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A bi-objective environmental-economic optimisation of hot-rolled steel coils supply chain: A case study in Thailand

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ABSTRACT

Steel production is an energy intensive industry, emitting a considerable amount of CO_2 which contributes to global warming. Many sources of energy may be used in steel production, incurring different costs. This research studies the effects of different decisions in the supply chain network for the production of hot-rolled steel coils (HRSC) in Thailand. The objectives are to minimise the total cost of HRSC production as well as to minimise the total CO_2 emissions in order to reduce environmental impact. Towards meeting these two objectives, a mathematical model is proposed to simultaneously determine the choices of energy, raw materials, and transportation modes with regard to production, network, and business constraints. Via examination of the price differences for available raw materials and energy sources several scenarios are investigated to evaluate their impact on both environmental and economic requirements of the supply chain. The analysis shows that the optimal solutions are greatly affected by changes in the prices of slabs and scrap, and the cost of electricity, whereas fuel oil and natural gas prices only affect the choice of fuel for the pre-heating process of the slabs. Strategies to operate under different scenarios are also discussed.

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1. Introduction

Climate change induced by global warming and carbon emissions has been a growing concern in recent decades. Steel manufacturing is one of the most energy intensive industries, and is responsible for 25 % of industrial carbon emissions, or about 9 % of the carbon emissions from energy and processes [1]. The World Steel Association [2] collected crude steel production data from 66 countries and recorded that the annual production in 2015 reached 1,621 million metric tonnes, accounting for approximately 98 % of the total world crude steel production. In order to tackle climate change and reduce carbon emissions caused by the iron and steel industry, the International Iron and Steel Institute (IISI) submitted proposals to governments in many countries to seek cooperation in order to develop and create new methods of production [3]. New technologies alone, however, are not sufficient to effectively reduce carbon emissions, and there is a need to develop suitable management decision tools to facilitate the carbon reduction mission.

There are several studies addressing energy consumption, environmental impacts, and cost reduction in the steel industry in many countries across the globe. For instance, Geilen and Moriguchi [4] developed a mathematical model in the context of the Japanese iron and steel industry, and investigated the impact of CO_2 taxes on technology selection and other factors. Ruth and Amato [5] investigated the implications of changes in the cost of carbon on energy usage and carbon emission. They indicated that in the case of the US iron and steel industry, emissions could be reduced by accelerating the shift to electric arc furnaces or by increases in the penalty costs of carbon emissions by perhaps technology-led policies. Zhang and Wang [6] identified that energy in iron and steel manufacturing could be saved by adopting certain production techniques such as pulverised coal injection and continuous casting, and observed that large Chinese steel manufacturers tended to be more energy efficient than the smaller ones. Soheili [7] estimated that by improving production technology the oil consumption in the Iran iron and steel industry could be reduced by about 45.8 million barrels. Tongpool *et al*. [8] studied environmental impacts of various steel product forms such as slab, hot-rolled, cold-rolled, and galvanised steel in Thailand. They recommended that energy consumption could be reduced by the use of more steel scrap. Johansson and Soderstrom [9] investigated energy efficiency measures and fuel conversion options in order to reduce CO_2 emissions in the Swedish iron and steel industry. It must be noted that the above studies tend to be based on iron and steel production processes in individual plants in particular countries, rather than on considerations of the supply chain as a whole, and as such the studies have not taken the effects of transportation into account.

Modern management forces firms to integrate transportation planning in their management decisions in order to reduce costs and provide improved service to customers. Simultaneous integration of production and transportation in a supply chain has gained considerable interest in various models. Lee and Kim [10] extended the concept of Byrne and Bakir [11] by combining analytical and simulation models to solve production-distribution planning problems that involved multi-products and multi-periods in supply chains. Zamarripa *et al*. [12] considered two different supply chains, each consisting of three stages, to simultaneously minimise system costs and accumulated delivery times from different production echelons to the storage centres. They used a mixed integer linear programming model to optimise the supply chain planning problem. Dehghanbaghi and Sajadieh [13] studied complementary products and jointly optimised their production, inventory, and transportation by assuming certain convexity properties. Gholamian and Heydari [14] integrated transportation operations and routing with location decision and inventory control to minimise the overall cost. Koc *et al*. [15] coordinated inbound and outbound transportation with production schedules. Their study assumed that the vehicles for both inbound and outbound transportation could be jointly utilised.

Even though steel is being increasingly substituted by lighter materials in automobiles, it still accounts for about half of the vehicle weight. Steel sheets produced from hot-rolled coils (HRSC) are perhaps the highest value added item among steel products and are extensively used in the automotive industry [16]. Since the whole steel supply chain encompasses a spectrum of steel manufacturers and products, this research is focused on the HRSC portion of the supply chain, by using the case of Thailand. Thailand is the second largest economy in the Southeast Asia region (based on the 10 member states of ASEAN), and a leading car manufacturing country in the region. In 2016, the country was ranked 12th in the world in total automotive production with specialisation in light trucks and passenger cars [17]. It is also the third largest steel producer in the ASEAN region with annual production of 10 million metric tonnes [18].

The organisation of the paper is as follows. The next section gives the background of the HRSC supply chain problem in more detail. Section 3 describes the mathematical model of the problem by which the energy cost and CO_2 emission are to be minimised. The energy cost in the model considers both the production and transportation costs. Section 4 contains numerical data of the HRSC supply chain case study in Thailand. The results and operational strategies are then discussed in Section 5. Finally, Section 6 concludes the observations of the study.

2. Background of hot-rolled steel coils supply chain in Thailand

The steel supply chain starts from iron ore smelting factories as the upstream part of the supply chain. The products from the smelting factories are called pig iron, crude iron or crude steel (depending upon the shape and chemical composition). Refined liquid steel is cast into billets, blooms, and slabs to suit the production in the next part of the chain. The midstream steel mills transform these primary steel products into beams, rods, or coils, known as semi-finished products, through various methods such as hot rolling and cold rolling. The semi-finished products are later processed into the final products in various industries in the downstream of the supply chain [19].

Thailand is the second largest economy among the 10 member states of ASEAN, behind only Indonesia. The two countries together account for over half of the GDP of the ASEAN region, a contribution of over 1.25 trillion USD annually [20]. They are also leading automotive manufacturers of the region, and are major users of steel products. Nonetheless, the steel supply chain in these countries differ as there are iron ore smelting factories in Indonesia but none in Thailand. Hot-rolled steel coils (HRSC) make up over 30 % of the semi-finished steel products in Thailand as they are a versatile material that can be used in a wide–range of economically important industries [21].

For the HRSC supply chain in Thailand, there are two steel mills that can produce suitable steel slabs. The slabs are processed by five HRSC factories, two of which are also slab producers. The study also considers 13 customers who use the HRSC as the raw material for their production routes. These customers manufacture steel products such as cold-rolled steel pipes and cold formed structural steel sections. The pig iron used in primary steel production for HRSC can be imported through four ports. The mode of transportation from the ports is by road, with additional marine transportation to a customer from a HRSC producer.

The two steel mills can also use steel scrap as raw material for primary steel production cast as slabs and can then send slabs directly through conveyers for integrated HRSC production. Therefore, they require only internal transportation between the slab and HRSC production processes. Imported steel scrap arrives at sea-ports. Domestic scrap is collected and the suppliers also often transport the scrap by marine transportation to save cost. Thus, it is assumed that steel scrap is obtained through ports. Some HRSC are directly imported from overseas and sold through the HRSC factories. Fig. 1 summarises the HRSC supply chain network in Thailand.

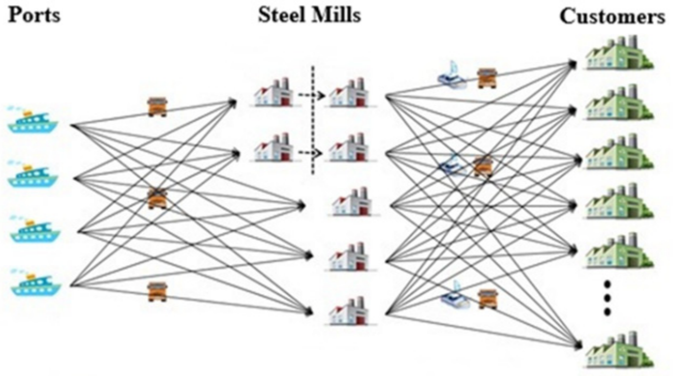

Fig. 1 The structure of the HRSC supply chain network in Thailand

To minimise the total costs in the HRSC supply chain, there are three sets of decision variables involved. The first set indicates the amounts of pig iron, steel scrap, and slabs to be acquired through the ports, and the proportions to be sent to the different HRSC mills. The second set determines the suitable production at each of the HRSC mills. The third set represents the amounts of HRSC to be transported to the customers via the two transportation modes. The values of these decision variables influence the total cost as well as the total CO_2 emissions in the supply chain. The objectives are to minimise both the total costs and the CO_2 emissions.

HRSC production may use fuel oil or natural gas as the energy source in the pre-heating process. Some of the mills in the supply chain do not locate along the national natural gas pipeline, so these mills do not have access to natural gas and can only use fuel oil in their production. The HRSC supply chain situation can be formulated as a bi-objective optimisation problem as shown in the next section.

3. Mathematical formulation

The HRSC supply chain optimisation problem with total costs and CO_2 emission minimisation objectives can be formulated as follows.

3.1 Notation

The notation of the mathematical programme is below:

Indices

i	fuel input i = 1,2,3 (1 = electricity, 2 = fuel oil, 3 = natural gas)
j	product j = 1,2,3,4 (1= pig iron, 2 = steel scrap, 3 = steel slabs, 4 = HRSC)
k	steel mill k = 1,2,…,5
l	customer l = 1,2,…,13
m	mode of transportation m = 1,2 (1 = road, 2 = marine)
n	source of raw material n = 1,2 (1 = domestic, 2 = imported)
p	port p = 1,2,3,4
q	% load

Decision variables

X_{ijk}	production volume by fuel input i to produce product j at steel mill k
Y_{jknp}	purchased volume of product j for steel mill k from source of raw material n and from port p
HRC_{klm}	volume of HRSC from steel mill k to customer l by transportation mode m

Costs

PC_{ijk}	unit production cost by fuel input i to produce product j at steel mill k
MC_{jknp}	unit material cost of product j for steel mill k from source of raw material n from port p
MTC_{jknp}	unit material transportation cost of product j for steel mill k from source of raw material n from port p
$FGTC_{klm}$	unit HRSC transportation cost from steel mill k to customer l by transportation mode m

Demand and capacities

D_l	demand volume of customer l
$CAPF_{jk}$	capacity of production of product j by steel mill k
$CAPRM_{jn}$	maximum amount of product j that can be purchased from source n
$CAPT_m$	capacity of transportation mode m

Emission factors

PE_{ijk}	emission factor of production process by fuel input i to produce product j at steel mill k
MTE_{jknpq}	emission factor of material transportation of product j to steel mill k from source of raw material n and from port p with % load q
$FGTE_{klmq}$	emission factor of HRSC transportation from steel mill k to customer l with % load q

Loss and raw materials

α	proportion of pig iron used to produce slabs
β	loss percentage of raw material in the production process
RM	amount of raw material

3.2 Constraints

Demand and supply

The total production and imported HRSC must meet the total demand of the customers.

$$\sum_{k=1}^{5}\sum_{i=1}^{3} X_{i4k} \geq \sum_{l=1}^{13} D_l \tag{1}$$

The HRSC delivered from the steel mills must meet the demand of each customer.

$$\sum_{m=1}^{2}\sum_{k=1}^{5} HRC_{klm} \geq D_l, \qquad \forall l \tag{2}$$

The total amount of HRSC produced and imported must at least equal to the total amount of HRSC delivered to the customers.

$$\sum_{k=1}^{5}\sum_{i=1}^{3} X_{i4k} \geq \sum_{m=1}^{2}\sum_{l=1}^{13}\sum_{k=1}^{5} HRC_{klm} \tag{3}$$

The amount of HRSC produced and imported by each HRSC mill must at least equal to the total amount sent to the customers.

$$\sum_{i=1}^{3} X_{i4k} + \sum_{p=1}^{4} Y_{4k2p} \geq \sum_{m=1}^{2}\sum_{l=1}^{13} HRC_{klm}, \qquad \forall k \tag{4}$$

There is no HRSC received from domestic sources.

$$Y_{4k1p} = 0, \qquad \forall k, p \tag{5}$$

The total amount of slabs produced and/or purchased as the raw material by each steel mill must be at least equal to the total amount of HRSC.

$$\sum_{i=1}^{3} X_{i3k} + \sum_{p=1}^{4} Y_{3k2p} \geq \sum_{i=1}^{3} X_{14k}, \qquad \forall k \tag{6}$$

For HRSC mills 3, 4 and 5, there is no HRSC received from domestic sources.

$$Y_{4k1p} = 0, \qquad \text{for } k = 3,4,5 \text{ and } \forall p \tag{7}$$

Capacity and utilization

The total production of each product at each HRSC mill must not exceed its capacity.

$$\sum_{i=1}^{3} X_{ijk} \leq CPAF_{jk}, \qquad \forall j, k \tag{8}$$

The HRSC mills 3, 4, and 5 cannot produce slabs.

$$\sum_{k=3}^{5}\sum_{i=1}^{3} X_{i3k} = 0 \tag{9}$$

Every HRSC mill cannot produce pig iron or scrap.

$$\sum_{j=1}^{2}\sum_{i=1}^{3} X_{ijk} = 0, \qquad \forall k \tag{10}$$

Material balance

The production of slabs in the mills 1 and 2 must equal the production of HRSC.

$$\sum_{i=1}^{3} X_{i3k} = \sum_{i=1}^{3} X_{i4k}, \qquad \text{for } k = 1,2 \tag{11}$$

A portion of the raw material for slabs is from pig iron.

$$\sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5} Y_{1knp} = \alpha RM \tag{12}$$

The rest of the raw material for slabs is from scrap.

$$\sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5} Y_{2knp} = (1-\alpha)RM \tag{13}$$

The amount of raw material must accommodate the loss in the slab production process.

$$RM = \beta \sum_{k=1}^{5}\sum_{i=1}^{3} X_{i3k} \tag{14}$$

The scrap purchased must not exceed the amount of available scrap.

$$\sum_{p=1}^{4}\sum_{k=1}^{5} Y_{jknp} \le CAPRM_{jn}\ , \qquad \forall j,n \tag{15}$$

Business structure

The following constraints are based on the business structure of the HRSC supply chain network in Thailand in which there are certain subsidiary companies within the chain. As a result, certain mills prefer to serve some customers more than the others.

The total transportation from HRSC mills 1 and 2 must meet the demand of customer 6.

$$\sum_{m=1}^{2}\sum_{k=1}^{2} HRC_{k6m} + \sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{2} Y_{4knp} \ge D_6 \tag{16}$$

The total HRSC transported from mill 3 must meet the demand of customer 1.

$$\sum_{m=1}^{2} HRC_{31m} + \sum_{p=1}^{4}\sum_{n=1}^{2} Y_{43np} \ge D_1 \tag{17}$$

The total HRSC transported from mill 4 must satisfy the demand of customer 12.

$$\sum_{m=1}^{2} HRC_{412m} + \sum_{p=1}^{4}\sum_{n=1}^{2} Y_{412np} \ge D_{12} \tag{18}$$

The total HRSC transported from mill 5 must meet the demand of customer 11.

$$\sum_{m=1}^{2} HRC_{511m} + \sum_{p=1}^{4}\sum_{n=1}^{2} Y_{411np} \ge D_{11} \tag{19}$$

The HRSC mills 1, 2, 4, and 5 cannot access marine transportation.

$$HRC_{kl2} = 0\ , \qquad \text{for } k = 1,2,4,5 \text{ and } \forall l \tag{20}$$

Decision variables

All of the decision variables are non-negative.

$$X_{ijk} \ge 0\ , \qquad \forall i,j,k \tag{21}$$

$$Y_{jknp} \ge 0\ , \qquad \forall j,k,n,p \tag{22}$$

$$HRC_{klm} \ge 0\ , \qquad \forall k,l,m \tag{23}$$

3.3 Objectives

Two objectives as in this formulation.

z_1 : Cost Optimisation (CO). This objective is to minimise the total costs which consist of production cost (TPC), raw material cost (TMC), and transportation cost (TTC).

Min $$z_1 = TPC + TMC + TTC \tag{24}$$

z_2 : Emission Optimisation (EO). This objective is to minimise the total CO_2 emission which includes emission from production process (TPE) and transportation (TTE).

Min $$z_2 = TPE + TTE \tag{25}$$

Total costs

The total production cost is determined by the unit production cost multiplied by the production volume.

$$TPC = \sum_{k=1}^{5}\sum_{j=1}^{5}\sum_{i=1}^{3} C_{ijk} X_{ijk} \tag{26}$$

The material cost is calculated from the unit material cost multiplied by the total amount of material acquired.

$$TMC = \sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5}\sum_{j=1}^{5} MC_{jknp} Y_{jknp} \tag{27}$$

The transportation cost includes the raw material transportation cost from the ports to the mills, and the HRSC transportation cost from the mills to the customers. The raw material transportation cost is determined by the unit material transportation cost multiplied by the number of trips from the ports. Similarly, the HRSC transportation cost is given by the unit HRSC transportation cost multiplied by the number of trips that the HRSC is transported. The notation ⌈•⌉ represents rounding up of the number inside the symbol.

$$TTC = \sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5}\sum_{j=1}^{5} MTC_{jknp} \left\lceil \frac{Y_{jknp}}{CAPT_m} \right\rceil + \sum_{m=1}^{2}\sum_{l=1}^{13}\sum_{k=1}^{5} FGTC_{klm} \left\lceil \frac{HRC_{klm}}{CAPT_m} \right\rceil \tag{28}$$

Total CO_2 emission

The total emission is determined by the unit emission per tonne of production multiplied by the production volume.

$$TPE = \sum_{k=1}^{5}\sum_{j=1}^{5}\sum_{i=1}^{3} PE_{ijk} X_{ijk} \tag{29}$$

The emission from transportation consists of the emissions from raw material and HRSC transportation. The raw material transportation emission comprises of the emissions of full-load and no-load of the trucks. Similarly, the HRSC transportation emission includes the full-load transportation emission calculated from the unit emission of full-load HRSC transportation per tonne multiplied by the total HRSC volume, and no-load transportation emission determined by the unit emission of no-load HRSC transportation multiplied by the total number of no-load trips.

$$\begin{aligned} TTE = &\left(\sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5}\sum_{j=1}^{4} MTE_{jknp1} Y_{jknp} + \sum_{p=1}^{4}\sum_{n=1}^{2}\sum_{k=1}^{5}\sum_{j=1}^{4} MTE_{jknp2} \left\lceil \frac{Y_{jknp}}{CAPT_m} \right\rceil \right) \\ &+ \left(\sum_{m=1}^{2}\sum_{l=1}^{13}\sum_{k=1}^{5} HRC_{klm} FGTE_{klm1} + \sum_{m=1}^{2}\sum_{l=1}^{13}\sum_{k=1}^{5} FGTE_{klm2} \left\lceil \frac{HRC_{klm}}{CAPT_m} \right\rceil \right) \end{aligned} \tag{30}$$

4. A case study

The steel mills are indicated as P1-P5. Their production capacities are shown in Table 1. The demands of the customers, D1-D13, are given in Table 2. The unit production costs based on the energy source in different steel mills are displayed in Table 3 (THB refers to Thai Baht which is Thailand's currency). The unit production costs of slabs in the steel mills 3, 4, and 5 are not shown in the table since these mills cannot produce slabs. Table 4 presents the unit material costs and availability of different materials.

Table 5 presents the unit transportation cost from the ports to the mills by trucks, each with 40 tonnes capacity. The unit transportation costs by road and marine of HRSC are shown in Table 6. Trucks of the same 40 tonnes capacity are also used in HRSC transportation. Only P3 has access to the marine transportation mode with 8,000 tonnes capacity per trip by barges. However, the barge transportation cannot be applied to customer 1.

Table 1 Production capacities of the steel mills (in 1,000 tonnes)

Product	Plant				
	P1	P2	P3	P4	P5
Slab	3,000	1,800	0	0	0
HRSC	3,000	1,800	4,000	1,000	500

Table 2 HRSC demands of the customers (in 1,000 tonnes)

Customer	D1	D2	D3	D4	D5	D6	D7
HRSC	720	240	600	150	180	336	60
Customer	D8	D9	D10	D11	D12	D13	
HRSC	180	176.4	104.4	3,900	54	180	

Table 3 Unit production costs by energy source and product (THB/tonne)

Energy	Plant				
	P1	P2	P3	P4	P5
Electricity – Slab	1,200	1,314	-	-	-
Electricity – HRC	1,104	930	408	540	474
Fuel oil – HRC	464	487	876	914	895
Natural gas – HRC	320	336	2,183	1,108	1,330

Table 4 Unit material costs and availability of raw materials

Cost/Availability	Product				
	Imported pig iron	Domestic scrap	Imported scrap	Imported slab	Imported HRC
Price (THB/tonne)	16,591	12,276	14,731	18,228	35,000
Capacity (tonnes)	560,063	2,478,273	12,599,807	452,9038	23,534,220

Table 5 The unit material transportation cost from ports to steel mills (THB/trip)

Port	Plant				
	P1	P2	P3	P4	P5
Port1	4,011	1,995	37,170	7,980	11,970
Port2	1,799	4,543	33,460	4,669	8,330
Port3	34,020	37,170	469	29,750	25,410
Port4	8,540	11,760	26,110	4,333	1,225

Table 6 The unit HRSC transportation cost by truck and barge (THB/trip)

Customer	Plant					
	P1	P2	P3	P3 (Barge)	P4	P5
D1	34,090	37,310	147	-	29,890	25,550
D2	3,948	1,806	36,750	17,000	7,770	11,830
D3	3,941	1,925	37,100	17,000	7,910	11,900
D4	1,316	2,611	34,930	14,500	5,719	9,730
D5	2,303	1,561	35,490	17,000	6,258	10,290
D6	10,010	13,230	24,780	13,500	5,950	1,547
D7	8,400	11,620	26,110	13,500	4,193	903
D8	10,360	13,510	26,950	13,500	6,111	1,540
D9	9,800	13,020	26,390	13,500	5,586	1,015
D10	8,890	12,110	25,970	13,500	4,669	791
D11	9,240	12,390	25,830	13,500	4,998	427
D12	8,890	12,110	25,340	13,500	4,746	427
D13	1,316	2,611	34,720	14,500	5,747	9,800

The unit production emission factors are presented in Table 7. The CO$_2$ emission in the production process is calculated from the energy used in the melting and pre-heating processes. Tables 8 to 12 show unit material and HRSC transportation emission factors, for both full-load and no-load of the two transportation modes.

Table 7 Unit production emission factors (kgCO$_2$/tonne)

Energy	Plant				
	P1	P2	P3	P4	P5
Elec – Slab	224.40	245.72	0	0	0
Elec – HRC	206.45	173.91	76.30	100.98	88.64
Fuel – HRC	65.37	68.62	123.32	128.74	126.03
NG – HRC	47.40	49.76	89.42	93.35	91.39

Table 8 Unit material transportation emission factors by full-load truck (kgCO$_2$/tonne)

Port	Plant				
	P1	P2	P3	P4	P5
Port1	2.30	1.14	21.29	4.57	6.86
Port2	1.03	2.60	19.17	2.67	4.77
Port3	19.49	21.29	0.27	17.04	14.56
Port4	4.89	6.74	14.96	2.48	0.70

Table 9 Unit material transportation emission factors by no-load truck (kgCO$_2$/trip)

Port	Plant				
	P1	P2	P3	P4	P5
Port1	44.72	22.24	414.45	88.98	133.47
Port2	20.06	50.65	373.08	52.06	92.88
Port3	379.32	414.45	5.23	331.71	283.32
Port4	95.22	131.12	291.13	48.31	13.66

Table 10 Unit HRSC transportation emission factors by full-load truck (kgCO$_2$/tonne)

Customer	Plant				
	P1	P2	P3	P4	P5
D1	19.53	21.37	0.08	17.12	14.64
D2	2.26	1.03	21.05	4.45	6.78
D3	2.26	1.10	21.25	4.53	6.82
D4	0.75	1.50	20.01	3.28	5.57
D5	1.32	0.89	20.33	3.58	5.89
D6	5.73	7.58	14.20	3.41	0.89
D7	4.81	6.66	14.96	2.40	0.52
D8	5.93	7.74	15.44	3.50	0.88
D9	5.61	7.46	15.12	3.20	0.58
D10	5.09	6.94	14.88	2.67	0.45
D11	5.29	7.10	14.8	2.86	0.24
D12	5.09	6.94	14.52	2.72	0.24
D13	0.75	1.50	19.89	3.29	5.61

Table 11 Unit HRSC transportation emission factors by no-load truck (kgCO$_2$/trip)

Customer	Plant				
	P1	P2	P3	P4	P5
D1	380.10	416.01	1.64	333.27	284.88
D2	44.02	20.14	409.76	86.64	131.90
D3	43.94	21.46	413.67	88.20	132.69
D4	14.67	29.11	389.47	63.77	108.49
D5	25.68	17.41	395.71	69.78	114.73
D6	111.61	147.51	276.30	66.34	17.25
D7	93.66	129.56	291.13	46.75	10.07
D8	115.51	150.64	300.49	68.14	17.17
D9	109.27	145.17	294.25	62.28	11.32
D10	99.12	135.03	289.57	52.06	8.82
D11	103.03	138.15	288.00	55.73	4.76
D12	99.12	135.03	282.54	52.92	4.76
D13	14.67	29.11	387.13	64.08	109.27

Table 12 Unit HRSC transportation emission factors of marine transportation of P3 to customers (kgCO$_2$/trip)

Customer	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13
Barge (full-load)	-	0.43	0.43	0.38	0.43	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.38
Barge (no-load)	-	0.43	0.43	0.38	0.43	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.38

5. Results, discussion and operational strategies

5.1 Numerical results

Using the data in Section 4 and Excel Premium Solver to obtain the optimal solutions, the results show that the total cost obtained based on the cost optimisation (CO) model is lower than for that based on emission optimisation (EO) by approximately THB 9.56 million or 16.08 %. Table 13 shows these results in more detail. On the other hand, the EO model emphasises reduction of the overall CO$_2$ emission of the supply chain. Therefore, the EO model yields lower total CO$_2$ emission than for that based on the CO model by about 620.63 thousand tonnes of CO$_2$ or 47.82 %. It is important to note that the solution from the EO model yields higher slab usage for which (not shown here) a large part must be imported. The EO model also suggests substantially lower scrap usage to reduce the energy (which leads to CO$_2$ emission) required for slab production.

The cost saved by the CO model is mainly from processing scrap to produce slabs because the price of imported slabs is higher than that of domestic slabs produced by P1 and P2. However, the cost saving incurs higher energy usage of electricity and fuel oil in comparison to the EO model. Electricity is consumed mainly in P1 and P2 to produce slabs. Moreover, among all the production plants P3 is the most active one using the highest amount of imported slabs. It should be noted that P3 utilises mainly fuel oil, and this leads to a sharp increase (46 %) in fuel oil usage in the solution to the EO model.

These results imply that there is a price to pay to obtain lower CO$_2$ emission. In comparing the results based on the CO and EO models, the reduction of about 620.63 thousand tonnes of CO$_2$ emission comes with the disadvantage of increased total cost of over 9.56 billion THB, or approximately 15.40 THB/kgCO$_2$. This cost per kgCO$_2$ may be used as a benchmark for the government when introducing policies to encourage steel mills to reduce their emissions. For example, CO$_2$ emission may be reduced by simply using cleaner energy sources such as natural gas.

The government may choose to subsidise the cost of natural gas to lower its price and encourage steel mills to use more natural gas for production. On the other hand, the results from the EO model involve greater use of imported slabs. To prevent excessive use of imported slabs and the weakening of the competitiveness of domestic slab manufacturers, the government may temporarily impose a higher import tax rate on slabs sourced overseas as and when required.

The production of HRSC involves costs and CO$_2$ emissions and their distribution (in percentage) is as shown in Table 14. From the table, the majority of the cost is located at P1 and P2 where scrap is processed to make slabs and then HRSC. In addition, these two mills also have access to the national natural gas pipeline. Natural gas is a cheaper source of energy than fuel oil. Hence, the production of HRSC is allocated to these two mills in order to reduce the overall cost

Table 13 The total cost, total emission, proportion of energy usage and material usage for the cost and emission optimisation models

Opt. model	Total cost (Millions THB)	Total emission (Millions kgCO$_2$)	Energy usage (%)			Material usage (%)		
			Melting process	Pre-heating process		Pig Iron	Scrap	Slab
			Electricity	Fuel Oil	Natural Gas			
Cost (A)	59,420.27	1,297.80	64	18	18	7	59	34
Emission (B)	68,975.51	677.18	32	0	68	1	9	90
(A)-(B)	9-,555.24	+620.63	+32	+18	-50	+6	+50	-54

of the supply chain. The cost incurred at P3, the third highest cost percentage, is spent on processing imported slabs to make HRSC. Since P3 can access marine transportation, which results in lower cost than trucks to the customers, it is highly utilised compared to P4 and P5. The results also show that P5 is preferred over P4 to process slabs, as indicated by the higher cost percentage. This is perhaps due to the proximity of customers, not already served by P1 to P3, being closer to P5 than P4.

Table 14 also shows that the production of HRSC in P1 and P2 is greatly reduced due to the import of slabs as already mentioned. Moreover, P3 imports most of the slabs and processes them to HRSC in this model because the model tries to utilise the cheaper marine transportation to the customers. P5 is also preferred over P4 in this model because close proximity between P5 to the customers leads to lower CO_2 emission.

Table 14 Percentage distribution of HRSC production

Model	Plant				
	P1	P2	P3	P4	P5
CO (%)	25	40	21	2	12
EO (%)	0	10	77	2	12

5.2 Sensitivity analysis and operational strategies

The prices of different energy sources and raw materials are key in the decisions to be made in the CO and EO models. Using the data from the past five years, the prices of the energy sources and raw materials change with ± 35 % range. Three energy sources, electricity, fuel oil and natural gas, as well as two raw materials, steel scrap and slabs, are tested for +35 % (High or H) and −35 % (Low or L) change in prices from the nominal values used in Section 5.1. The pig iron price is not examined here because its price often changes similarly with the price of the slabs.

A notation HHHHH represents the high level of all prices of electricity, fuel oil, natural gas, scrap, and slabs, respectively, whereas LLLLL denotes the low level in all five factors. Since there are five factors, each with two levels (high and low), there is a total of 32 scenarios to be tested. The results are summarised in Fig. 2. Table 15 highlights the total costs and total emission of the HHHHH, LLLLL, HHLLL, and LLLHL scenarios. The scenario of HHHHH yields the highest total cost as expected since prices of all the factors are at the high level (or most expensive). Likewise, the LLLLL scenario results in the lowest anticipated total costs. Fig. 2 also shows two interesting scenarios which are HHLLL and LLLHL. They are both trade-off points between the total costs and the total emission.

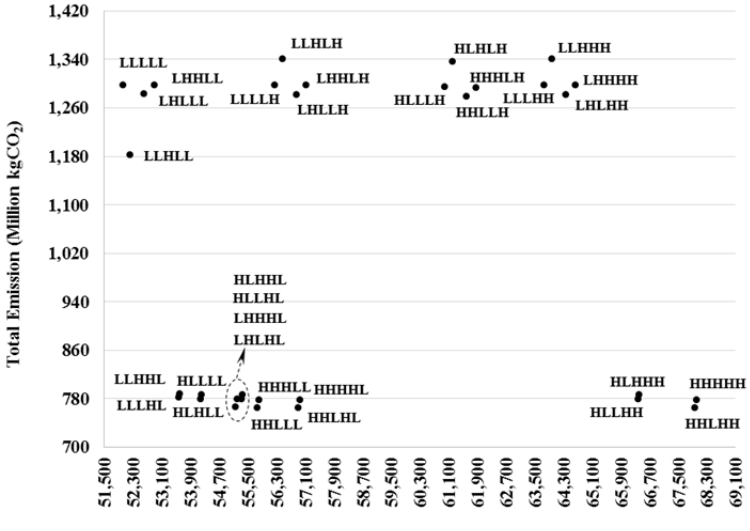

Fig. **2** Plot of total costs and total emission of 32 cases tested

Table 15 Total costs (in Millions THB) in the case of all high or low price levels

Case	Total Costs (Millions THB)	Total Emission (Millions kgCO$_2$)
HHHHH	68,017.83	778.51
LLLLL	52,015.28	1,297.80
LLLHL	53,562.74	782.42
HHLLL	55,759.24	765.00

In the LLLHL scenario in which all three energy sources are at their lowest price levels, the model may select any inexpensive source of energy to minimise the total costs. Comparing this scenario with the HHHHH situation, their total emission values are relatively similar but the total costs of the LLLHL scenario is less due to lower energy costs. As for the HHLLL scenario, both materials (scrap and slabs) are at their low price levels. Thus, the model tries to balance the usage of both materials to lower the total costs. Since only the natural gas factor is at the low level in the HHLLL scenario (the other two sources of energy are at the high levels), natural gas is preferred to keep the total costs low. However, the emission of the HHLLL scenario is lower than that of the LLLHL one.

We may conclude from these results and from Fig. 2 that the availability of inexpensive energy sources tends to lead to lower total costs. As for the total emission, it may not be totally conclusive. It should be noted, however, that the combination HL of the scrap and slabs, respectively, often leads to lower total emission.

In the HRSC supply chain, electricity is the primary source of energy in the production process. Increase in the electricity price will encourage imports of HRSC from overseas to avoid high production cost. Although not ideal from a metallurgical viewpoint fuel oil and natural gas could be used to melt scrap prior to casting into slabs. Increase in the prices of either fuel oil and natural gas may lead to reduction in scrap processing to keep the overall cost low. Increase in the domestic scrap price is likely to boost slab imports to be used as the raw materials for HRSC production. On the contrary, if the price of imported slabs increases, the steel mills may decide to increase utilisation of domestic scrap. Solutions that increase raw material imports are likely to decrease the total emissions in Thailand, but they may not yield the lowest total costs. To lower the total emission, the use of fuel oil should be avoided but the use of electricity and natural gas should be encouraged as the latter two are cleaner sources of energy.

Hence, the operational strategies could be summarised as the followings.

- The combination of high price of domestic scrap and low price of domestic slabs encourages lower total emission of the HRSC supply chain.
- When the domestic electricity price is high, HRSC should be imported to avoid high production cost.
- When the prices of fuel oil and natural gas are high, scrap processing should be reduced.
- When the price of the domestic scrap increases, scrap imports could be increased to lower the total costs; and domestic CO$_2$ emission is consequently decreased.
- To lower the total emission, fuel oil should be avoided.

Moreover, in the steel supply chain, there could be a sudden increase of imported raw materials, especially slabs, from "price dumping", particularly when the oversea suppliers have excess stocks. This can weaken the competitiveness of local suppliers if the situation becomes prolonged. In this situation, the government may impose temporary measures to counterbalance the price of the imported materials. To encourage the use of cleaner sources of energy, the government may issue policies to subsidise certain sources of energy that has low CO$_2$ emission rate, or impose additional taxes to those energy sources with high rate of CO$_2$ emission.

6. Conclusion

This research develops a bi-objective model of the HRSC supply chain in Thailand. The objectives are to minimise the total costs (CO model) of the HRSC production as well as to minimise the total CO$_2$ emission (EO model) in order to reduce environmental impact. The HRSC supply chain consists of four ports, five steel mills (P1 to P5), and 13 customers. There are three sources of energy, four types of products, and two modes of transportation, full-load and no-load trips, and two sources of materials. To demonstrate the use of the model, numerical data from the HRSC supply chain in Thailand are applied.

The results show that different objectives yield different production and energy usage. In the solution of the CO model, P2 and P1 should produce 40 % and 25 % of the total production, respectively, while electricity is used as the primary source of energy in the production of about 2/3 of all the energy required. But in the EO model, the total domestic production is reduced to cut down emissions. Among the other three steel mills, the majority or 77 % of the additional production is assigned to P3 which is located closest to the customers, resulting in reduction of the emissions caused by transportation. The steel mill P1, on the other hand, should limit its production since it is located furthest from the customers. This, however, may be difficult to implement in certain situations as there is a minimum production requirement to keep the mill open and operating efficiently.

Strategies for certain circumstances are suggested depending upon the objective of minimising the total costs or the total emissions or both. Moreover, during the initial period of price dumping, the government may temporarily impose import tax to safeguard competitiveness of the local manufacturers. Governmental policies and support to promote the use of cleaner energy sources are highly encouraged to stimulate sustainability of the industry.

The model presented in this research is a specific example of a more general three-echelon supply chain model, specifically suppliers (or ports in this case)-manufacturers-customers. Future research may consider inclusion of uncertainty, such as via demands and costs.

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