

# Approach towards Sustainable and Smart Coal Port Development: The Case of Huanghua Port in China

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**Abstract:** This paper focuses on measures towards sustainable development of coal ports based on the economic, environmental, and social dimensions of the triple bottom line, and examines the integration and optimization roles of smart technologies on coal port sustainability in the era of the Internet of Things. By investigating the representative case of Huanghua Port, one of the largest coal transportation ports in China, this paper enables a better understanding of the coal port's sustainable practices driven by smart technologies. This study provides measures on the intelligent renovation, coal dust pollution treatment, air pollution treatment and sewage treatment, the customer and employee satisfaction improvement, and community involvement as well as social reputation enhancement. The research investigates the effectiveness of measures on the coal port's sustainability by examining changes in key performance indicators and further examines the integration and optimization roles of smart technologies. The findings show that the approach taken by the port can effectively promote the coal port's sustainability. The intelligent operation control system linking the separate nodes in operation, the ecological intelligent control system integrating environmental protection functions, and the intelligent service platform linking supply chain members are interrelated and interact to achieve the continuous optimization of decisions towards coal port sustainability. This study offers managerial insights for the port operators and policymakers towards the sustainable and smart development of ports.

**Keywords:** port sustainability; coal port; smart port; triple bottom line; case study

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## 1. Introduction

As nodes in international transport networks, ports make a substantial contribution to regional and global economic development. Even though port operators strive for economic viability, increasing environmental awareness posits new challenges to the management and development of ports. Besides air pollution and noise pollution, there are also severe pollutions from the goods themselves, such as coal dust pollution, coal-containing sewage, and chemical pollution in coal ports. The Sustainable Development Goals (2030 UN Agenda) bring forward a higher requirement for the growth of ports. A total of 17 goals related to poverty, environmental degradation, economic growth, oceans, peace, and other critical elements are proposed to achieve a more sustainable future. In pursuit of port sustainability, an increasing number of researchers and practitioners have recognized the crucial role of the triple bottom line principle in port management. According to the triple bottom line, sustainability is achieved when environmental, economic, and social responsibilities are integrated, which underlines the balance between the planet (the ecological system), profit (the economic system), and people (the social system) [1–3]. Therefore, sustainable development is challenging ports around the world to evaluate the impacts of their current operations and find ways

of improving economic, environmental, and social performance and minimizing negative impacts [4,5]. This paper focuses on approaches towards the coal port's sustainability and investigating the role of smart port development in it.

With respect to economic efficiency, the role of intelligent renovation and port expansion in economic performance is gaining more attention. The environmental aspect is focused on the reduction of environmental pollution and the recycling of resources by the port operation. Furthermore, waste recycling in ports brings forward a higher requirement for environmental-friendly operations of the port. The social dimension emphasizes balanced and sustained relations with the port's stakeholders, i.e., its stockholders, employees, customers, local communities, etc. [6]. Embedding corporate social responsibility concepts in port management has emerged as a critical concern [7].

The smart port is related to the improvement of port productivity and efficiency by adopting an automated system using technologies including the Internet of Things, big data, automation, and eco-friendly technology [8,9]. Smart technologies have become the dominant information technology paradigm and have been applied to the port industry with the advent of the fourth industrial revolution. Examples of projects related to smart ports in the era of the Internet of Things can be found from Europe to Asia, to Australia, and to North America [10]. The smart port has the advantages of high-productivity and energy saving; thus the smart port construction can be a feasible way to achieve the development of the sustainable port. The smart technology-driven business process redesign should be planned strategically by the port operators with the participation of the port stakeholders.

In light of these concerns, the objective of this research is to investigate the measures to improve the sustainability of coal ports in the era of the Internet of Things and examine the integration and optimization roles of smart technologies in port sustainability to provide managerial insights for the port operators, supply chain members, and policymakers. The case study method is widely used to discuss the issue of port sustainability development [2,6,9]. This paper reports the representative case of Huanghua Port, one of the largest and fastest-growing coal ports in North China, which widely adopted technologies based on the Internet of Things over the last few years. Specifically, we analyze the port's intelligent renovation of production operations, and the environment treatment of coal dust pollution, air pollution, and sewage, and the port's social efforts on customer satisfaction improvement, employee satisfaction improvement, community involvement, and social reputation improvement, as well as the integration and optimization roles of smart technologies. By analyzing changes of key performance indicators in economic, environmental, and social dimensions, we further examine the effectiveness of measures taken by Huanghua port in enhancing coal port sustainability.

The contributions of this research are twofold: theoretically, this paper enriches current studies on port sustainability by investigating the sustainable development strategies of coal ports and showing the role of smart technologies in promoting port sustainability; practically, it highlights the managerial implications on sustainable and smart coal port construction in the era of the Internet of Things based on the practical experience of Huanghua Port.

The paper is organized as follows. Following the introduction section, the literature review on port sustainability and smart ports is presented in Section 2. Section 3 discusses the case of Huanghua Port from the aspects of location, economic performance, environmental protection, and social efforts, as well as the roles of smart technologies. Section 4 analyzes the future development of Huanghua Port and provides managerial implications for the government and port operators on port management. Finally, conclusions are drawn in Section 5.

## 2. Literature Review

This research is closely related to two areas of literature: port sustainability and smart ports. We review them below.

### 2.1. Port Sustainability

Due to the great environmental impact and social influence from port operations, increasing attention has been drawn to port sustainability from the academia. Dinwoodie et al. (2012) propose a business process framework to identify strategic, tactical, and operational levels of sustainable management in ports, which provide principles to identify relevant inputs, processes, and outputs in the environmental management [11]. Denktas-Sakar and Karatas-Cetin (2012) propose a conceptual framework to identify the influence of supply chain stakeholders on port sustainability from the viewpoint of the social dimension based on the resource dependence theory [7]. They show that the port's ability to exploit inter-organizational long-term relationships with supply chain stakeholders is one of the most critical prerequisites for port sustainability. Based on this, our research highlights the collaboration among supply chain members in reaching sustainability. Yap and Lam (2013) adopt a longitudinal approach to examine the growth path exhibited by the container ports of Shanghai, Singapore, Hong Kong, and Shenzhen, discussing sustainability issues in port and coastal development [12]. They show that the port will face greater complexities with the increase in throughput and that there are negative externalities leading to environmental and social problems. Therefore, it is necessary to further investigate the interactions among increasing throughput and environmental approaches. Drobetz et al. (2014) construct a corporate social responsibility disclosure index for listed shipping companies and show the positive correlation between corporate social responsibility disclosure and the firm's financial performance [13].

Asgari et al. (2015) investigate the sustainability performance of five major UK ports, considering both the economic and environmental dimensions by use of questionnaires and the Analytic Hierarchy Process (AHP) method [5]. The criteria they selected in the environmental aspect, such as waste management, energy consumption, and risk management, as well as the cost-efficiency in the economic aspect, can offer insights for our research. Puig et al. (2015) analyze the current status and trends of the environmental performance of European ports, showing that air quality, port waste, and energy consumption emerged as the three major environmental priorities of the European port sector in 2013 [14]. Therefore, the air quality, port waste, and energy consumption should be paid more attention by researchers when developing port sustainability. Kuznetsov et al. (2015) assess the sustainability needs and propose a port sustainability management system for smaller ports in Cornwall and Devon within a UK case-study context [2]. They provide 11 dimensions of port sustainability, such as environmental management, stakeholder engagement, business planning, and management. Davarzani (2016) reviews the past and present research on green ports and maritime logistics using rigorous bibliometric and network analysis tools [15]. Hou and Geerlings (2016) investigate sustainability measures and their effectiveness in the Port of Shanghai case, highlighting that the biggest challenge for the transition to a sustainable port is to develop new governance arrangements [3]. They shed light on sustainable port and hinterland operations that should be considered as an organizational issue.

Sislian et al. (2016) integrate port sustainability indicators in the ocean's carrier network problem [16]. Roh et al. (2016) explore the economic, social, and environmental dimensions of sustainable port development through interviews with port authorities, and discuss the challenges and opportunities for Vietnamese ports [4]. They list the internal and external management criteria for port sustainability, throwing light on our research. Laxe et al. (2016) address the methodological development to calculate the port sustainability synthetic index in the Spanish port system [17]. They highlighted the performance in the economic and environmental dimensions. Laxe et al. (2017) use a global synthetic index of sustainability, covering the full scope of sustainable development, to assess the port sustainability in the case of Spanish ports [18]. They further incorporate elements of employment, training, gender equality, and health into the global synthetic index. Wang et al. (2017) investigate customers' port services expectations through a port sustainable services decision model in the context of Ningbo port, China [19]. They provide implications on strengthening relationships between the port and its neighboring cities and enhancing business attractiveness for greater sustainability.

Di Vaio et al. (2018) develop a set of managerial key performance indicators for port authorities on air pollution and waste management processes, and then investigate their applicability based on case studies of Italian ports [20]. Langenus and Doooms (2018) propose an inter-organizational network for sustainable development in the ports industry based on a virtual learning model [21]. They propose the necessity of a net broker as the coordinator among stakeholders of the sustainable network. Vejvar et al. (2018) use institutional theory and the case study approach and show that although inland ports are inclined to social sustainability, economic benefits are still most accentuated, and environmental issues are mostly regarded in conformity to the legally mandated minimum [6]. Thus it is critical to motivate the port to improve the awareness and take action on environmental protection. Wan et al. (2018) establish a quantitative evaluation model of green port development based on the Drivers, Pressures, States, Impacts, and Responses (DPSIR) framework, and demonstrate this model through a comparative analysis of five major ports in China [22]. Woo et al. (2018) investigate the impact of environmental policies on the cost–benefit structure in a port [23]. In our research, we will also pay attention to the cost of approaches towards sustainability and the benefits they bring.

Schipper et al. (2015) focus on no-impact port development, which means that the port's development exerts no negative impact on the ecosystem. They analyze the influence of port development on the ecosystem and imply that the negative impacts of port development should be minimized [24]. The research emphasizes that factors related to port location, morphology, ecosystem services, governance, and socio-economics should be comprehensively evaluated in sustainable port development. García-Onetti et al. (2018) emphasize that port management should include both its socio-ecological influences and its consequences on the coastal environment. They propose an integrated and ecosystem-based port environmental management system [25].

Based on the above-mentioned literature, we endeavor to investigate approaches towards the coal port's sustainability from the economic, environmental, and social dimensions. Since the Huanghua Port's coal throughput ranked first in China in 2016 and it has made a big achievement in sustainable port development and intelligent renovation, we use the case study method and adopt the representative case of Huanghua Port to discuss measures towards sustainability of coal port and examine their effectiveness and influences.

## 2.2. Smart Port

With the development of the Internet of Things, a growing area in academic research is focusing on smart ports. Siror et al. (2011) study the design and operation of an intelligent model of a port based on the Radio Frequency Identification (RFID) technology, describing the architecture, devices, functions, and workings of this system [26]. They find implications on how to enable intelligence of the port. Girard (2013) proposes a circularized smart development model in port areas and uses the historic urban landscape approach to manage changes towards a circular model [27]. They highlighted the principles of synergy, creativity, and circularization in the smart sustainable development of port areas. El-sakty (2016) discusses the criteria and key performance indicators guiding the evaluation of smart ports, involving the energy utilization rate of the main energy-using equipment, application of energy-saving and low-carbon technology, and the carbon intensity of port equipment, showing the challenges and obstacles in transformation into smart seaports [28]. They provide guidance in the selection of indicators related to the evaluation of smart port. Ferretti and Schiavone (2016) investigate the impacts of Internet of Things technologies on business processes redesign based on the case study of the German Port of Hamburg, showing that the smart technologies widely redesign and enhance the performance of all main business processes of the German seaport [9]. In this paper, we will also examine the influence of intelligent renovation on economic performance. Jun et al. (2018) examine the economic impacts of the smart port industry on the Korean national economy using the Delphi survey and input–output analysis [8]. Furthermore, Yang et al. (2018) investigate technologies and challenges in the adoption of the Internet of Things for smart ports [10]. They show that smart sensing and Internet of Things technologies will exert significant influences on future port development.

Based on these researches, we examine the adoption of smart technologies in coal ports, and the integration and optimization roles of smart technologies in promoting the sustainable development of coal ports. To summarize, Table 1 contrasts the most relevant literature to this paper and positions our research.

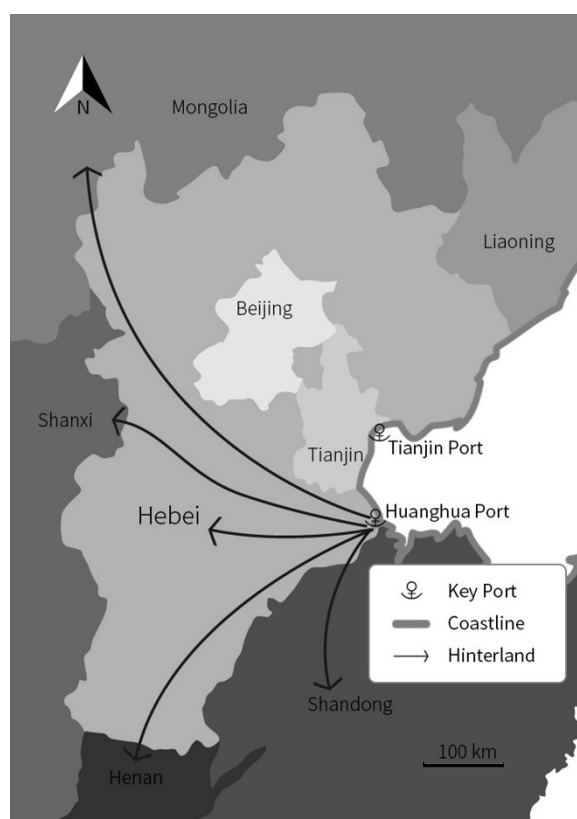
**Table 1.** Summary of the most relevant literature.

Authors	Port Sustainability			Smart port	Focus	Methodology
	Economic Dimension	Environmental Dimension	Social Dimension			
Yap and Lam (2013)	√	√	√		Sustainability issues in port development	Longitudinal approach
Asgari et al. (2015)	√	√			Sustainability ranking of major UK ports	Analytic Hierarchy Process (AHP) method and case study
Kuznetsov et al. (2015)	√	√	√		Sustainability management system for smaller ports	Case study
Roh et al. (2016)	√	√	√		Sustainable development for Vietnamese ports	Semi-structured interviews with data analysis
Ferretti and Schiavone (2016)				√	Process redesign in ports based on the Internet of Things	Case study
Jun et al. (2018)	√			√	Economic impacts of the smart port industry on economy	Input–output analysis
Vejvar et al. (2018)	√	√	√		Strategic responses to institutional forces towards sustainability	Case study
This Research	√	√	√	√	Smart sustainable development of port	Case study

### 3. The Case of Huanghua Port

#### 3.1. Port Location

Huanghua Port, located in the southeastern part of Hebei province, is a major coal hub in Bohai Bay in northern China. Its hinterland covers areas including central and southern Hebei Province, central and southern Shanxi Province, northern Shandong, northern Henan, and Inner Mongolia. The location of Huanghua Port and the corresponding hinterland are shown in Figure 1. Huanghua Port contributes largely to the efficiency of hinterland connections. It is also the nearest coal transfer port for Shaanxi and Inner Mongolia. Huanghua Port thus became the crucial channel for the country's coal shipping from western production areas to end-users in the eastern and southern coastal provinces and has emerged as one of China's largest coal export ports. As one of the main ports in Hebei province, the Huanghua port is essential to the collaborative development of the Beijing–Tianjin–Hebei metropolitan region.



**Figure 1.** Location of Huanghua Port.

Huanghua Port contains four port areas, namely the coal port area, the comprehensive cargo port, the bulk cargo port area, and the estuary port area. This paper focuses on the sustainable development of the coal port area, which is mainly operated by Shenhua Huanghua Harbor Administration Corporation, with 17 coal berths, two general cargo terminals, and one oil terminal. The coal port area has a coastline of 12.5 km ready for development and construction, a land area of 11.65 square kilometers as shown in Figure 2, and a water area of 12.35 square kilometers as shown in Figure 3.



**Figure 2.** Land area of the coal port area of Huanghua Port.



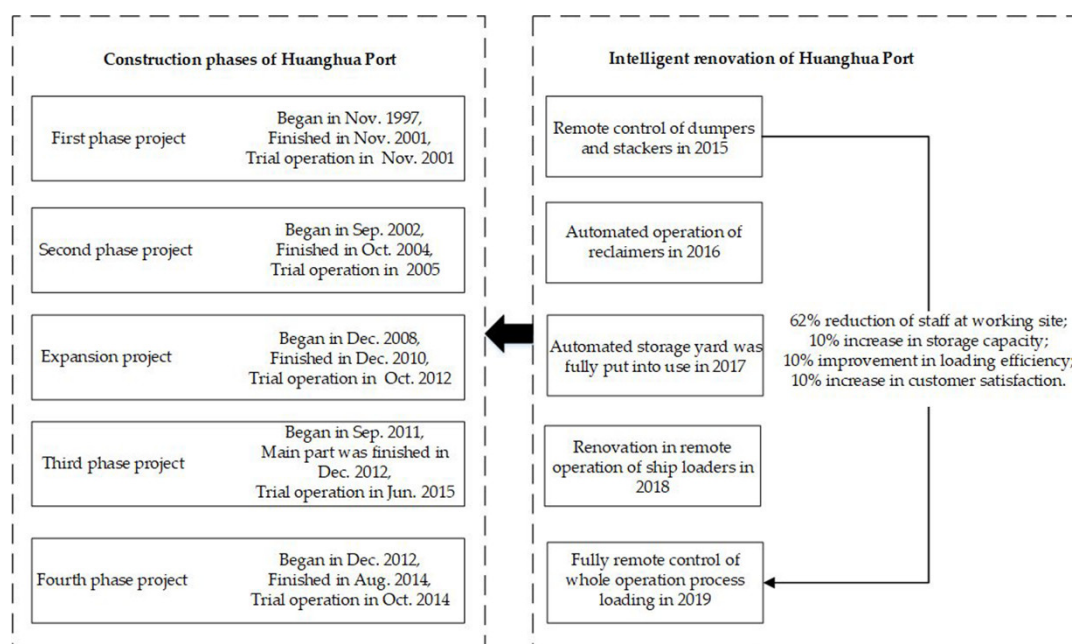
**Figure 3.** Water area of the coal port area of Huanghua Port.

We will investigate the measures that Huanghua Port has taken to improve the port sustainability from the economic, environmental, and social aspects. We propose key performance indicators to examine the effectiveness of these measures and further examine the roles of smart technologies in port sustainability.

### *3.2. Economic Development Aspects of Sustainability*

Transforming the traditional port into a smart port has become an important way of enhancing the comprehensive capabilities of the port and achieving sustainable development. A series of innovative measures have been adopted in Huanghua Port on the production operation. The processes of construction and intelligent renovation on operations are shown in Figure 4. We chose the handling efficiency, energy consumption, port throughput, and port revenue as the key performance indicators of the economic performance of Huanghua Port.





**Figure 4.** Construction phases and intelligent renovation in the operations of Huanghua Port.

Figure 4 shows that the construction of Huanghua Port can be divided into four phases and the expansion of the first and second phases' projects. The first production department (D1) and second production department (D2) of Huanghua Port were responsible for the production operations in the first phase's project and second phase's project, respectively. Huanghua Port strives to utilize advanced technologies to improve working efficiency and to reduce energy consumption. In 2015, by use of Internet of Things technologies, such as wireless communication technology and vehicle terminal bar code technology, a system to exchange data throughout the port was installed. The port has carried out an intelligent renovation in projects of the first and second phases, which was completed at the end of 2016.

The third and fourth phases played an important role in the production operation of the entire port. There are 48 silos, four ship loaders, 288 activated feeders, eight unloading trolleys, and four car dumpers in the project of the third phase. The third production department (D3) that is in charge of this project undertook nearly half of the port's operation tasks. The project of the fourth phase consists of two sets of unloading systems with corresponding real-time clean production control systems. On the basis of the maturity of the automation control system in the third and fourth phases, the corresponding production management system was also continuously improved. Through the development of the interface program for central control, the port has realized the data transmission between the control system and the management system, as well as functions such as uploading operations information and issuing process instructions. The intelligent reports can be generated according to specific production operations, providing decision support for the production.

Specifically, the main items of equipment such as dumpers, stackers, reclaimers, and ship loaders in the port have their own independent operation rooms. Huanghua Port has designed a central control system to integrate the separate nodes in the past operation process in 2017. The whole process is controlled by computers in the control center. The duty supervisor is responsible for the overall control, and the dispatcher acts as the bridge between the loading instructor and the unloading instructor. The unloading instructor informs the central control dispatcher to release the unloading task after the train arriving at the port, while the loading instructor delivers the loading task to the control center after the ship safely berths. The central system informs ship loaders to complete the instructions. All of the unloading, stacking, and fetching of coal in the third and fourth phases have realized remote automatic operation, with the staff issuing instructions by mobile phones and computers. It not only significantly improved production efficiency but also saved energy consumption. The energy consumption for operations in the coal port area of Huanghua Port in each quarter (i.e., Q1, Q2, Q3, Q4) of the year 2017 is shown in Table 2.



**Table 2.** Energy consumption of coal operations in Huanghua Port in each quarter of the year 2017.

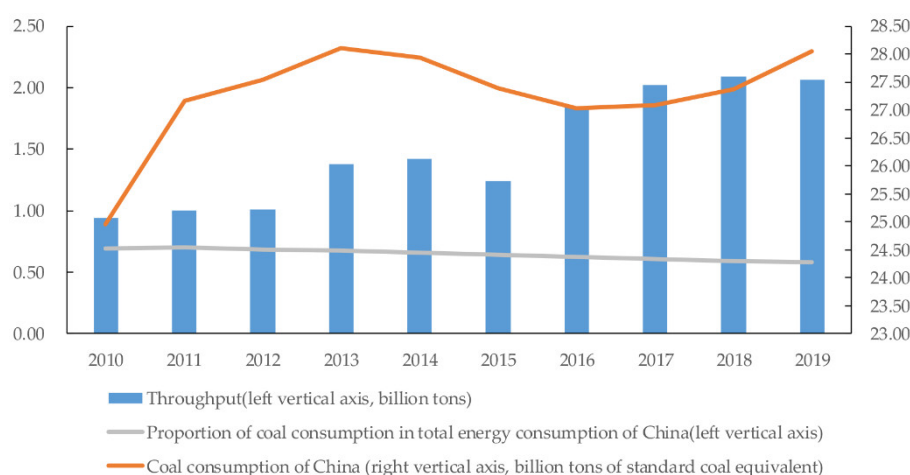
	Department	Operations	Power Consumption (MWh)	Handling Volume (1000T)	Tons Consumption (KWh/T)	Total (KWh/T)
Q1, 2017	D1	unloading	4900	9464	0.52	1.15
		loading	7690	12,236	0.63	
	D2	unloading	8154	15,338	0.53	1.12
		loading	6734	11,451	0.59	
	D3	unloading	15,194	23,087	0.66	1.09
		loading	10,244	23,899	0.43	
Q2, 2017	D1	unloading	4459	9132	0.49	1.12
		loading	7065	11,187	0.63	
	D2	unloading	7779	15,423	0.50	1.07
		loading	6456	11,380	0.57	
	D3	unloading	15,413	24,364	0.63	1.05
		loading	10,327	24,970	0.41	
Q3, 2017	D1	unloading	4719	9649	0.49	1.13
		loading	7711	12,112	0.64	
	D2	unloading	7992	15,888	0.50	1.08
		loading	6625	11,445	0.58	
	D3	unloading	15,392	24,115	0.64	1.05
		loading	10,210	24,707	0.41	
Q4, 2017	D1	unloading	4841	9246	0.52	1.19
		loading	7570	11,320	0.67	
	D2	unloading	8695	15,965	0.54	1.13
		loading	7000	11,871	0.59	
	D3	unloading	16,157	24,682	0.65	1.08
		loading	10,733	25,342	0.42	

Table 2 shows that the handling volume (both unloading and loading) of the third production department (D3) was almost equivalent to the total handling volume of the first and second production departments (D1 and D2) in each quarter. The reason is that all the operations of D3 are automatically controlled by the central control system and it is easy to collect energy consumption information, as mentioned above; while part of the operations in D1 and D2 are semi-automatic and disconnected. It is worth noting the corresponding total power consumption of D3 is smaller than the total of D1 and D2 in each quarter, and the total power consumption per ton of D3 is the smallest one. Therefore, Table 2 implies that Huanghua Port has reduced energy consumption, benefiting from the exploitation of smart technologies in production operation.

Huanghua Port has been cooperating with the Australian expert team and Tianjin Port in facility upgrading and sustainable smart port construction, developing the transformation of a smart loading system to realize the automatic identification of ships' draft and the automatic operation of ship loading. In 2019, Huanghua Port has achieved the full remote control of the whole operation process, which means all operations from the arrival of the train to the loading of coal on the ship can be controlled by the remote computer. The port overcomes the challenge of remote centralized control of ship loaders, for which the loading operations are usually irregular due to different shapes and loading tonnages of ships. According to preliminary calculation, the port storage capacity and handling efficiency have increased by more than 10% due to the automatic planning and handling. Unloading efficiency reaches 4600 tons per hour. This implies that the annual throughput will increase by 10 million, bringing the benefit of 200 million. By the end of 2019, the Huanghua Port had

automatically operated 596.52 million tons of coal in the stacking and reclaiming process, and loaded 124.20 million tons of coal with remote control.

The throughput of coal area in Huanghua Port and the amount and proportion of coal consumption of China during the years from 2010 to 2019 are shown in Figure 5. In this figure, the data of throughput are sourced from the Shenhua Huanghua Harbor Administration Corporation; the data on coal consumption are sourced from the China 2019 Statistical Yearbook [29]. Figure 5 shows that the port's throughput in 2019 has increased by 66% since the intelligent renovation began in 2015. The coal consumption of China also increased from 27.38 billion tons of standard coal equivalent (coal with a calorific value of 7000 kilocalories per kilogram) in 2015 to 28.04 billion tons of standard coal equivalent in 2019. The proportion of coal consumption in total energy consumption of China shows a downward trend, which is largely due to the policy of energy structure optimization in China. It is noted that the throughput in 2019 is slightly lower than that in 2018, and there are three main causes for this phenomenon. First, the project of changing fuel from coal to natural gas in China led to a decrease in downstream customers of Huanghua Port. For instance, among the customers of Huanghua Port, many factories located in southern China have converted from coal to natural gas. Second, the project of cutting overcapacity in the coal industry caused a reduction in upstream customers. For example, the government closed a number of small coalmines with low efficiency and heavy pollution problem. Third, the debugging of the automatic control system on ship loaders also affected the increase of throughput from January 2019 to April 2019. Therefore, although the handling efficiency was improved after achieving full automation of operations in 2019, the throughput was decreased compared to that in 2018. Figure 5 implies that since the pollution treatment in 2012 and the intelligent renovation in 2015, the port throughput has increased significantly. The increasing coal throughput benefited from the significant enhancement of efficiency through intelligent renovation.



**Figure 5.** Throughput of Huanghua Port, amount and proportion of coal consumption in China from 2010 to 2019.

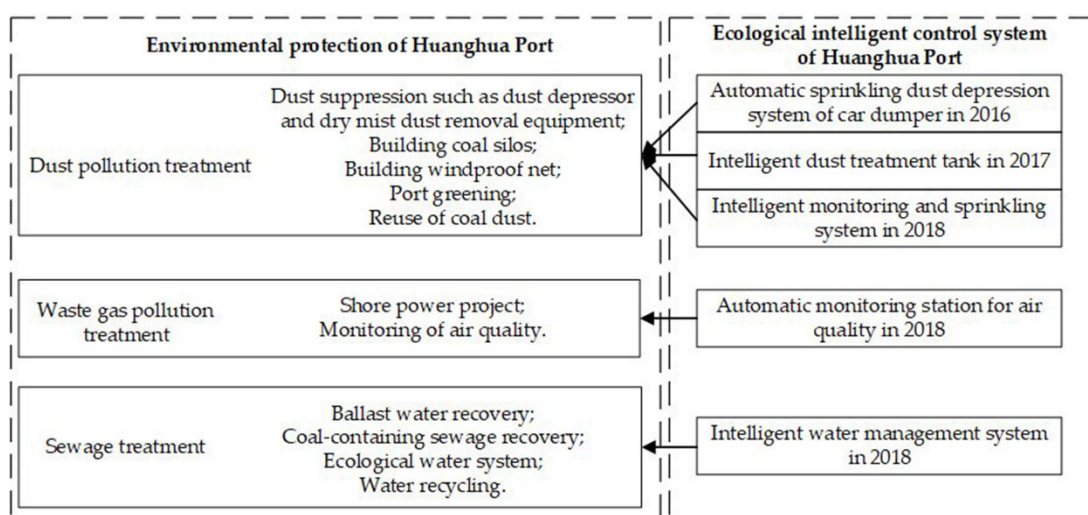
The revenues of Huanghua Port in the period from the year 2010 to the year 2019 are given in Table 3. Table 3 shows that since the completion of the intelligent reconstruction project in 2016, the port's revenue has been promoted significantly. In combination with the increase in port throughput from the year 2015 to the year 2019 as shown in Figure 5, it is demonstrated that intelligent renovation can effectively promote the port's productivity and profitability. Currently, the port is at the forefront of the Chinese port industry in automatization and intelligence.

**Table 3.** Revenue of Huanghua Port in the period from 2010 to 2019.

Year	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Port revenue (billion RMB)	2.13	2.3	2.38	3.08	3.14	2.78	3.96	4.72	4.76	4.55
Year-on-year change (%)	N/A	8.0	3.4	29.4	1.9	−11.1	42.4	19.2	0.8	−4.4

### 3.3. Environmental Development Aspects of Sustainability

Pollution from port operations will not only damage the ecological balance of nature but also further increase the risk associated with port operations. Since the environmental challenges in the coal port area of Huanghua Port are especially severe in comparison to other port areas, we mainly focus on the environmental protection ways adopted by the coal port area of Huanghua Port, which is a typical representative of coal-handling ports in China. The measures taken on environmental protection with the adoption of smart technologies are shown in Figure 6. Driven by the Internet of Things technologies and big data analysis, Huanghua Port put forward the ecological intelligent control system, which has realized the intelligent management of environmental perception, analysis, and prediction as well as environmental governance. We selected the coal dust concentration, the air pollution index, and sewage recovery amount as the key performance indicators of environmental performance and will discuss the environmental protection measures in detail.

**Figure 6.** Environmental protection with the adoption of smart technologies in Huanghua Port.

#### 3.3.1. Dust Pollution Treatment

Dust pollution is one of the biggest problems facing coal ports. In the operation of car dumpers, the coal is dumped into the funnel at a relatively high speed, generating heavy dust in the semi-closed space and diffusing to the top of the funnel. After materials fall on the belt conveyor running at high speed, massive dust will be produced in the process of coal transportation under the force of airflow and spread all around. To protect the environment and ensure the health of workers, Huanghua Port has taken the following measures to overcome the dust pollution problem.

First, by means of benchmarking management, using the Port of Newcastle, Australia as the target for benchmarking, Huanghua Port analyzed their dust suppression sprinkler systems and developed a series of technologies on dust suppression in 2016. For example, in addition to the widely used dust depressor and dry mist dust removal equipment, Huanghua Port innovatively implements the car dumper automatic sprinkling dust depression system. Starting with the coal unloading, the sprinkling system operates automatically according to the surface moisture of the coal. The sprinkler is installed in the feeder machine at the bottom of the dumper, facilitating the mixture of the water mist and the coal in the process of vibrating the feeder. Additionally, the sprinkler can function

normally in winter since the temperature of the water mist is always above zero. This automatic sprinkling dust depression system has been successfully applied to all dumpers in the port, and this system was awarded China's National patents.

With the adoption of smart technologies, Huanghua Port established the ecological intelligent control system in 2018. Driven by the big data analysis, the platform predicts the optimal sprinkling and dust suppression plan in advance based on the real-time monitoring of air and water quality at each monitoring point. Based on the plan, the control system automatically controls the dust suppression sprinkler equipment and realizes the accurate dust suppression.

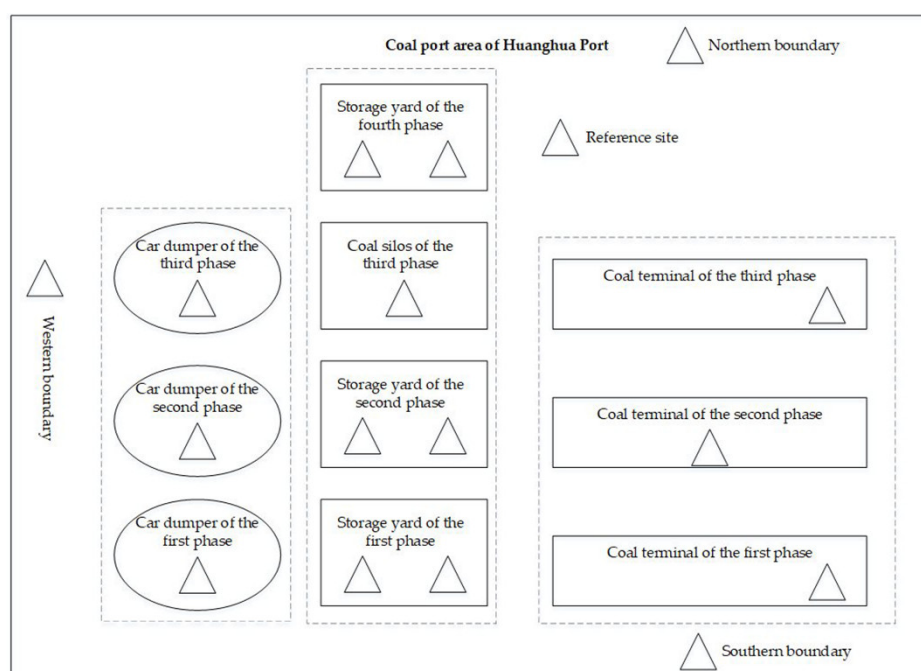
Second, the port has built 48 closed coal silos in the third and fourth phases of coal port construction, each of which is 40 m in diameter and 43 m in height. With a total capacity of 1.44 million tons, this group of coal silos is the largest in Asia. As the coal transfer station in the port, these silos have the advantages of small area coverage, high automation level, and being rainproof, windproof, and erosion-proof, which guarantees the quality of coal. They also effectively avoid producing dust in stacking and taking materials, and significantly reduce the dust emission compared with open storage yards. Therefore, the coal is dumped into the funnel by the dumper with dust suppression equipment, then discharged into the coal storage silos through the enclosed conveyer-belt corridor, and finally loaded into the ship's hold by the ship loader.

Third, a windproof net with a length of 10,176 m and a height of 23 m, as a useful tool to control the diffusion of dust, is placed around the coal silos. Designed with herringbone steel support, the windproof net has a retaining wall in the bottom and a windproof screen on the top, covering all of the storage yards. More than 90% of coal dust in the bulk coal storage yard can be isolated from outside. The wind speed in the coal yard area can be effectively reduced by controlling and improving the airflow fields.

Fourth, in the road outside the windproof net, large road sweepers and sprinklers work regularly as an auxiliary means to prevent dust spillover and secondary dust pollution. The green land and gardens in the surrounding of the windproof net form the unique control system of the Huanghua Port. The greening rate in the coal port area of Huanghua Port has reached 31.3%. Reaching 1.21 million square meters, the greening area not only decreases the wind speed in the yard but also realizes the effective absorption of dust.

In order to realize the reuse of coal dust, Huanghua Port invested in research and development and constructed the intelligent dust treatment tank, which was officially put into operation at the end of 2017. This intelligent facility can convert the coal dust collected by the sweeper and coal slime deposited in drains into coal. It was found that when the ratio of water and coal dust is 7:3, the coal-containing sewage can be pressed into coal for resale. The project is expected to handle about 50 tons of coal dust per day, generating 30 RMB per ton of dust handled. This project successfully produces good ecological benefits by avoiding secondary dust pollution and brings the economic benefit of more than 0.5 million RMB per year. The investment in the intelligent dust treatment tank was about 15 million RMB, which implies that the static capital recovery cycle is 30 years. It is beneficial to sustainable development from both the environmental aspect and the economic aspect in the long run.

To show the effectiveness of the above measures, we selected four observation areas in the coal port area and 17 observation points in the coal port area of Huanghua Port, which are shown as triangles in Figure 7.



**Figure 7.** Map of the observation points in the coal port area of Huanghua Port.

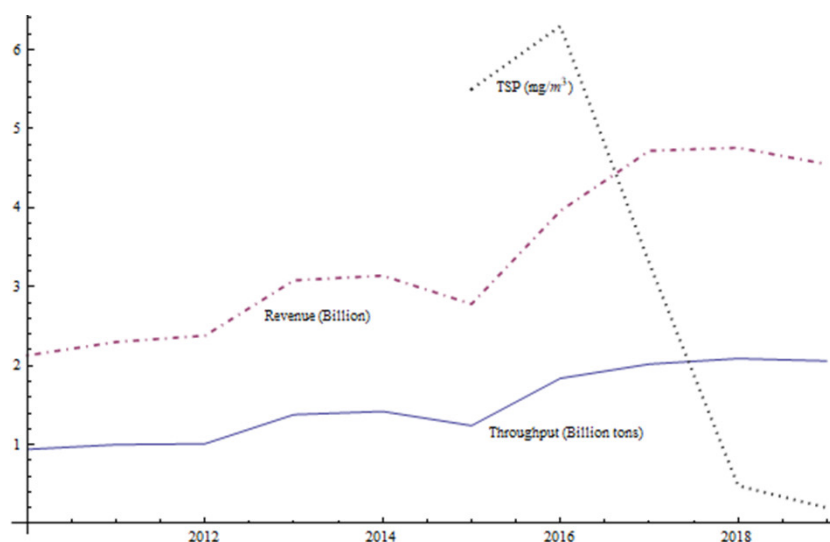
Before the building of coal silos, the dust concentration was in the range of 10 to 20 mg/m<sup>3</sup> in the open storage yard in 2012, according to the manager of Huanghua Port. It may even exceed the national dust emission standard (15 mg/m<sup>3</sup> according to JT 464-2001 of China). After the 48 closed coal silos and the windproof net were fully put into use in 2015, the range of dust concentration was decreased to 5 to 10 mg/m<sup>3</sup> in 2015 and 2016. With the car dumper automatic sprinkling dust depression system fully put into use in 2017, the dust concentration was in the range of 1 to 4 mg/m<sup>3</sup>.

Since the ecological smart control system was built at the end of 2017, the automatic dust monitoring system was put into use. Using TSP (Total Suspended Particles) as the dust concentration indicator, in 2018, the average dust concentration near the storage yard significantly fell to 0.48 mg/m<sup>3</sup>. In 2019, the dust concentration was further reduced to around 0.20 mg/m<sup>3</sup>. It implies that since 2018, the dust emission had been well controlled. The dust concentration at each observation area in March 2020 is shown in Table 4. Table 4 demonstrates that the dust concentrations after taking measures are far below than the national dust emission standard, reflecting the effectiveness of the adopted measures.

**Table 4.** Dust concentration at each observation area with dust pollution treatment in March 2020.

Observation Area	Number of Observation Points	Mean Dust Concentration (mg/m <sup>3</sup> )	Range of Dust Concentration (mg/m <sup>3</sup> )	Qualified Point
Storage yard	7	0.10	0.01–0.18	7
Coal terminal	3	0.14	0.13–0.15	3
Car dumper	3	0.14	0.11–0.17	3
Boundary	4	0.11	0.03–0.16	4

To visually show the relationship between the environmental improvement and the economic performance, we took the average TSP of the storage yard as an example to examine the evolutions of the throughput and revenues and changes of dust concentration, as shown in Figure 8. Figure 8 implies that the environmental measures that Huanghua Port took can effectively reduce the dust emission despite the throughput increases. The revenue has a great improvement when the dust concentration significantly decreases.



**Figure 8.** Evolutions of throughput, revenue, and dust concentration in the coal port area of Huanghua Port. TSP: Total Suspended Particles.

### 3.3.2. Air Pollution Treatment

In order to reduce emissions of pollutants such as sulfur dioxide and nitrogen oxides, the Huanghua Port adheres to the green development plan and vigorously promotes the construction of the shore power project. Shore power is the connection of a berthed ship to the area electricity grid in order to be able to shut down its own generators. The International Maritime Organization (IMO) reported that the shipping industry emits about 0.94 billion tons of carbon dioxide in 2012, accounting for approximately 2.2% of global carbon dioxide emissions [30]. Supplying power to ships by shore power instead of diesel generators can effectively reduce the emission of carbon dioxide, sulfur dioxide, and nitrogen oxide, as well as the noise pollution of ships. Huanghua Port took the advantages of shore power technology in the control of air pollutant emissions and noise reduction, which brought considerable environmental benefit.

At the end of 2017, 11 berths for handling coal in the Huanghua Port supplied shore power to all ships there, accounting for 78.57% of the 14 shore power berths in Hebei Province. For example, the average utilization rate of a berth was around 67% (3600 h of using the shore power system/5400 h of berth occupancy) in the year 2018. The coal port area of Huanghua Port has become the port with the largest total power supply capacity in China, striving to decrease the impact of ships' daily operations on the coastal environment.

To further monitor air quality, Huanghua Port built an automatic monitoring station for air quality in the operation area. Through the monitoring of indicators such as nitrogen dioxide, sulfur dioxide, carbon monoxide, particulate matter (PM10 and PM2.5), the atmospheric conditions of the Huanghua Port can be readily available. For example, compared to the data in the year 2013 before the intelligent renovation, in 2017, the 24 h average daily level of the primary pollutants including sulfur dioxide, nitrogen dioxide, carbon monoxide, PM10, and PM2.5 in the core area decreased from 55 to 10; the ambient air pollution index changed from 100 to 50; and the air pollution index in peripheral areas changed from 150 to 60. Therefore, air pollution can be prevented with accurate analysis and source control.

### 3.3.3. Sewage Treatment

Another pollution problem in Huanghua Port is the treatment of coal-containing sewage. Since coal in traditional coal ports is piled up in the open air, some coal-containing sewage will be discharged into the sea during heavy rain. Additionally, the untimely drainage of sewage will cause storage yard waterlogging and interrupt the production process. To tackle the problem, Huanghua Port took the following measures.



On the one hand, the port accelerated the construction of the ecological water system consisting of four projects, i.e., the landscape lake, the artificial lake, and the south and north wetlands, and further reconstructed the sewage pipe network. By the control of valves, the interconnection among waterways can be realized to ensure the circulation of water. Even in extreme weather, all sewage can be stored internally. The sewage is transported to the sewage treatment station through pipelines, avoiding discharging the coal-containing sewage directly into the sea. The water reaching the standard after treatment is used for greening and dust suppression, the economic benefits of which are prominent. On the other hand, the port has built eight new ballast water recovery devices to maximize the recycling of ballast water, saving freshwater resources and satisfying the needs of sprinkling and irrigating.

Furthermore, an intelligent water management system was built to automatically deploy the water resources in order to form an intelligent ecological water circulation by effectively collecting, and reusing ballast water, coal-containing sewage, and rainwater. Taking the recovery of ballast water as an example, the system can analyze and predict the amount of ballast water recovery and the recovery time, through collecting information such as berthing schedule and ship drainage time. The system then offers the water transferring plan based on the water demand and the real-time status of each pump station for maximizing water recycling.

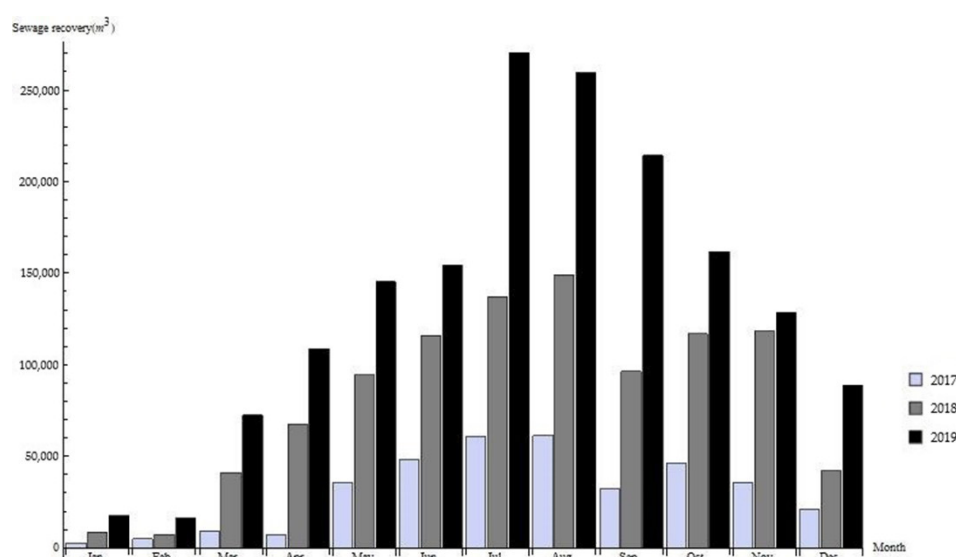
This system creates good environmental and economic benefits by saving water to the maximum level. On the one hand, it has greatly improved the quality of the ecosystem, turning the port area into a park, as shown in Figures 9 and 10. On the other hand, it brings tangible economic benefits as the initial investment of nearly 18 million RMB has been fully recovered in less than 3 years. In 2017, the Port had recovered 0.53 million tons of ballast water and reused 0.37 million tons of sewage, saving nearly 5 million RMB; in 2018, the Port had recovered 0.6 million tons of ballast water and reused 1 million tons of sewage, saving more than 7 million RMB; in 2019, the Port had recovered 0.98 million tons of ballast water and reused 1.64 million tons of sewage, saving about 11.5 million RMB. Taking the sewage as an example, the comparison of the sewage recovery of the same period in the last three years (the year 2017 to the year 2019) is shown in Figure 11. It visually demonstrates that the intelligent ecological water circulation system can effectively recycle the water resource and reduce the purchasing amount of water.



**Figure 9.** The coal port area before rehabilitation in 2010.



**Figure 10.** The coal port area after rehabilitation in 2019.



**Figure 11.** Comparison of sewage recovery of the same period in the last three years (2017–2019).

To conclude, the decreases in the coal dust concentration and the air pollution index and the increase of sewage recovery amount demonstrate that measures adopted in the port can effectively control pollution and promote the ecological environmental quality.

### 3.4. Social Development Aspects of Sustainability

Social efforts play a crucial role in determining the reputation and influence of the port [7]. In the following, we will provide a detailed analysis of the approaches to improving social performance. We adopt the customer satisfaction rate, the wage level, the employee's training, and the amount of social donation as key indicators to examine the social performance.

#### 3.4.1. Customer Satisfaction Improvement

To improve service quality and create greater value for customers, Huanghua Port developed an intelligent service platform by integrating offline services and online data. Connecting all links of the supply chain through the platform, ship owners can submit a port application online and inquire about the business process, as well as select service providers and monitor progress. Similarly, service providers can release information on services and make contracts online. Customers can obtain real-

time data of cargo, evaluate the service, and provide suggestions through the platform. Interaction of information on the business process and interchange of data on coal operations greatly improve the service quality of the port and enhance the user experience. The platform not only realizes the monitoring of personnel, vehicles, and operations but also facilitates the continuous optimization of business processes through the data analysis of the entire supply chain. According to the report published by Huanghua Port, the customer satisfaction rate improved from around 80% in 2015 to 96.4% in 2019.

### 3.4.2. Employee Satisfaction Improvement

Huanghua Port endeavors to not only create greater value for the enterprise and customers but to provide more benefits for its employees. The Port had about 900 employees in 2018. Port sustainability is closely related to the interests of employees.

First, the working environment and personal safety were improved. The clean production and pollution treatment with the use of smart technologies provide a better working and living environment for the employees. The pursuit of intelligent operation also reduces labor intensity. For example, two workers used to operate one machine, while one worker can now control several machines remotely. Additionally, the port provides sports facilities and organizes sports activities to encourage employees to participate and keep fit. The intelligent operation can avoid the risk of casualty accidents and improper manual operation.

Second, the salary level of the front-line operator has greatly improved. For example, the average basic wage for an operator in 2013 was around 4000 RMB, and it increased to 6000 RMB in 2016, and the average wage level was around 9500 RMB in 2019. Based on the annual inflation rate of China from the year 2014 to the year 2019 [31], we can derive that 6000 RMB in 2016 was equal to about 5690 RMB in 2013 and 9500 RMB in 2019 was equivalent to around 8440 RMB in 2013 after accounting for inflation. Therefore, the wage level of an operator in Huanghua Port has increased over the past six years when adjusted for inflation. Besides the basic wages, employees can also gain a performance-based bonus, and receive a holiday gift during Chinese traditional festivals.

Third, Huanghua Port has improved skills appraisal and training systems. The staff relieved from the site operation replenished the management and technical positions and obtained more opportunities in career development. Huanghua Port is committed to providing employees with the platform for self-fulfillment. As reported by Huanghua Port, the investment in employee training in 2019 was increased by 107% compared to that in 2015. Similarly, the number of participants in training has grown by 176% in 2019 compared to that in 2015.

### 3.4.3. Community Involvement

The port donates generously to charity every year, including cash, goods, and services. The port regularly supports the local poor students to accomplish their studies. Specifically, it donates tuition and living expenses to poverty-stricken students in Huanghua High School each year. Additionally, Huanghua Port donated 60 million RMB for fighting the COVID-19 epidemic in China, which was nearly 1% of the port revenue. In the past five years, the company has paid more than 3 billion yuan in taxes, making positive contributions to supporting local construction and serving local economic development.

Huanghua Port offered a train from the port to Cangzhou, allowing commuters as well as residents to travel on it for free. The train journey of 87 km takes one hour, reducing the use of private cars and facilitating the communities. This free service helps the port to enhance its strategic position, shorten the urban space distance, and attract investment in project construction. The approaches for pollution treatment improve the air quality and greening rate of the surroundings, thus enhancing the community's living environment.

In addition, Huanghua Port boosted the collaboration between the port and research institutes. For example, Huanghua Port and Beijing Jiaotong University carried out a strategic alliance for transforming theoretical achievements and promoting regional development. Huanghua Port and Yanshan University jointly built the research and practice base in 2016. Huanghua Port cooperates

with CCCC First Harbor Consultants Co., Ltd. in port expansion and intelligent renovation. The research institutes have a strong ability in scientific research and technology innovation, while the port has the advantages of transferring scientific research results into real production. On the basis of complementary advantages, the port and the research institute can promote pragmatic cooperation in sustainable port construction.

#### 3.4.4. Social Reputation Improvement

In January 2020, Huanghua Port was rated as a national AAA grade scenic spot of China. There are five grades from A grade to AAAAA grade according to the classification criteria of Chinese scenic spots, and Huanghua Port is the first industrial coal port to win this grade. The port will develop industrial tourism and show the charm of modern industrialization. This is a positive initiative to enhance the port's social influence, fulfill social responsibility, and give back to society.

The sustainable and smart development of Huanghua Port was approved by the National Development and Reform Commission of China, the Ministry of Transportation of China, Hebei provincial government, and other regional organizations. The port had held many conferences, such as the green port construction promotion meeting of Hebei Province, attracting many port enterprises. The social influence was improved significantly.

The increase of the customer satisfaction rate, the wage level, the employees' training and the amount of social donation, and the improvement of social reputation show that the efforts in the social dimension can effectively promote the port sustainability.

#### 3.5. Integration and Optimization Roles of Smart Technologies Towards Sustainability

In this section, we show the utilization of smart technologies in integrating dispersed nodes of Huanghua port and optimizing decisions of the port towards sustainability. Using the Internet of Things technologies and big data analysis, Huanghua Port established an intelligent operation control system, an ecological intelligent control system, and an intelligent service platform to realize real-time sensing, deep visualization, comprehensive integration, and intelligent decision-making. The intelligent control systems in Huanghua Port are shown in Figure 12.

In the intelligent operation control system and the seamless connection and coordination between control systems of reclaimers, car dumpers, ship unloaders, belt conveyors, stackers, ship loaders, and the central control system allow the port to make instant responses to instructions. Based on the vessel traffic information, coal types, and loading quantity information offered by the intelligent service platform, as shown in Figure 12, the central control system can make optimal production scheduling decisions, which include the berthing plan, unloading and loading plan, and storage plan. Moreover, using the data collected from separate control systems, the central control system can comprehensively evaluate the scheduling plan and adjust the decision-making models in order to continuously optimize the scheduling. The intelligent scheduling can enhance the working efficiency, as mentioned in Section 3.2, and reduce the storage period of coals. Since the moisture content of coals decreases with the storage period, a shorter storage period is conducive to alleviate the dust pollution problem.

Connecting all aspects of business operations and logistics activities, the data-driven intelligent service platform was established to improve service efficiency, service capacity, and service quality. The platform converts the information on the production process, cargo handling, and port services into quantifiable data, and realizes the overall monitoring of port activities. With the unified information access portal and data standard, the platform simplifies the business process and facilitates the coordination between different entities in the supply chain. Since all businesses can be conducted on the platform, the port can save both human resources and physical resources, and conveniently gain users' feedback. Through data mining and data analysis, the platform can facilitate business innovation, as well as continuous supply chain optimization.

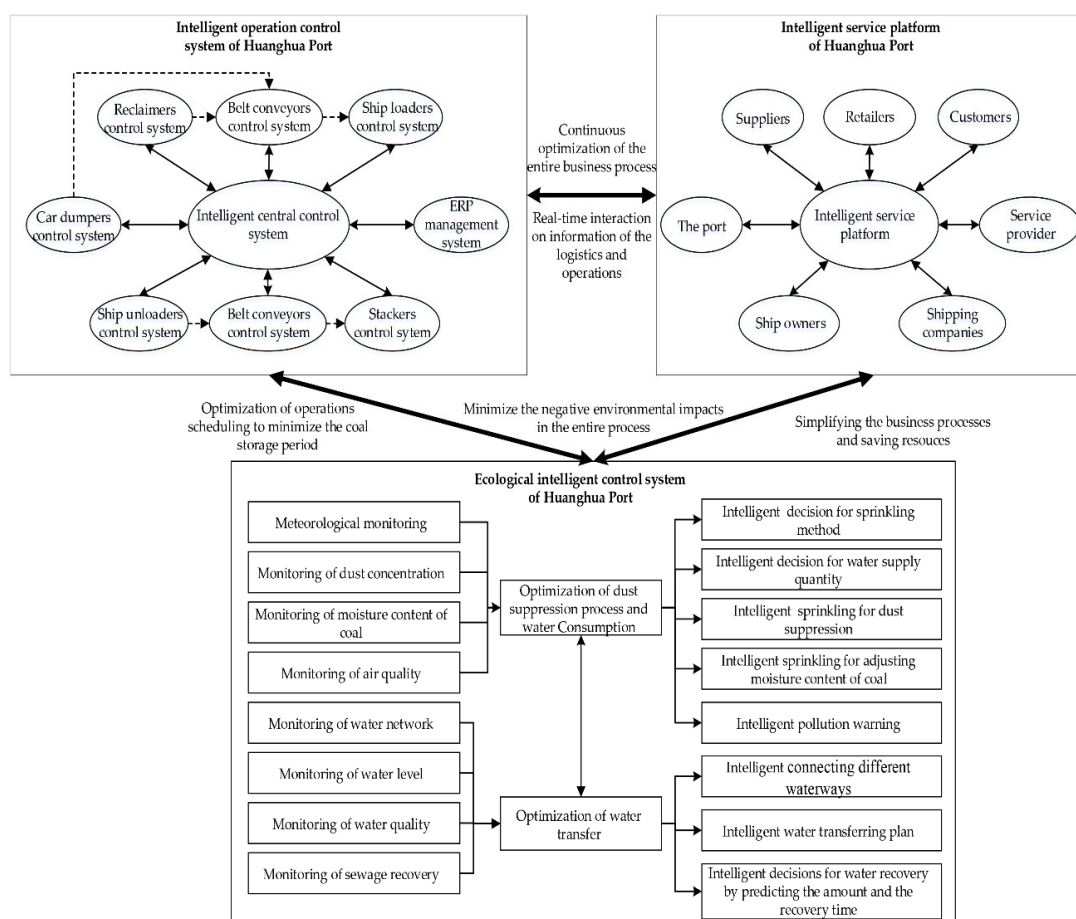


Figure 12. Intelligent control systems in Huanghua Port.

The ecological intelligent control system, as demonstrated in Figure 12, can realize real-time monitoring of environmental conditions with various sensors installed in the port, including the meteorological condition, the dust concentration in observation areas, the moisture content of coals, the air quality, the water quality, the water level, and the status of sewage. Driven by big data analysis, the system can optimize the planning of dust suppression and water consumption. Specifically, the ecological smart control system helps the port select the most appropriate sprinkling method for different areas and the corresponding water supply quantity according to factors such as coal type, moisture content, stacking time, temperature changes, and wind force. Based on the water transfer model in the system, the system dispatches and operates the entire water system according to the real-time calculation and analysis. By transmitting the instructions to the control systems, the system automatically controls the dust suppression sprinkler equipment, achieving the preventive water replenishment and accurate dust suppression. Furthermore, the ecological intelligent control system can analyze key pollution factors and predict the changing trend of environmental quality. Thereby the system can provide early warning of potential pollution and design an appropriate response plan for the port to minimize negative environmental impacts of activities in the port.

In summary, the intelligent operation control system, the intelligent service platform, and the ecological intelligent control system are interrelated and interacting. With smart technologies and big data analysis, the port can formulate the optimal scheduling of operations, the optimal environmental protection plan, and facilitate the coordination of the supply chain to achieve the integration of economic development, environmental protection, and social contribution.

#### 4. Discussion and Implications

All of the progress demonstrates that Huanghua Port has devoted itself to the economic, environmental, and social development towards sustainability. Significant improvement has been

made in all three sustainability pillars. Referring to the 17 goals of the 2030 Agenda for Sustainable Development, Huanghua Port strives to achieve sustainable development. The improvements in the port's sustainability are in line with the Sustainable Development Goals, particularly with Goal 12, which is concerned with responsible consumption and production.

Huanghua Port still has a long way to go in order to reach the goal of a world-class sustainable smart port. There is a great potential for smart development in realizing the seamless connection of each operation process and the optimal allocation of total resources. On the basis of the existing central control system of operations, the port can further establish the smart production monitoring platform to realize the standardization management of equipment, as well as automatic status monitoring, fault identification, and independent maintenance. Through integrating data sources and implementing data mining analysis, the port can further establish the data-driven smart decision support system for production management. By identifying the internal and external constraints of port production and analyzing the influences of shipping transportation, the system will achieve production process optimization and intelligent scheduling.

Besides the innovations of operation processes, the construction of the smart port will lead to a new environmental management model and thus contribute to the long-term sustainable growth. With regard to environmental protection, Huanghua Port should accelerate the improvement of the integrated ecological intelligent control system by incorporating all environmental protection functions. Since the port has realized the intelligent control of dust suppression and water recycling by virtue of the integrated system, the port should intensify the monitoring and emergency scheduling of oil spillage, as well as the prevention of plant diseases and insect pests, the monitoring of soil moisture and the management of plant greening. The establishment of such a comprehensive intelligent system of energy conservation and environmental protection will promote the Huanghua Port to make solid progress towards a sustainable and smart port.

The measures taken by Huanghua Port in the development of a sustainable and smart port can provide significant managerial implications for the development of ports in other regions.

First, port operators should take on a key role in constructing a sustainable and smart port through a synergistic approach. On the basis of connecting physical objects to the network via Internet of Things technologies and upgrading equipment via automation technologies, port operators should actively adopt these new technologies to facilitate the real-time information interaction and automatic control. Thereby the port can achieve the intelligent perception and control of the environment, the traffic, the equipment, and facilities. They should focus on strengthening the integration of modern information technology and port operations in all three dimensions—economic, environmental, and social. Although sustainable and smart port construction may cause possible negative effects on operation costs in the short term, port operators should actively assume their social responsibility and invest in sustainable and smart development from a long-term perspective, which will bring considerable economic benefit and social influence for the ports. They can make a five-year or even longer-term plan for the construction of sustainable and smart ports rather than overemphasize the short-term returns on investment. For example, the overall plan of Huanghua Port (the year 2016 to the year 2035) was approved by Hebei government in 2019, which emphasized transforming the port into a comprehensive port, the sustainable port development with further reducing pollution and increasing the greening space, and smart port construction including intelligent monitoring, intelligent operations, and intelligent logistics [32].

Instead of passively complying with the regulations and industry standards stipulated by the policymakers, port operators should take the initiative to participate in defining certification schemes and standards, since they have a better understanding of the actual influence of rules and regulations on port management.

Second, greater collaboration among supply chain members is crucial to foster smart and sustainable development. According to Gimenez et al. [1], supply chain assessment has no impact on the triple bottom line, whereas supply chain collaboration contributes to improving all of the three pillars of sustainability. Port operators should undertake a collaborator role in facilitating cooperative action and managing the mutual interests of different stakeholders of the port. For example, the



service platform can be created to link the stakeholders, as in the case of Huanghua Port, and thus vigorously promote the online–offline collaboration and sharing of both the risks and rewards.

Third, port operators should emphasize ports' cooperation to promote sustainable and smart development. The case of Huanghua Port provides tips for more effective port management with cooperation partners. On the one hand, the port should be benchmarked against the domestic and international advanced ports. On the other hand, port operators should further study the strategy of regional integration and form complementary advantages with homogeneous competitors. For instance, the governments of Tianjin and Hebei Province issued the Work Plan for Coordinated Development of Tianjin–Hebei Ports (the year 2017 to the year 2020) in 2017, and the operators of Huanghua Port followed their instructions on enhancing collaboration in resources integration, pollution control, safety management, smart port development etc. [33].

Fourth, together with a proactive role played by port operators, the government is advised to issue adequate regulations and technical standards to enhance the sustainable and smart growth of the port. The government has done much in the overall planning. For example, the Ministry of Transport of China released the action plan for green port construction (the year 2018 to the year 2022) [34] and proposed the demonstration project for the smart port construction [35]. The government of Hebei Province formulated the overall plan of Bohai New Area (the year 2016 to the year 2030), in which the government clearly pointed out that the Huanghua port should actively promote sustainable and smart development in order to play the role of a portal for the “one belt one road” policy [36]. It would be advisable for the government to establish technical standards for the sustainable and smart development of the port industry and monitor their enforcement, since ports are mostly prone to conform to the minimum environmental requirements [6]. Reward and punishment mechanisms may be an effective way to incentivize ports towards sustainable development.

## 5. Conclusions

Scholars and practitioners have paid increasing attention to port sustainability. Through reviewing the literature on port sustainability and smart port construction, it was shown that few researchers discuss the coal port's sustainability development based on the adoption of smart technologies. This paper mainly focused on the approaches towards coal port sustainability and the effectiveness of these measures, as well as the integration and optimization roles of smart technologies in enhancing sustainability in the era of the Internet of Things. By investigating the representative case of Huanghua Port, China, we provide managerial insights for the port operators, supply chain members, and policymakers towards sustainable and smart development.

The paper introduced the case of Huanghua Port and analyzed its sustainability efforts based on the triple bottom line. It provides experiences on the coal port's intelligent renovation and environmental protection, especially in the aspects of coal dust pollution treatment, air pollution treatment, and sewage treatment, as well as the port's social efforts on customer and employee satisfaction improvement, community involvement, and social reputation enhancement. We selected key performance indicators in evaluating the effectiveness of measures taken by the port. The indicators include handling efficiency, energy consumption, port throughput, and port revenue in the economic dimension; coal dust concentration, the air pollution index and sewage recovery amount in the environmental dimension; and the customer satisfaction rate, the wage level, the employees' training and the amount of social donation in the social dimension.

The findings show that the measures taken by the Huanghua Port can effectively increase the handling efficiency, reduce energy consumption, and increase the port throughput and revenue. Moreover, the approach can reduce the coal dust concentration, decrease the air pollution index, and increase the amount of sewage recovery. Furthermore, the efforts towards sustainability can increase the customer satisfaction rate, improve the wage level, increase the investment in employees' training, and increase the amount of social donation. The research also shows in detail that the intelligent operation control system, the ecological intelligent control system, and the intelligent service platform play roles of integration and optimization in enhancing the coal port's sustainability.

The study enables a better understanding of the coal port's sustainable practices driven by smart technologies. To boost the transformation and upgrading of the port towards the sustainable development of the port, port operators should promote the construction of the sustainable and smart port in an all-round way, for example by benchmarking the port against a world-class advanced port, cooperating with other ports to mutually complement advantages, and making full use of the Internet of things, big data, cloud computing, and mobile Internet, etc. It is advisable for port operators to invest in sustainable and smart development from a long-term perspective. Port operators should undertake a collaborator role in facilitating the coordination among supply chain members, such as establishing the integrated service platform. The government is advised to provide institutional guarantee and industry guidelines for the sustainable and smart development of the coal port industry.

Despite this paper's contributions to the literature and its implications for managerial practice, there are certain limitations to our research. The consideration of the port practice only from one representative port is one limitation, and thus future research could involve comparisons among typical ports around the world. This paper focuses on achievements made in the sustainable and smart development of a coal port, such that the investigation on the barriers to smart port construction is also an interesting topic for future research.

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