

Comparing the productivity of major shipyards in China, South Korea, and Japan – an application of a metafrontier framework

Productivity of
major
shipyards

193

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Abstract

Purpose – This study aims to measure the productivity of 21 major shipyards in China, South Korea and Japan.

Design/methodology/approach – Data envelopment analysis was applied to measure the productivity of shipyards. The contemporaneous and intertemporal productivity scores of each shipyard were measured. Additionally, the technical gaps among shipyards in China, South Korea and Japan were measured and compared.

Findings – The results indicate that Japan led the global shipbuilding industry in 2014 and South Korea dominated in 2015. Additionally, from 2014 to 2015, shipyards in South Korea and Japan maintained their levels of productivity. Comparatively, major shipyards in China made substantial progress from 2014 to 2015, revealing their strong ambition to improve productivity.

Originality/value – This study first used a metafrontier framework to measure the technical gap of shipyards among major shipbuilding countries. The model and approach objectively analyze the productivity of major shipyards and considers their nationalities. Additionally, this study is the first to measure changes in the productivity of shipyards. By decomposing the metafrontier Malmquist productivity index, major shipyards were categorized into eight sets. The results of this study can provide a clear direction for shipyards to improve their productivity.

Keywords Data envelopment analysis (DEA), Malmquist productivity index, Metafrontier framework, Productivity evaluation, Shipyards

Paper type Research paper

1. Introduction

Shipbuilding is an upstream industry that plays a critical role in the maritime system by supplying various types of new ships. Some countries attach great importance to and encourage the development of their shipbuilding industry, a mixed manufacturing industry that promotes the development of the steel, machinery, paint and banking industries. These



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output values and employment opportunities promote a country's economy. Additionally, because the demand and supply for new ships are globalized, the substantial worldwide demand for various ships creates considerable business opportunities for a country to earn foreign exchange through export.

To increase competitiveness in the global shipbuilding market, shipyard operators must understand and improve their productivity. Therefore, measuring the productivity of shipyards has become a concern for shipyard operators and a critical topic in the literature. [Mickeviciene \(2011\)](#) indicated that shipbuilding is an old, open and competitive market. With the onset of the Industrial Revolution, the UK led the world's shipbuilding industry from 1860 to 1950. In the mid-1950s, Japan gradually took over the lead because shipyards in the UK did not improve their facilities and technology in a timely manner. Shipbuilding is an industry that requires many skilled workers and a considerable amount of steel. Most shipyards in Japan, which could not afford the substantial cost of labor and had insufficient steel resources, were surmounted by South Korean shipyards, where low cost and highly competitive strategies helped them gain the upper hand. Since 2010, due to the low cost of labor and abundant iron ore, China has held the leading position in the global shipbuilding industry. Currently, China and South Korea are the world's top two shipbuilding countries in market share, followed by Japan, ranked third in the global shipbuilding industry. [Table 1](#) presents the market share of world's leading shipbuilding countries from 2010 to 2015 as follows: China was the largest shipbuilding country, with a market share of 39.11%, followed by South Korea and Japan, with market shares of 29.28% and 17.03%, respectively ([Clarksons Research, 2017](#)).

The aforementioned discussion indicates that shipbuilding is a highly competitive global industry. Therefore, measuring the productivity of major shipyards is a critical and helpful means by which to examine the use of their costly resources, which is directly related to their competitiveness. Notably, because shipbuilding is globalized, there might be technical heterogeneity among regions. For example, Chinese shipyards tend to deploy many workers and Japanese shipyards have the least workers because of high labor costs. Additionally, shipyards in South Korea own large dock areas, but the dock areas of Japanese shipyards are smaller than those of the other two countries. Because the market is dominated by China, South Korea and Japan, this study aims to measure the productivity of their major

Table 1.
Market share of the
major shipbuilding
nations (2010-2015)

Nations	Million CGT*						Average	(%)
	2010	2011	2012	2013	2014	2015		
China	63.50	52.50	37.10	46.40	45.60	23.70	44.80	39.94
South Korea	44.20	38.30	30.90	35.10	33.30	15.40	32.87	29.30
Japan	25.20	19.70	15.60	18.90	19.70	8.90	18.00	16.05
Philippines	3.50	2.60	1.50	2.80	2.10	1.20	2.28	2.04
Brazil	2.20	2.60	3.20	3.00	3.00	0.80	2.47	2.20
Germany	1.40	1.30	1.20	1.30	1.40	0.40	1.17	1.04
Vietnam	2.20	1.50	1.10	1.00	0.70	0.50	1.17	1.04
Italy	1.20	1.10	1.10	1.10	1.50	0.30	1.05	0.94
Taiwan	1.10	1.30	0.90	1.10	1.00	0.50	0.98	0.88
India	1.90	1.50	1.00	0.40	0.20	0.10	0.85	0.76

Note: *CGT denotes compensated gross tonnage
Source: [Statista \(2015\)](#)

shipyards. Additionally, the technology gaps and changes in intertemporal productivity in shipyards in China, South Korea and Japan are also measured and compared.

The remainder of this paper is organized as follows: Section 2 reviews literature related to the global shipbuilding industry and shipyard productivity measurements, Section 3 reviews the methodology, Section 4 presents the empirical results and Section 5 concludes and suggests topics for further research.

2. Literature review

[Cho and Porter \(1986\)](#) mentioned that after the Second World War, from the 1950s to the 1970s, Japan surpassed Britain to become the world's largest shipbuilding country, capturing more than 50% of the market share. Subsequently, the Japanese shipbuilding industry was threatened by the rise of the South Korean shipbuilding industry. [Mickeviciene \(2011\)](#) mentioned that shipbuilding is an ancient, highly competitive industry. Although many shipyards avoided the impact of the financial crisis in 2008 because of their business strategies, the advantage of the European shipbuilding industry was replaced by the rise of shipyards in China, South Korea and Japan because the European shipyards did not actively upgrade their production equipment. Additionally, China, with its low labor costs, governmental support and rich supplies of iron ore, gradually replaced South Korea to become one of the leading shipbuilding countries.

According to [Table 1](#), China and South Korea are the top two leading countries in the shipping industry and the facilities in China and its innovative policies have further increased its lead in the industry. Although the compensated gross tonnage (CGT) produced by Chinese shipyards is higher than that of South Korea, the competitiveness of major shipyards in South Korea should not be overlooked. In [Table 1](#), from 2010 to 2015, China, South Korea and Japan were the top three shipbuilding countries and accounted for 85.42% of the global shipbuilding market; thus, the global shipbuilding market is dominated by these three countries.

Shipyard operations are capital intensive because operators must build docks for assembling and floating ships. To shorten the working time for building a ship, modern shipyards prefer to prebuild multiple blocks in the yard and then lift them to the dock for assembly because the working time in the yard is shorter than that at the dock. Therefore, large cranes and yard areas are necessary. Because the input for running a shipyard is costly, productivity is a concern of shipyard operators and has been investigated in the literature. For example, [Stanić et al. \(2017\)](#) proposed a four-phase framework to determine the optimal solution for improving the productivity of the existing shipbuilding process. Three principles – design for production, design for maintainability and group technology – were suggested to generate alternatives and the analytical hierarchy process method was applied to determine the relative importance of the alternatives. To shorten shipbuilding time, many shipyards prebuild ship blocks and then assemble them at a dock to build a ship. Therefore, how to use the block erection area efficiently is a determinant of the productivity of a shipyard. [Dixit et al. \(2018\)](#) used a priority rules-based simulation approach to address the block spatial scheduling problem with uncertain erection duration. They observed that rules based on combinations of the time criticality index, resource criticality index and shortest processing time yield the most and the least efficient trade-off, respectively, between time and resource-oriented objectives. [Xue et al. \(2020\)](#) indicated that building technique, resource ability and management level are the three major drivers of the production efficiency of shipbuilding. Based on an empirical study on one of the largest state-owned shipbuilding companies in China, they suggested that improving management

efficiency and technique efficiency should be the main direction taken to improve Chinese shipbuilding efficiency.

Measurements of productivity to examine the utilization of these resources are essential. [Zakaria et al. \(2010\)](#) investigated the status of the shipbuilding industry in Bangladesh as follows: 67 shipyards were surveyed and categorized into four classes. The competitiveness was measured by one index, namely, the ratio between average man-hour used and the CGT produced by each shipyard. The results indicated that with the world's lowest labor costs, more than 25% of shipyards in Bangladesh increased their output level. [Jiang et al. \(2013\)](#) demonstrated that China has had the majority of the market in the global shipbuilding market in terms of CGT. They analyzed the shipbuilding competitiveness of China and its determinants, based on a quantitative approach and then compared them with those of South Korea and Japan. They proposed a profit-based measurement for assessing the competitiveness of a shipyard that considered both internal and external factors. A regression model was established to investigate the determinants of the profit rate, where time charter rate, shipbuilding costs, contract price deviations and market condition dummies were the independent variables. The results demonstrated that shipbuilding cost had a negative correlation with the profit rate and the market condition dummies, time charter rate and contract price deviation were positively related to the profit rate. [Jiang et al. \(2013\)](#) concluded that although market demand was the critical determinant of the competitiveness of these three countries, the shipbuilding competitiveness of China was based on its low costs and the deviations in contract price were the drivers for shipyards in Japan and South Korea.

To measure the productivity of shipyards, [Colin and Pinto \(2009\)](#) ranked the performance of the world's major shipyards by using data envelopment analysis (DEA). The dry dock areas, berth length and total crane load were used as the input items and the average annual CGT in 2000-2006 and the types of ships were the output items. The input and output (I/O) items used in [Colin and Pinto \(2009\)](#) provided a fundamental concept for measuring the productivity of shipyards using DEA. [Zhangpeng and Flynn \(2006\)](#) pointed out that, as the rise of China's shipbuilding industry, all the shipyards in other countries have had to manage the strong pressure to compete. They suggested that dock area, length of a berth, workers per hour, workers per CGT requirements and the unit cost of deadweight tonnage (DWT) were appropriate input items. For the output, the CGT was suggested as a representative item because it can reflect the complexity of building various types of ships. [Pires and Lamb \(2008\)](#) used DEA to measure the productivity of major shipyards in Brazil. They defined the working area, the technological development index and the shipbuilding environment index as the input items and labor productivity and building time as the two output items. [Krishnan \(2012\)](#) also defined suitable indexes for measuring the efficiency of major shipyards, of which dock area, berth length, workers per hour and workers per CGT requirements were the input items. The output items were the CGT, DWT and profits. [Chudasama \(2016\)](#) used three input items, shipyard capacity, ship size area and total employees and one output item, income, to measure the productivity of 19 major shipyards in India.

In addition to assessing the overall productivity of shipyards, [Park et al. \(2014\)](#) investigated the productivity of a shipyard from a micro perspective. Because the process for building a ship comprises multiple stages, [Park et al. \(2014\)](#) measured the productivity of the block manufacturing process (BMP) instead of the productivity of an entire shipyard. DEA was used to measure the productivity of the BMPs with two input items, total execution time and waiting time and two output items, the number of operations and the material produced. According to their empirical study based on a South Korean shipyard,

they concluded that the productivity of a shipyard can be effectively assessed by measuring the efficiency of the BMP. The common I/O items that have been in the literature are summarized in [Tables 2](#) and [3](#).

According to the aforementioned review, the main research gap between the studies on measuring the productivity of shipyards and related models in other fields can be summarized in two aspects. First, most studies have measured shipyard productivity in terms of a specific year; however, according to our review of the literature, no study has measured changes in productivity. Notably, contemporaneous measures can reflect the efficiency of shipyards from only a static perspective; thus, the productivity change over multiple time periods cannot be observed. Because observing productivity change is also a concern for practitioners and researchers, measuring the intertemporal productivity to discover additional management implications is necessary. Because models and indexes, for example, the Malmquist productivity index (MPI), have been proposed and applied to measure intertemporal productivity ([Estache et al., 2004](#); [Fu et al., 2009](#)), applying such approaches to investigate the productivity change trend of major shipyards is worthwhile. Second, the technology gap between different production groups could be measured and compared using a metafrontier framework ([Oh and Lee, 2010](#)). However, according to our review of the literature, such a survey has not been conducted in the literature related to shipyard productivity measurement. To address these two research gaps, this study uses the MPI to measure the intertemporal productivity change in the world's leading shipyards. Additionally, because today's market is dominated by China, South Korea and Japan, the technology gaps among these three countries are also measured and compared.

3. Methodology

The methodology used in this study comprises two main steps. In the first step, empirical I/O data of leading shipyards in China, South Korea and Japan were collected and tested to ensure the discriminant power of our proposed models. In the second step, the scores for contemporary productivity, technical gaps and intertemporal productivity of the shipyards were measured. Contemporary scores reflect the productivity of the shipyards in a specific year. Because a two-year data set was collected in this study, two contemporary productivity analyzes were conducted to examine the productivity of each shipyard in each year. The intertemporal productivity of each shipyard was also measured to observe the productivity change over the two years. Finally, by using a metafrontier framework, the technical gaps among leading shipyards in China, South Korea and Japan were measured and compared. The details of the methodology used in this study are as follows.

3.1 Data preparation

3.1.1 Decision-making unit selection and classification. This study attempted to measure the productivity of major shipyards in the world's leading shipbuilding countries. Accordingly, major shipyards in China, South Korea and Japan as ranked by annual CGT in 2014 were selected as the DMUs for the productivity evaluation. In total, 21 leading shipyards with public I/O data were selected as the DMUs in this study. Among these DMUs, eight shipyards are located in South Korea, namely, Daewoo, Hyundai H.I., Samsung H.I., Hyundai Mipo, Hyundai Samho, Sungdong S.B., STX shipbuild and SPP shipbuilding. All these shipyards in South Korea were ranked among the world's top 50 shipyards in 2014 because of their considerable output measured in CGT. The other seven shipyards are located in China – Shanghai Waigaoqiao, Jiangsu New YZJ, Hudong Zhonghua, Jiangsu Rongsheng, Chengxi shipyard, Weihai Samjin and Jiangnan Changxing – of which four shipyards were ranked among the world's top 50 shipyards in 2014 as measured in CGT. Six

Table 2.
Common input items
for shipyard
productivity
evaluation

Study (year)	Dock area	Largest dock area	Crane total load	Input variables					Total execution time	Waiting time	Erection area	ITechIndEnv
				Worker/ CGT	Worker/ Hour	Cost/ DWT	Worker					
Colin and Pinto (2009)	•		•				•					
Zhangpeng and Flynn (2006)	•			•		•	•				•	•
Pires and Lamb (2008)												
Krishnan (2012)	•			•	•		•		•	•		
Park <i>et al.</i> (2014)												
This study	•		•				•		•	•		

Notes: CGT = compensated gross tonnage; DWT = deadweight tonnage; ITech = technological development index; IndEnv = shipbuilding environment index

Study (year)	Productivity of major shipyards						
	CGT	DWT	Type of vessel	Output variables			Material amount
				Profit	Labor productivity	Building time	
Colin and Pinto (2009)	•		•				
Zhangpeng and Flynn (2006)							
Pires and Lamb (2008)					•	•	
Krishnan (2012)	•	•		•			
Park <i>et al.</i> (2014)							•
This study	•						•

Notes: CGT = compensated gross tonnage; DWT = deadweight tonnage

Table 3.
Common output items for shipyard efficiency evaluation

shipyards are located in Japan – Oshima S.B. Co., Imabari S.B., Namura shipbuilding, Mitsubishi H.I., JMU Ariake shipyard and Tsuneishi Zosen – of which five were ranked among the world’s top 50 shipyards in 2014.

3.1.2 Input and output items selection. According to the literature review, two items were commonly selected input items to measure the efficiency of a shipyard as follows: the dock area set up for building ships (Colin and Pinto, 2009; Krishnan, 2012) and the total number of workers in a shipyard (Colin and Pinto, 2009; Zhangpeng and Flynn, 2006; Krishnan, 2012). These two items can appropriately represent the critical input for running a shipyard; thus, we included them as input items in our model. For output items, the CGT was the only item used in our model because it can consider the complexity related to building various types of ships and has been recommended in the literature (Colin and Pinto, 2009; Krishnan, 2012). Table 4 presents the I/O items used in this study and their definitions.

3.1.3 Data collection and test. All data for the I/O items in this study were collected from public records. The data for the two input items were collected from the websites of shipyards. The values of the output items were sourced from World Shipyard Monitor and Shipping Intelligence Network, two representative periodicals in the shipbuilding industry. Table 5 presents the descriptive statistics of the I/O items for all DMUs. In 2014, the difference in the dock area was remarkable. The area of Hyundai H.I., the world’s largest shipyard, was 262,254 square meters, providing a sufficient area for building ships. However, the SPP Shipbuilding Co. had a small area (8,060 m²). This large range and deviation revealed significant differences in land use for shipbuilding. A number of workers is the second input item in our model. Jiangsu Rongsheng had the largest number of workers, 22,083 persons, among all the considered shipyards. However, the SPP Shipbuilding Co. had 700 workers, the least number of workers among all of the shipyards. This large range and deviation revealed significant differences in the hiring of workers

Item	Unit	Definition
<i>Input items</i>		
Dock area	m ²	Total area for building ships in a shipyard
Workers	Person	Total workers used by a shipyard
<i>Output items</i>		
CGT	Ton	Total CGT outputted output by a shipyard

Table 4.
Definition of I/O items used in this study

necessary to operate a shipyard. For the output, with 2,571 tons of CGT, Deawoo was the leader in 2014 and demonstrated an excellent ability to build ships. By contrast, some shipyards were operating with small CGTs. The large range (2,514,000 tons) and deviation (725,860 tons) revealed the significant differences in shipbuilding performance among these shipyards.

The ranges and deviation patterns in the I/O items in 2015 were similar to those in 2014 and they all reflected significant differences among the shipyards evaluated in this study and demonstrated that the collected data were suitable for a DEA analysis. Table 6 presents the descriptive statistics for the I/O of the three countries, namely, during the period under examination, shipyards in China had the most workers and Japanese shipyards had the least workers because of high labor costs. South Korean major shipyards tended to use large dock areas for production. Comparatively, the dock area of Japanese major shipyards was significantly smaller than that of the shipyards in the other two countries. The difference in I/O items implies that technology heterogeneity might exist between China, South Korea and Japan. Accordingly, this study measures the technology gaps among these three countries and statistical tests are conducted to examine the significance of the technology gaps.

3.2 Measuring the productivity and technology gap scores

3.2.1 Contemporaneous productivity and technology gap. To explain how to determine a productivity score, we first defined a distance function (DF) with equation (1), in which x and y denote the I/O of a DMU, respectively. The possible production set in equation (1) comprises all possible combinations of I/O. As equation (1) indicates, for an observed DMU with an input (x^o) and an output (y^o), its corresponding DF is the maximum ratio that its output can project to the frontier curve. Three scores were used to examine the contemporaneous productivity of a DMU. The first score was based on the model proposed by Charnes *et al.* (1978), called “Model CCR” here, which is based on the assumption of constant returns to scale. We let $x = (x_1, x_2, \dots, x_n) \in R_{m \times n}$; $y = (y_1, y_2, \dots, y_n) \in R_{s \times n}$; and $\lambda \in R_n$ be a weight vector. Next, the efficiency score of a DMU was determined by solving the Model CCR as defined by equation (2), in which the score is the reciprocal of its corresponding DF. The second score was based on the model proposed by Banker *et al.* (1984), called “model BCC” here, which is based on the assumption of variable returns to scale. The model BCC score was obtained by solving equations (2) and (3) simultaneously. The third score was scale efficiency (SE), which is the ratio between the scores obtained from models CCR and BCC. The SE score was between zero and one, in which a larger score indicated that the DMU was operating closer to its optimal production scale.

Table 5.
Descriptive statistics
for I/O items (all
shipyards)

Year	Item	Maximum	Minimum	Range	Mean	SD
2014	Dock area	262,254	8,060	254,194	53,702	79,560.40
	Workers	22,083	700	21,383	5,974	5,842.60
	CGT*	2,571	57	2,514	501	725.86
2015	Dock area	318,604	7,048	311,556	42,800	82,909.77
	Workers	30,000	700	29,300	4,500	7,092.91
	CGT	2,490,000	29,000	2,461,000	519,000	684,250

Note: *CGT denotes compensated gross tonnage

								Productivity of major shipyards
Country	Year	Item	Maximum	Minimum	Average	Range	SD	
South Korea	2014	Dock Area	262,254.0	8,060.0	128,513.5	254,194.0	78,073.5	201
		Worker	14,243.0	2,200.0	8,968.0	12,043.0	3,914.4	
		CGT*	2,571.0	501.0	1,514.5	2,070.0	717.2	
	2015	Dock Area	318,604.0	8,060.0	129,992.0	310,544.0	94,023.1	
		Worker	12,760.0	2,700.0	7,459.8	10,060.0	3,810.8	
		CGT	2,490.0	368.0	1,384.3	2,122.0	723.6	
China	2014	Dock Area	238,478.0	13,280.0	91,513.7	225,198	82,260.3	
		Worker	22,083.0	4,000.0	10,830.3	18,083	6,070.9	
		CGT	599.0	57.0	366.7	542	174.4	
	2015	Dock Area	238,478.0	13,280.0	68,496.5	225,198	71,818.3	
		Worker	30,000.0	2,500.0	11,071.4	27,500	9,450.7	
		CGT	682.0	29.0	433.3	653	235.5	
Japan	2014	Dock Area	45,090.0	9,073.0	26,622.2	36,017	12,869.1	
		Worker	2,500.0	700.0	1,184.8	1,800	646.4	
		CGT	657.0	80.0	360.7	577	173.1	
	2015	Dock Area	45,090.0	7,048.0	29,431.3	38,042	14,582.7	
		Worker	4,500.0	700.0	1,430.7	3,800	1,375.4	
		CGT	620.0	201.0	301.2	419	145.6	

Note: *CGT: compensated gross tonnage (measured in 1,000 tons)

Table 6.
Descriptive statistics
for I/O items
(separated by
countries)

The purpose of using a DF was to project a DMU to a benchmark frontier curve. In this study, two types of frontier curves were used for such projections. The first was called a group frontier curve, formed by the DMUs of the same country in the same period. The second was called a metafrontier curve, formed by the DMUs belonging to all countries in all periods. The ratio between these two scores was defined as the technology gap ratio (TGR). The TGR score was between zero and one. A larger TGR score indicated a higher technology level because the corresponding group frontier curve is closer to the metafrontier curve. A TGR score of one indicated that the group was the leader in the industry because the group frontier curve and the metafrontier curve overlapped.

$$D(y^o, x^o) = \min \left[u \left| \left(\frac{y^o}{u}, x^o \right) \in \text{PPS} \right. \right] \leq 1 \tag{1}$$

$$\theta^* = \min[\theta | \theta x^o \geq X\lambda, y^o \leq Y\lambda, \lambda \geq 0] \tag{2}$$

$$e\lambda = 1 \tag{3}$$

3.2.2 Change in productivity. Extending the concept of a DF, [Oh and Lee \(2010\)](#) proposed a measure of the change in productivity, which we called the metafrontier MPI (MMPI) in this study, by benchmarking the metafrontier curve. We let P^G be the global benchmark technology, $P^j_{R_j}$ be the benchmark technology of group j over both periods, $P^i_{R_j}$ be the benchmark technology of group j in period i and (x^t, y^t) be the observed I/O of a specific DMU in period t . Then, the MMPI can be defined by [equation \(4\)](#), the ratio of two DFs benchmarking P^G .

$$\text{MMPI} = M^G(x^t, y^t, x^{t+1}, y^{t+1}) = \frac{D^G(x^{t+1}, y^{t+1})}{D^G(x^t, y^t)} \quad (4)$$

Equation (4) can be further decomposed to become equation (5), which proves that an MMPI is a product of three indexes. The first index, called efficiency change (EC), reveals the change measured by $P_{R_j}^t$ within-group j . The second index, best practice change (BPC), measures the change in the gap between $P_{R_j}^t$ and $P_{R_j}^I$. The third index is named technical gap change (TGC) because it measures the gap between $P_{R_j}^I$ and P^G , the ratio of the TGR scores between two periods.

$$\begin{aligned} M^G(x^t, y^t, x^{t+1}, y^{t+1}) &= \frac{D^G(x^{t+1}, y^{t+1})}{D^G(x^t, y^t)} \\ &= \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \left\{ \frac{D^t(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^G(x^{t+1}, y^{t+1})}{D^G(x^t, y^t)} \right\} \\ &= \frac{D^{t+1}(x^{t+1}, y^{t+1})}{D^t(x^t, y^t)} \times \left\{ \frac{D^t(x^t, y^t)}{D^{t+1}(x^{t+1}, y^{t+1})} \times \frac{D^I(x^{t+1}, y^{t+1})}{D^I(x^t, y^t)} \right\} \\ &\quad \times \left\{ \frac{D^I(x^t, y^t)}{D^I(x^{t+1}, y^{t+1})} \times \frac{D^G(x^{t+1}, y^{t+1})}{D^G(x^t, y^t)} \right\} \\ &= \frac{TE^{t+1}}{TE^t} \times \frac{BPG^{I,t+1}}{BPG^{I,t}} \times \frac{TGR^{t+1}}{TGR^t} \\ &= EC \times BPC \times TGC \end{aligned} \quad (5)$$

4. Empirical study

This section comprises three subsections that describe the results of our empirical study. Section 4.1 presents the result of the contemporaneous productivity analysis, including the scores obtained from models BCC, CCR and SE. Section 4.2 measures and analyzes the TGR scores for individual shipyards and countries, respectively. Section 4.3 applies the MMPI to measure and examine productivity changes from 2014 to 2015 in the major shipyards in South Korea, China and Japan.

4.1 Contemporaneous productivity analysis

We used the DEA-Solver Pro 5.0 package to obtain the productivity scores of each DMU for 2014 and 2015, respectively. The scores were output-oriented because the input of a shipyard is more difficult to adjust than its output. For a DMU, the scores were solved by models CCR and BCC, respectively; next, the ratio of these two scores was calculated to determine the score of SE. All contemporaneous productivity scores solved in this study are summarized in Table 7 and discussed as follows.

In 2014, the major South Korean shipyards Hyundai Mipo and SPP shipbuilding had perfect scores based on Model CCR. The other six shipyards were relatively inefficient, in which Sungdong S.B. had the lowest score (0.339). In 2015, one more shipyard, Daewoo,

Table 7.
Scores of
contemporary
productivity

DMU	Shipyards	CCR	2014			CCR	2015		
			Efficiency scores	Efficiency scores	Efficiency scores				
			BCC	SE	RTS		BCC	SE	RTS*
<i>(a) Shipyards of South Korea</i>									
K1	Daewoo	0.574	1.000	0.574	Constant	1.000	1.000	1.000	Decreasing
K2	Samsung H.I.	0.381	0.696	0.547	Constant	0.418	0.818	0.511	Constant
K3	Hyundai Mipo	1.000	1.000	1.000	Constant	0.902	1.000	0.902	Decreasing
K4	SPP shipbuilding	1.000	1.000	1.000	Constant	1.000	1.000	1.000	Decreasing
K5	Sungdong S.B.	0.339	0.535	0.634	Constant	0.191	0.264	0.723	Constant
K6	STX shipbuild	0.358	0.722	0.496	Increasing	0.440	0.464	0.948	Increasing
K7	Hyundai H.I.	0.538	1.000	0.538	Constant	0.562	1.000	0.562	Decreasing
K8	Hyundai Samho	0.419	0.656	0.639	Constant	0.408	0.742	0.550	Decreasing
<i>(b) Shipyards of China</i>									
C1	Shanghai Waigaoqiao	0.655	0.978	0.670	Decreasing	0.483	0.856	0.564	Constant
C2	Jiangsu New YZJ	1.000	1.000	1.000	Decreasing	1.000	1.000	1.000	Decreasing
C3	Hudong Zhonghua	0.373	0.546	0.683	Constant	0.809	1.000	0.809	Decreasing
C4	Jiangsu Rongsheng	0.104	0.576	0.181	Constant	0.030	0.227	0.132	Constant
C5	Chengxi shipyard	0.172	0.429	0.401	Constant	1.000	1.000	1.000	Decreasing
C6	Weihai Samjin	0.162	1.000	0.162	Constant	0.074	1.000	0.074	Increasing
C7	Jiangnan Changxing	0.174	0.661	0.263	Decreasing	0.235	0.584	0.402	Decreasing
<i>(c) Shipyards of Japan</i>									
J1	Oshima S.B. Co.	0.902	1.000	0.902	Increasing	1.000	1.000	1.000	Constant
J2	Imabari S.B.	0.938	1.000	0.938	Decreasing	1.000	1.000	1.000	Constant
J3	Namura shipbuilding	0.900	1.000	0.900	Constant	0.629	0.692	0.909	Increasing
J4	JMU Ariake shipyard	1.000	1.000	1.000	Decreasing	0.501	1.000	0.501	Increasing
J5	Mitsubishi H.I.	0.189	0.204	0.926	Constant	0.401	0.574	0.699	Increasing
J6	Tsuneishi Zosen	1.000	1.000	1.000	Decreasing	1.000	1.000	1.000	Constant

Note: *RTS denotes return to scale

became efficient, with a perfect score and Sungdong S.B. remained in the last place. Notably, SPP shipbuilding performed perfectly in both years. For model BCC, more DMUs were in the group frontier than in Model CCR. The results in 2014 and 2015 were similar. The same four shipyards had perfect scores and Sungdong S.B. ranked last in both years. For SE, Hyundai Mipo and SPP shipbuilding had perfect SE scores from 2014 to 2015, indicating that their production scale was optimal. The SE score of the STX shipbuild in 2014 was 0.496, reflecting an obvious deviation from the optimal production scale.

Regarding the major Chinese shipyards, in 2014, only Jiangsu New YZJ had a perfect score when using model CCR. The other six shipyards were relatively inefficient, in which Jiangsu Rongsheng had the lowest score (0.104). In 2015, one more shipyard, Chengxi shipyard, became efficient and Jiangsu Rongsheng remained in the last place. Jiangsu New YZJ performed perfectly in 2014 and 2015. When model BCC was used, more shipyards were located on the group frontier than was the case in model CCR. Jiangsu New YZJ and Weihai Samjin had perfect scores in 2014 when measured by model BCC. The other five shipyards were relatively inefficient, of which the Chengxi shipyard had the lowest score (0.429). The scores in 2015 improved slightly from those in 2014. Two more shipyards, Hudong Zhonghua and Chengxi shipyard became efficient and Jiangsu Rongsheng remained in the last place. For SE, Jiangsu New YZJ has perfect SE scores from 2014 to 2015, demonstrating that its production scale was optimal.

Most Japanese major shipyards had satisfactory scores in 2014. JMU Ariake shipyard and Tsuneishi Zosen had perfect scores in 2014. The other four shipyards were relatively inefficient, in which Mitsubishi H.I. had the lowest score (0.198). In 2015, two more shipyards, Oshima S.B. Co. and Imabari S.B. became efficient and Mitsubishi H.I. remained in the last place. Based on model CCR, Tsuneishi Zosen performed perfectly in 2014 and 2015. When we used model BCC, all shipyards had perfect scores in 2014 except Mitsubishi H.I. (0.204). In 2015, one shipyard, Namura shipbuilding, did not maintain its perfect score. In terms of SE, Tsuneishi Zosen had perfect SE scores during 2014 and 2015, demonstrating its production scale was optimal in both years.

4.2 Technology gap ratio analysis

The contemporaneous productivity, metafrontier productivity and TGR scores for all the DMUs are summarized in Table 8, in which the metafrontier productivity scores were measured without considering the nationality of shipyards. A TGR score is the ratio between the corresponding contemporaneous and metafrontier productivities. In terms of metafrontier productivity in 2014, the scores obtained by Japanese shipyards were higher than 0.6, except for Mitsubishi H.I. By contrast, except for Hyundai Mipo and SPP shipbuilding, all shipyards in South Korea had scores below 0.6 and the scores of the Chinese shipyards were all below 0.6. Accordingly, the productivity of Japanese shipyards measured by metafrontier was better than that in the other two countries. The shipyard productivity in South Korea and China improved slightly in 2015 because Daewoo, Hudong Zhonghua, Chengxi shipyard and Jiangnan Changxing made substantial progress. Shipyards in Japan continued to exhibit satisfactory performance because only two shipyards had scored lower than 0.5.

Table 8 also lists the TGR scores of shipyards, to compare the technology gap. In 2014, the average TGR score of Japanese shipyards was as high as 0.914 and four Japanese shipyards remained industry leaders with perfect TGR scores. South Korea and China had TGR scores of 0.834 and 0.433, respectively, on average, in which one shipyard, SPP shipbuilding, in South Korea had a perfect score. In 2015, Japan again had the most shipyards with perfect TGR scores, namely, Oshima S.B. Co., JMU Ariake shipyard and Mitsubishi H.I. South Korea had one shipyard, SPP shipbuilding, with a perfect TGR score. No Chinese shipyards had perfect scores in 2015. Notably, major South Korean and Chinese shipyards improved their TGR scores from 2014 to 2015, for example, major Chinese shipyards improved their TGR scores by 13%. South Korea had the highest average TGR score in 2015.

The TGR scores of each shipyard in the considered countries differed; thus, we conducted a Kruskal–Wallis test to determine if the population mean TGR scores differed among the three countries. For 2014 and 2015, the p -values of the test statistics were 0.001 and 0.004, respectively, and obviously less than 0.005. The result demonstrated that the average TGR scores for the three countries differed at a 99.5% confidence interval. The results of TGR analysis and Kruskal–Wallis test prove that in 2014 and 2015, Japan and South Korea, respectively, were the leaders in the global shipbuilding industry.

4.3 Productivity change

In addition to measuring contemporaneous productivity and TGR, we applied MMPI to investigate the productivity change in each DMU from 2014 to 2015. Because EC, BPC and TGC were ratios of corresponding scores between two years, a score larger than one means the index improved in the second year. By contrast, an index was worse in the second year if

DMU	Shipyards	2014			2015		
		Metafrontier productivity	Contemporary productivity	TGR	Metafrontier productivity	Contemporary productivity	TGR
K1	Daewoo	0.426	0.574	0.742	0.821	1.000	0.821
K2	Samsung H.I.	0.284	0.381	0.746	0.373	0.418	0.891
K3	Hyundai Mipo	0.865	1.000	0.865	0.816	0.902	0.904
K4	SPP shipbuilding	1.000	1.000	1.000	1.000	1.000	1.000
K5	Sungdong S.B.	0.272	0.339	0.801	0.177	0.191	0.926
K6	STX shipbuild	0.326	0.358	0.909	0.410	0.440	0.933
K7	Hyundai H.I.	0.465	0.538	0.864	0.470	0.562	0.837
K8	Hyundai Samho	0.311	0.419	0.743	0.377	0.408	0.924
C1	Shanghai Waigaoqiao	0.228	0.655	0.348	0.169	0.483	0.349
C2	Jiangsu New YZJ	0.554	1.000	0.554	0.602	1.000	0.602
C3	Hudong Zhonghua	0.159	0.373	0.426	0.477	0.809	0.590
C4	Jiangsu Rongsheng	0.041	0.104	0.393	0.017	0.030	0.575
C5	Chengxi shipyard	0.092	0.172	0.533	0.457	1.000	0.457
C6	Weihai Samjin	0.069	0.162	0.426	0.026	0.074	0.349
C7	Jiangnan Changxing	0.062	0.174	0.354	0.138	0.235	0.586
J1	Oshima S.B. Co.	0.741	0.902	0.821	1.000	1.000	1.000
J2	Imabari S.B.	0.619	0.938	0.660	0.389	1.000	0.389
J3	Namura shipbuilding	0.900	0.900	1.000	0.608	0.629	0.967
J4	JMU Ariake shipyard	1.000	1.000	1.000	0.501	0.501	1.000
J5	Mitsubishi H.I.	0.189	0.189	1.000	0.401	0.401	1.000
J6	Tsuneishi Zosen	1.000	1.000	1.000	0.814	1.000	0.814

Table 8.
Scores of TGR

its score was less than one. A score equal to one indicated no change in the index in both years.

Table 9 lists the intertemporal indexes of each DMU measured. The average of the MMPI scores for the major shipyards in these three countries was all larger than one; thus, they all improved their productivity over the period under consideration. Chinese shipyards made more active improvement than did the South Korean and Japanese because the average MMPI score of the Chinese shipyards was as high as 1.86. Although the average MMPI scores of South Korea and Japan were both larger than one, these two countries only maintained their productivity because the scores were very close to one.

Table 9 also presents the average EC, BPC and TGC scores for each shipyard. In terms of TGC, only the average score of China was larger than one. The strong growth of EC, BPC and TGC increased China's average MMPI score. The pattern of EC and BPC scores for the South Korean shipyards was opposite to that of the Chinese shipyards. Although the average EC and BPC scores were slightly greater than one, the decline in TGC weakened the growth of the MMPI score of the South Korean shipyards. Japanese shipyards maintained their productivity because the average scores of these indexes were all close to one.

Finally, as equation (5) demonstrates, an MMPI score can be decomposed into the product of three indexes – EC, BPC and TGC – and the change of an MMPI score can be ascertained by observing whether each index is progressing or regressing. Because each index indicated two statuses, all shipyards could be divided into eight sets according to the combination of the status indicated by a shipyard's EC, BPC and TGC. Based on this idea, all shipyards were divided into eight sets (Table 10) to further examine the reason for changes in intertemporal productivity as follows:

Country	DMU	Shipyards	EC	BPC	TGC	MMPI
South Korea	K1	Daewoo	1.743	1.046	1.019	1.857
	K2	Samsung H.I.	1.098	0.953	0.961	1.005
	K3	Hyundai Mipo	0.902	0.921	0.931	0.774
	K4	SPP shipbuilding	1.000	1.131	1.026	1.160
	K5	Sungdong S.B.	0.563	1.005	0.982	0.556
	K6	STX shipbuild	1.227	1.045	0.902	1.157
	K7	Hyundai H.I.	1.044	0.944	0.979	0.965
	K8	Hyundai Samho	0.974	0.981	1.045	0.999
China	Average		1.07	1.00	0.98	1.06
	C1	Shanghai Waigaoqiao	0.738	1.220	0.842	0.758
	C2	Jiangsu New YZJ	1.000	1.112	1.000	1.112
	C3	Hudong Zhonghua	2.170	1.112	1.510	3.643
	C4	Jiangsu Rongsheng	0.289	1.187	1.114	0.382
	C5	Chengxi shipyard	5.827	1.119	0.707	4.607
	C6	Weihai Samjin	0.458	1.112	1.000	0.509
	C7	Jiangnan Changxing	1.349	1.215	1.240	2.032
Japan	Average		1.69	1.15	1.06	1.86
	J1	Oshima S.B. Co.	1.108	1.006	1.278	1.425
	J2	Imabari S.B.	1.066	1.014	0.643	0.696
	J3	Namura shipbuilding	0.699	1.047	1.000	0.732
	J4	JMU Ariake shipyard	0.501	1.181	1.000	0.592
	J5	Mitsubishi H.I.	2.128	1.181	1.000	2.513
	J6	Tsuneishi Zosen	1.000	0.610	1.000	0.610
	Average		1.08	1.01	0.99	1.09

Table 9.
Scores of
intertemporal
indexes of each DMU
(2014-2015)

									Productivity of major shipyards
No.	Sets	DMU	Shipyards	EC	BPC	TGC			
1	Shipyards with efficiency gain, technology progress and technical leadership progress	K1	Daewoo	1.74	≥ 1	1.05	≥ 1	1.02	≥ 1
		K4	SPP shipbuilding	1.00		1.13		1.03	
		C2	Jiangsu New YZJ	1.00		1.11		1.00	
		C3	Hudong	2.17		1.11		1.51	
			Zhonghua						
		C7	Jiangnan	1.35		1.21		1.24	
			Changxing						
2	Shipyards with efficiency gain, technology progress and technical leadership regress	J1	Oshima S.B. Co.	1.11		1.01		1.28	
		J6	Mitsubishi H.I.	2.13		1.18		1.00	
		K6	STX shipbuild	1.23	≥ 1	1.05	≥ 1	0.90	≤ 1
		J2	Imabari S.B.	1.07		1.01		0.64	
		C5	Chengxi shipyard	5.83		1.12		0.71	
3	Shipyards with efficiency gain, technology regress and technical leadership progress	J6	Tsuneishi Zosen	1.00	≥ 1	0.61	≤ 1	1.00	≥ 1
4	Shipyards with efficiency loss, technology progress and technical leadership progress	C4	Jiangsu	0.29	≤ 1	1.19	≥ 1	1.11	≥ 1
			Rongsheng						
		C6	Weihai Samjin	0.46		1.11		1.00	
		J3	Namura shipbuilding	0.70		1.05		1.00	
5	Shipyards with efficiency gain, technology regress and technical leadership regress		JMU Ariake shipyard	0.50		1.18		1.00	
		K2	Samsung H.I.	1.10	≥ 1	0.95	≤ 1	0.96	≤ 1
		K3	Hyundai H.I.	1.04		0.94		0.98	
6	Shipyards with efficiency loss, technology progress and technical leadership regress	K5	Sungdong S.B.	0.56	≤ 1	1.01	≥ 1	0.98	≤ 1
		C1	Shanghai Waigaoqiao	0.74		1.22		0.84	
7	Shipyards with efficiency loss, technology regress and technical leadership progress	K8	Hyundai Samho	0.97	≤ 1	0.98	≤ 1	1.04	≥ 1
8	Shipyards with efficiency loss, technology regress and technical leadership regress	K3	Hyundai Mipo	0.90	≤ 1	0.92	≤ 1	0.93	≤ 1

207

Table 10. Categorization of shipyards by intertemporal indexes (2014-2015)

207

Table 10.
Categorization of
shipyards by
intertemporal
indexes (2014-2015)

- (1) Shipyards with efficiency gain, technological progress and technical leadership progress as follows: from 2014 to 2015, Daewoo, SPP shipbuilding, Jiangsu New YZJ, Hudong Zhonghua, Jiangnan Changxing, Oshima S.B. Co. and Mitsubishi H.I. obtained excellent EC, BPC and TGC scores, which put these shipyards into this set. Shipyards in this set should maintain their advantage in the shipbuilding industry.
- (2) Shipyards with efficiency gain, technological progress and technical leadership regression as follows: STX shipbuild of South Korea, Imabari S.B. of Japan and Chengxi Shipyard of China were included in this set because they improved their productivity within their countries but did not catch up with the leading technology in other countries. Therefore, shipyards in this set should further improve their productivity by referring to the technologies used by shipyards in other countries that exhibit high productivity.
- (3) Shipyards with efficiency gain, technological regression and technical leadership progress as follows: one Japanese shipyard, Tsuneishi Zosen, was in this set. It improved its efficiency and curtailed the technology gap between the best practice

frontier of Japan and the metafrontier but widened the gap between the contemporaneous frontier and best practice frontier of Japan. Tsuneishi Zosen should attempt to increase its productivity by referring to the efficient shipyards in Japan.

- (4) Shipyards with efficiency loss, technological progress and technical leadership progress as follows: this set comprises Jiangsu Rongsheng and Weihai Samjin of China and Namura shipbuilding and JMU Ariake shipyard of Japan. These four shipyards made substantial progress by narrowing the gaps between the metafrontier, country frontier and the contemporaneous frontier. However, these four shipyards did not get closer to their contemporaneous frontier in 2015. Therefore, the shipyards in this set should attempt to catch up with their peer-efficient shipyards in the same country.
- (5) Shipyards with efficiency gain, technological regression and technical leadership regression as follows: Samsung H.I. and Hyundai H.I. of South Korea were included in this set. They improved their productivity to get closer to their contemporaneous frontier in 2015. However, the productivity of their peer-efficient shipyards declined in 2015, enlarging the gaps between the contemporary frontier, best practice frontier and metafrontier. Accordingly, these two shipyards should make efforts to narrow these gaps by referring to efficient shipyards in Japan and China.
- (6) Shipyards with efficiency loss, technological progress and technical leadership regression as follows: Sungdong S.B. of South Korea and Shanghai Waigaoqiao of China were in this set. These two shipyards should increase their production technology and benchmark their production technology by referring to shipyards with high productivity in other countries, especially the leading shipyards of Japan.
- (7) Shipyards with efficiency loss, technological regression and technical leadership progress as follows: only Hyundai Samho of South Korea was in this set. Although its corresponding gap between the best practice frontier and the metafrontier narrowed, Hyundai Samho should attempt to increase its production technology. Additionally, because the gap between the contemporary frontier and the best practice frontier widened, Hyundai Samho should benchmark the best technology used by leading South Korean shipyards.
- (8) Shipyards with efficiency loss, technological regression and technical leadership regression as follows: only Hyundai Mipo of South Korea was in this set. This shipyard should attempt to improve its production technology by increasing the utilization of its dock area and workers. Additionally, the technology of peer shipyards with high productivity in South Korea should be surveyed and benchmarked because Hyundai Mipo did not use its input efficiently compared with its peer shipyards in South Korea. Furthermore, the technologies used by leading shipyards in Japan and China should also be benchmarked to narrow the gap in technical leadership.

5. Conclusions

Shipyards have been playing important roles in the shipping industry by providing various conveyances by water. Shipyard operations are capital intensive because the inputs are expensive and perishable, they cannot be reserved when no ships are being built in a shipyard. Therefore, measuring the productivity of shipyards is critical in the examination of the utilization of the critical inputs and the performance of outputs. This study focused on the top three countries in the global shipbuilding industry to evaluate the productivity of 21

major shipyards. The TGR of these shipyards were also measured and compared based on their nationalities.

The findings obtained from our empirical study can be summarized as follows. First, major shipyards in Japan and South Korea had better scores than shipyards in China in contemporaneous productivity in 2014 and 2015. We further measured the technology gap between these three countries and Japan held the leading position in 2014 but was replaced by South Korea in 2015. Notably, the difference in TGR scores between South Korea and Japan was nonsignificant, but significance was proven between China and the other two countries. This result implies that South Korea and Japan were the leaders in the industry in 2014 and 2015. Second, among shipbuilding countries, China ranked third and it excelled in productivity change, with a strong average score of MMPI in the period 2014-2015. This result indicates that shipyards in South Korea and Japan should use technological advancements to upgrade their productivity because shipyards in China were actively improving their productivity.

The contribution to the literature of this study is threefold. First, few studies in the literature have investigated the productivity of shipyards and this study is the first to use a metafrontier framework to measure the TGR of shipyards between major shipbuilding countries. Because the global shipbuilding market is oligopolistic and dominated by a few countries, measuring and comparing the shipbuilding productivity in terms of countries is a critical task. Our model and approach objectively analyze the productivity of major shipyards and considers their nationalities. Second, this study is the first to measure changes in the productivity of shipyards. Such an analysis examines the productivity of major shipyards and countries from a dynamics perspective. The results of this study demonstrate that in 2014 and 2015, the major shipyards of South Korea and Japan were the leads; however, they should pay attention to their major competitors in China, who made obvious progress in upgrading their productivity. Third, by decomposing the MMPI, major shipyards are categorized into eight sets according to their changes in EC, BPC and TGC. Thus, the results of this study provide a clear direction for shipyards to improve their productivity. Finally, because of data availability, the period for analysis covered only 2014 and 2015. Thus, further research should use a data set of more than two years to measure productivity change over a longer period to further examine the productivity change trend of leading shipyards and shipbuilding countries.

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