy-saving equipment and the promotion of the application of renewable energy in production, driving enterprises to transform towards green manufacturing. In order to meet the ESG environmental standards, enterprises need to invest funds in pollution control, energy conservation and emission reduction, etc. [20], but this also brings new opportunities.

At the social level, intelligent manufacturing reduces the opportunities for employees to engage in dangerous and repetitive work and lowers the labor intensity and safety risks. At the same time, enterprises require employees to master a higher level of technology and knowledge [2], providing more opportunities for skill improvement and career development. With the help of intelligent detection equipment and big data analysis, intelligent manufacturing can monitor the entire life cycle of products, promptly

identify and solve quality problems, and safeguard the rights and interests of consumers. For example, the intelligent production line of an automobile manufacturing enterprise can ensure product quality through automated detection equipment and visual recognition systems. It can also accelerate the research and development process and enhance the competitiveness of the enterprise [10]. The development of intelligent manufacturing can drive collaborative innovation among upstream and downstream industries, create new job opportunities, and employment growth in the industry [5]. For instance, the use of new energy in automobile manufacturing can drive employment growth in industries of components such as electric motors and related service industries. Enterprises with good ESG performance can have a better reputation, gain a larger number of loyal consumers, and attract high-quality talents to adapt to the development needs of smart manufacturing to assist enterprises in enhancing their intelligent manufacturing technologies.

In terms of corporate governance, the smart manufacturing system can achieve real-time data collection and sharing, promote the digital transformation of enterprises, enhance corporate transparency, and thus have an impact on the ESG performance of enterprises [21]. Smart manufacturing generates a large amount of data. By combining data analysis technologies, it provides comprehensive and accurate information support for corporate governance, helping the management to assess ESG risks and opportunities and formulate scientific strategic plans. To meet the needs of smart manufacturing, enterprises need to carry out reforms and innovations in aspects such as organizational structure and management processes, which helps to improve the corporate governance structure and enhance governance efficiency. When enterprise managers attach excessive emphasis on ESG performance ratings they will neglect certain more crucial aspects, or they may simply imitate the behaviors of peer enterprises [25], which will have an impact on the competitiveness of the enterprise.

3 Research and Results

3.1 Research Questions and Hypotheses

This study is guided by three main research questions. The first question is how ESG performance affects corporate competitiveness in the manufacturing industry. While previous research has indicated a potential positive relationship, the specific mechanisms remain unclear. For example, in terms of environmental aspects, it's uncertain how resource - use efficiency improvements driven by ESG initiatives translate into cost - based competitive advantages. Socially, the impact of employee - friendly ESG practices on customer loyalty and market share is yet to be fully explored. Governance - wise, the influence of sound ESG - related corporate governance on strategic decision - making and long - term competitiveness needs further investigation. The second question focuses on the role of smart manufacturing in the ESG - competitiveness relationship. Smart manufacturing, with its integration of advanced technologies like the Internet of Things and artificial intelligence, may act as a mediator or moderator. It could mediate by enabling better ESG practices implementation, such as more accurate carbon footprint tracking. As a moderator, the level of smart manufacturing adoption might

influence the effectiveness of ESG in enhancing competitiveness. For instance, in highly automated smart factories, ESG - related energy - saving measures may have a more significant impact on cost reduction and competitiveness. The third question is about how manufacturing enterprises can transform the combined advantages of ESG and smart manufacturing into sustainable corporate value. Even if ESG and smart manufacturing enhance competitiveness, the process of translating this into tangible value, like increased profitability and long - term growth, is not well - understood.

Based on these questions, three hypotheses are proposed. Hypothesis 1 posits that there is a positive and significant relationship between ESG performance and corporate competitiveness in the manufacturing industry. It is expected that higher ESG performance leads to greater competitiveness through cost savings, brand enhancement, and risk mitigation. Hypothesis 2 suggests that smart manufacturing positively moderates the relationship between ESG and corporate competitiveness. The adoption of smart manufacturing technologies is anticipated to strengthen the positive impact of ESG on competitiveness. Hypothesis 3 states that there is a definable pathway for manufacturing enterprises to transform the combined advantages of ESG and smart manufacturing into sustainable corporate value. Enterprises are hypothesized to be able to identify strategies, such as product differentiation and cost reduction, to achieve this transformation.

3.2 Data Sources and Research Methods

By collecting data such as the gross industrial output value, the number of patent applications, the number of R&D projects, the number of large enterprises, the total assets, the number of R&D personnel, and the total profit of Chinese manufacturing enterprises from CNKI and conducting a comparative analysis. According to the latest rating results of MSCI, a total of 100 enterprises belonging to the basic chemical industry, electronics industry, and mechanical equipment industry have been screened out and are closely related to this research. By collecting the total revenue in the first half of 2024, net profit, R&D investment and its proportion, the year-on-year growth rates of these indicators during the same period, and the return on assets of the enterprises. Among them, the proportion of R&D investment is calculated by dividing the R&D expenses by the total operating revenue, obtaining the proportion of R&D investment in operating revenue, which is also known as the intensity of R&D investment. This indicator reflects the proportion of funds invested by an enterprise in its operating revenue during a certain period for activities such as product R&D and technological innovation. Through this indicator, the degree of importance an enterprise attaches to R&D innovation and the level of its investment in R&D can be measured. Generally speaking, the higher the intensity of R&D investment, the greater the relative investment of the enterprise in R&D, the more attention it pays to technological innovation and product upgrading, and the stronger its possible innovation capabilities and development potential. By manually collecting and statistically aggregating data. The MSCI ratings are divided into seven levels in total, with the highest being AAA and the lowest being CCC. This essay represents ESG ratings from low to high using numbers 1-7. All ratings are the latest ones. The update date ranges from the second half of 2024 to the

beginning of 2025. Therefore, the data collected is from the first half of 2024. In this study, the total revenue, net profit and return on assets are used to represent the competitiveness of enterprises, while the R&D investment and its proportion are used to represent the intelligent manufacturing capabilities of enterprises. The year-on-year growth of R&D refers to the growth rate of the invested expenses, not the growth rate of the proportion.

3.3 Research Methodologies

This study aims to explore the relationships among ESG ratings, corporate financial performance, and R&D investment using the data collected from 100 manufacturing enterprises in the first three quarters of 2024. To achieve this, the methods of controlled variables and comparative analysis are employed.

Controlled Variable Method: In this research, when examining the influence of ESG ratings on corporate competitiveness (represented by revenue, net profit, and return on invested capital) and intelligent manufacturing capabilities (represented by R&D investment and its proportion), multiple variables need to be controlled. Industry type is a crucial controlled variable. Since different industries have distinct characteristics, such as different levels of technological intensity and market competition, enterprises from the basic chemical, electronics, and mechanical equipment industries are selected. By focusing on these specific industries, the impact of industry - specific factors on the relationships under study can be minimized. Another controlled variable is the economic environment. Although it is challenging to fully control the economic environment's complexity, data from the same time period (the first three quarters of 2024) are used. This ensures that all enterprises are affected by relatively similar economic conditions, reducing the interference of economic fluctuations on the analysis results. For example, during this period, factors like overall economic growth trends, interest rate levels, and inflation rates are consistent for all sample enterprises, allowing for a more accurate assessment of the relationships between ESG ratings, financial performance, and R&D investment.

Comparative Analysis: Comparative analysis is conducted in multiple aspects. First, enterprises with the same ESG rating are compared. By doing so, we can identify whether differences in other aspects, despite having the same ESG rating, lead to variations in corporate competitiveness and R&D investment levels. This helps to understand the role of non-ESG factors within the same ESG rating group. Secondly, enterprises with different ESG ratings are compared. Comparing high-rated enterprises and low-rated enterprises can reveal how ESG ratings are associated with corporate performance and R&D investment. For example, comparing the revenue growth rates, net profit margins, and R&D investment intensities of high - rated and low - rated enterprises can help determine whether higher ESG ratings are generally accompanied by better financial performance and more emphasis on R&D investment, which is crucial for verifying the impact of ESG performance on corporate competitiveness. In addition, the year - on - year growth rates of relevant indicators are compared. By observing how the growth rates of revenue, net profit, and R&D investment change with ESG rating

changes, we can determine whether there is a correlation between ESG rating fluctuations and the development trends of these indicators. By comparing the year-on-year growth rates of different data with the changes in ESG ratings can determine whether the changes in ESG ratings are related to the increase or decrease in a company's total revenue, net profit, and R&D investment. By using the controlled variable method and comparative analysis, it is possible to compare data from different companies with the same rating changes, or compare data from companies with different ratings, to determine whether a high ESG rating means that the company has a competitive advantage and places more emphasis on developing intelligent manufacturing technology.

Through the combined use of the controlled variable method and comparative analysis, we can more accurately explore the relationships among ESG ratings, corporate competitiveness, and intelligent manufacturing capabilities, providing strong evidence for the research conclusions.

3.4 Research Findings

Through the application of the controlled variable method and comparative analysis on the data of 100 manufacturing enterprises in the first three quarters of 2024, several significant conclusions have been drawn regarding the relationships among ESG ratings, corporate competitiveness, and intelligent manufacturing capabilities.

ESG Ratings and Corporate Financial Performance: Generally, a positive correlation exists between higher ESG ratings and better financial performance in terms of revenue and net profit. For example, among the enterprises with a relatively high ESG rating of 5, Foxconn Industrial Internet Co., Ltd has a revenue of ¥266.091 billion with a growth rate of 28.69% and a net profit of ¥8.739 billion with a growth rate of 22.04%. In contrast, some enterprises with a lower ESG rating like Loongson Technology, which has an ESG rating of 1, has a revenue of only ¥0.22 billion with a decline of 28.68% and a significant net loss of ¥ - 2.38 billion. However, there are also exceptions. Salcomp Precision Manufacturing Co.,Ltd, with an ESG rating of 5, has a net profit growth rate of - 44.53%, indicating that other factors besides ESG ratings also influence financial performance.

ESG Ratings and R&D Investment: Higher ESG - rated enterprises tend to invest more in R&D. Enterprises with an ESG rating of 4 or 5 often have a relatively high proportion of R&D investment. For instance, AMEC with an ESG rating of 4 has an R&D investment proportion of 28%, and Inovance Technology Co., Ltd with an ESG rating of 5 has an R&D investment proportion of 11.63%. This shows that companies with better ESG performance may recognize the importance of innovation through R&D to enhance their long - term competitiveness. However, the growth rate of R&D investment does not necessarily increase with the ESG rating. Some enterprises with lower ESG ratings also have significant R&D investment growth, such as Jiangsu Yoke Technology Co., Ltd with an ESG rating of 1, which has an R&D investment growth rate of 41.78%.

Impact of Rating Changes on Corporate Performance: An increase in the ESG rating is usually accompanied by positive changes in corporate performance indicators. For example, many enterprises with a rating increase from the previous period, like Supcon

Technology Co., Ltd with a rating change of 1, have shown growth in revenue (11.58%) and R&D investment (9.29%). On the contrary, a decrease in the ESG rating may be associated with less - favorable performance changes. Hangzhou Lion Microelectronics Co., Ltd, with a rating change of - 1, has a net profit decline and some fluctuations in other indicators.

Industry - specific and Comprehensive Analysis: Even within the same industry, enterprises with different ESG ratings show different levels of competitiveness and R&D investment. In the electronics industry, enterprises with higher ESG ratings are more likely to have stable revenue growth and sufficient R&D investment to support technological innovation. However, the return on invested capital does not always directly correspond to the ESG rating. Some enterprises with high ESG ratings may have a relatively low return on invested capital, suggesting that other aspects such as cost control and market competition also play important roles in determining this indicator.

Intelligent manufacturing and ESG performance do not exist in isolation but are intertwined and mutually reinforcing, jointly shaping corporate competitiveness. On the one hand, relying on advanced technologies and efficient production processes, intelligent manufacturing not only improves the efficiency of resource utilization but also reduces energy consumption and waste emissions during the production process, providing strong support for enterprises to fulfill their environmental responsibilities. Moreover, through precise production scheduling and quality control, it enhances product quality and optimizes the customer experience, thereby strengthening the market competitiveness of enterprises. On the other hand, good ESG performance creates a positive internal and external environment for the advancement of intelligent manufacturing. Internally, it attracts and retains outstanding talents who are concerned about social responsibility, stimulates employees' innovative vitality, and provides intellectual support for the research, development, and application of intelligent manufacturing technologies. Externally, it enhances the corporate brand image and reputation, strengthens consumers' trust, expands market share, and creates favorable conditions for the market transformation of the achievements of intelligent manufacturing.

From the perspective of corporate competitiveness, the synergistic effect of the two is remarkable. In terms of economic competitiveness, intelligent manufacturing reduces costs and improves production efficiency, while ESG performance helps enterprises obtain policy support and optimize the financing environment, jointly enhancing the profitability and financial stability of enterprises. In terms of environmental competitiveness, the application of green technologies in intelligent manufacturing is deeply aligned with the environmental protection concept of ESG, promoting the sustainable development of enterprises and enabling them to effectively respond to increasingly stringent environmental regulations. In terms of social competitiveness, intelligent manufacturing creates high-skilled employment positions, and the fulfillment of social responsibilities in ESG promotes harmonious coexistence between enterprises and communities, enhancing the social recognition of enterprises.

3.5 Limitations

The limitations of this study are primarily reflected in the following aspects: Firstly, financial indicators such as total assets, net profit, and return on assets cannot fully capture the comprehensive competitiveness of enterprises, as they fail to account for critical non-financial factors such as brand value and talent quality. Additionally, net profit is susceptible to short-term market fluctuations and policy changes, and significant differences in asset structures and profit models across industries make it challenging to accurately assess competitiveness using uniform metrics for enterprises selected from only three industries. Secondly, high R&D expenditures do not necessarily indicate advanced technological applications, as there may be a disconnect between R&D investments and the actual level of intelligent manufacturing capabilities. Furthermore, the lack of robust data to demonstrate whether R&D expenditures have been successfully translated into tangible intelligent manufacturing outcomes and economic benefits further constrains the depth and breadth of this research.

4 Conclusion and Recommendations

In today's complex and dynamic business environment, this study focuses on the joint impact of intelligent manufacturing and ESG (Environmental, Social, and Governance) performance on corporate competitiveness. Through in-depth analysis and empirical research, the following key conclusions have been drawn: smart manufacturing and ESG performance are intertwined and reinforce each other, jointly shaping corporate competitiveness with a remarkable synergistic effect. Smart manufacturing, by leveraging advanced technologies, improves resource utilization efficiency, reduces energy consumption and emissions, and can also optimize product quality and the customer experience, thereby enhancing market competitiveness. Good ESG performance creates a favorable internal and external environment for smart manufacturing, attracting talents, enhancing the brand image, and expanding market share.

For enterprises seeking to translate competitive advantages into corporate value enhancement, the following strategic recommendations are proposed. Firstly, organizations should optimize resource allocation based on their unique resource endowments. With sufficient budget allocation, increased investment in environmentally sustainable production processes can improve energy efficiency through intelligent manufacturing technologies. This technological integration enables supply chain optimization and inventory backlog reduction, thereby decreasing operational costs and enhancing profit margins. Secondly, enterprises demonstrating superior ESG performance should proactively communicate their sustainable practices and achievements. This strategic disclosure facilitates brand equity enhancement through improved corporate reputation, which attracts environmentally-conscious consumers and enables product premiumization. Such brand value creation effectively converts competitive strengths into tangible market advantages. Thirdly, corporations should prioritize talent acquisition strategies coupled with employee welfare improvement programs. Establishing innovative incentive mechanisms encourages workforce participation in R&D initiatives, particularly in intelligent manufacturing advancements. Concurrently, aligning product development

with ESG requirements enables the creation of sustainable products that meet evolving market demands. This dual focus on human capital development and ESG-compliant innovation supports market expansion and corporate value appreciation through technological leadership and sustainable growth achievement.

This study not only enriches the theory of corporate competitiveness but also reveals the internal mechanism of the synergistic effect between intelligent manufacturing and ESG performance. It also provides practical guidance for corporate strategic decision-making. Enterprises should organically integrate intelligent manufacturing and ESG strategies, formulate long-term development plans, and while pursuing economic benefits, take into account environmental and social responsibilities to achieve the comprehensive improvement and sustainable development of corporate competitiveness. Future research can further expand the sample scope and deeply explore the differences in the synergistic effects of the two among enterprises in different industries and of different sizes, so as to provide more targeted development suggestions for enterprises.

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