Evaluation of the integration of recycling unit in an iron manufacturing plant

E Arriola1,2, I H V Gue1,3, A T Ubando1,2,4, R R Tan5

1 Mechanical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
2 Thermomechanical Analysis Laboratory, De La Salle University – Manila: Laguna Campus, LTI Spine Road, Laguna Blvd, Biñan, Laguna 4024, Philippines
3 Mechanical Engineering Department, FEU – Institute of Technology, 839 P. Paredes Street, 1015 Manila, Philippines
4 Center for Engineering and Sustainable Development Research, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines
5 Chemical Engineering Department, De La Salle University, 2401 Taft Avenue, 1004 Manila, Philippines

aristotle.ubando@dlsu.edu.ph

Abstract. Manufacturing of new steel from virgin iron ore is not only an energy intensive process but also generates a considerable amount of annual carbon footprint with respect to the world’s total carbon generation. It is actually considered as the highest carbon footprint generated among the heavy industries. Considering these characteristics of steel making, recycling technologies from scrap metal had been an area of interest in the circular economy framework. Production of new steel from scrap metals only requires as little as 10% of the energy used in the production of steel from virgin materials. This study aims to integrate a scrap metal recycling unit in an existing iron manufacturing plant using an optimization model that evaluates the carbon footprint. LINGO is used for the optimization model. The results have shown that carbon emission was reduced by 10.35% and significantly reduced one of the raw materials, coal, by 35.44%. The total power consumption was also reduced by 15.42%.

1. Introduction
The steelmaking industry is notably connected in the development of the global economy. As majority of the world’s economic sector requires steel, economic growth is reliant on the industry’s production. The industry, however, is known to be resource-intensive and energy intensive. This is in addition to the logistical challenges between resource-rich countries and steel producing countries as sea trade becomes a necessary step [7]. The report of the International Energy Agency determined that the current steelmaking production results to 6.7% of the world’s annual carbon footprint, ranking the industry as the highest among ‘heavy industries’ [9]. The same report also ranked the industry as the largest consumer of coal as an energy
source. Considering its demand will increase three folds in the next 30 years, sustainable production practices must be implemented to ensure a sustainable future.

Although steel is a recyclable material, current production and consumption patterns have yet fully optimized this characteristic. Secondary steel production has significant advantages over primary steel production. Mousa et al. [15] showed that secondary steel requires approximately half of the required energy than that of primary steel. Although there is a larger energy requirement, primary steelmaking still accounts for three quarters of the world’s production. Shifting current practices towards cleaner production is necessary. Ma et al. [12] indicated that the steelmaking industry will need to shift towards a new sustainability paradigm, Circular Economy (CE), to maintain its development and improve its environmental impact.

The concept of CE promotes resource efficiency, waste minimization, and prolonged product life. Its application is not constrained to a specific scale as it is applicable to companies, industrial parks, and cities [10]. CE is a solution for synchronizing business models and sustainable development goals [6]. Towards the Sustainable Development Goals set by the United Nations, CE possesses the capacity in resolving three of its goals, namely, SDG-7 (Affordable and Clean Energy), SDG-8 (Decent Work and Economic Growth), and SDG-13 (Climate Action). Research works estimate that a CE transition for most economic systems will improve annual GDP by 2%, increase employment rate by 1.6% and reduce carbon emission by 24.6% [1].

Implementing CE for the manufacturing sector requires coordination from the political institutions and industry corporations [11]. A necessary step for implementation is the adoption of performance metrics to assess system performance against circularity. Notably, existing research works have designed a variety of indicators; of which, each one has its own specific applications [17]. Additionally, target performances can be set in realizing circularity [14]. Implementing these concepts among steelmaking industries will enable movement towards its sustainability.

As the use of indicators will result in an intricate reevaluation, the design process needs to be systematic. Mathematical programming possesses a systematic approach for industrial system design. Existing works have shown its potential in the design of bioenergy systems with negative carbon emission, as shown in Ubando et al. [18], and of trigeneration plants with product price change, as shown in Gue et al. [8].

This method is applied for steelmaking plants as well. For carbon reduction, existing works have integrated the plant with a polygeneration system, as shown in Ghanbari et al. [4], and with carbon capture and utilization, as shown in Ghanbari et al. [5]. Other works have applied the concept in biomass systems. Ubando & Chen [19,20] designed it with a biomass-based polygeneration system. Of which, Ubando et al. [19,20] extended its application with the consideration of negative carbon footprint. Their model reached an optimized result of 2.7 million tons of carbon dioxide reduction with USD 6.91 billion profit per year.

Given that the Ellen MacArthur Foundation [2] distinguished CE frameworks as biological and technical cycles, a technical regenerative cycle is needed to sustain the resource requirement of the steelmaking industry. Ohno et al. [16] designed a linear programming model to determine optimum flow of scrap metals from end-of-life vehicles in the Japan economy. Meanwhile, Majji & Kesavarao [13] used a chance-constrained approach to determine optimal scrap metal mixing. These studies, however, did not consider indicators and targets as parameters in the design.

CE transition of steelmaking entails the inclusion of indicators and targets in the design process. Consideration of these parameters to existing system designs is challenging and may entail non-optimal choices. Therefore, this work presents a mathematical programming approach in integrating circularity targets in the design of a steelmaking plant. The developed model can help future research works in the design of a circular steelmaking plant. Additionally, findings of this work illustrate the potential of adopting circularity in the industrial system.

Steel and iron industries provide the basic material for industrialization and economic development. However, this is an energy-intensive industry, thus it needs a large number of resources and it has a large
amount of carbon footprint. In line with this, the study aims to evaluate using fuzzy optimization the integration of a recycling unit to the iron manufacturing plant and how it will minimize its carbon footprint as well as its energy consumption due to the production of new steel through recycling requires only 10 times less energy compared to steel produces from virgin iron ore [21].

2. Methodology

A fuzzy linear programming model was developed to evaluate the effect of the attachment of a recycling plant to the iron manufacturing plant. The model was basically composed of the following objective function:

\[
\text{Maximize } \lambda_o + \sum_{q=1}^{\lambda} \frac{\lambda_q}{M} \quad \forall q = 1, 2, 3
\]  

s.t.

\[
\lambda_o \leq \lambda_q \quad \forall q = 1, 2, 3
\]

Where.

\(\lambda_o\) = overall membership level  
\(\lambda_1\) = satisfaction level for the product demand  
\(\lambda_2\) = satisfaction level for the annualized profit goal  
\(\lambda_3\) = satisfaction level for the carbon footprint  
M = Large scalar number

The 2nd term of Equation 1 ensures the Pareto optimality of the solution. As per the aggregation of max-min, the \(\lambda_o\) should be less than or equal to the individual goals, \(\lambda_i\) level of fulfillment (Equation 2). Equation 3 represents linear energy and material balance of the product output \(y\) of the iron recycling plant integrated in the main iron manufacturing plant.

\[
\sum_{j=1}^{A} A_{ij} x_j = y \quad \forall j
\]

Where.

\(A\) = process matrix of the iron manufacturing plant integrated with recycling unit  
\(x\) = Process scaling vector  
\(y\) = production level of the integrated system.

The A matrix includes the five-vector process of the main iron manufacturing plant and the single process vector of the added iron recycling unit. The model assumes that all process vectors in the A matrix are in steady state. The process scaling vector \(x\) simultaneously determines the capacity of the recycling plant and the optimum capacity of the main iron manufacturing plant. The product output \(y\) is modelled with the triangular fuzzy goal algorithm. The constraints and profit goals of the iron manufacturing plant are defined in Equation 4.

\[
AP \geq AP^L + \lambda_2 (AP^U - AP^L),
\]

\[
AP = \sum_{k=1}^{K} EF_k \quad \forall k = 1,2
\]

\[
EF_1 = HP^T y,
\]

\[
EF_2 = AFCC^T x_n \quad \forall n = 6,7,8,9,10
\]

Where.

\(AP\) = Annualized profit of the plant
\( AP^L \) = Lower bounding limit of AP  
\( AP^U \) = Upper bounding limit of AP  
EF = Economic factors  
\( EF_1 \) = Annualized gross profit of the plant  
\( EF_2 \) = Capital cost of the plant  
\( P^T \) = Transposed price for each stream  
\( CCT \) = Transposed capita cost per process unit  
H = Total plant hours in a year  
AF = annualizing factor  
N = specific process unit in the system

The carbon footprint goal is also considered in the model. Equation 8 describes how the model accounts for the carbon footprint of the integrated manufacturing plant. Equation 10 utilizes the linear minimization membership function to minimize the carbon footprint of the plant.

\[
\begin{align*}
z & \leq z^U + \lambda_3(z^L - z^U) \\
z &= \sum_{r=1}^{R} z_r \quad \forall r = 1,2 \\
z_1 &= b^T x \\
z_2 &= c^T y
\end{align*}
\]

Where.

\( z \) = Plant’s carbon footprint  
\( z^L \) = carbon footprint lower limit  
\( z^U \) = carbon footprint upper limit  
\( z_r \) = different types of carbon footprint  
\( b^T \) = transposed carbon emission vector per process  
\( c^T \) = transposed carbon emission vector per product

And lastly, Equation 12 shows the process scaling vector x of the main iron manufacturing plant operating at an optimal capacity range. Equation 13 is created to ensure that the overall satisfaction level falls within 0 to 1.

\[
\begin{align*}
x^L & \leq x_n \leq x^U \quad \forall n = 1,2,3,4,5 \\
0 & \leq \lambda_o \leq 1
\end{align*}
\]
The model was developed using a laptop computer powered by Intel core i7-6700HQ at 2.60 GHz with 8 GB of RAM. An educational licensed Lingo 18.0 aided with Microsoft Excel was utilized to solve the developed model. LINDO (Linear, Interactive, and Discrete Optimizer) were the software developers of Lingo which offers solvers and different programming models that have a wide variety of applications. Lingo basically aids the user to identify the best solution in an optimization problem considering well-defined constraints with the most efficient time. This program has the ability to read and write data on to an Excel spreadsheet and Microsoft access.

The materials and energy balance of the main iron manufacturing plant (Figure 1) was adopted from the study of Ubando et al. [22]. Majority of the prices of the product stream of the iron manufacturing plant integrated with a recycling plant were adopted from the study of Ubando et al. [22] and Ghanbari et al [5] in consideration of a conventional steelmaking process.

The optimization model considered an iron manufacturing plant which includes the 5 main processing units: blast furnace, sinter machine, hot stove, coke dry quenching, and coke oven. These process units are represented in different blocks in Figure 1 with their respective input-output material and energy balance. These assumptions allow the model to treat the operational capacity linearly. The blast furnace produces pig iron as the main product with by-products of slag and blast furnace gas. The blast gas was generated by the hot stove through heating and mixing the blast furnace gas with other raw materials. The coke oven on the other hand carbonized the coal through heat treatment to produce coke for the blast furnace. Before the utilization of hot coke in the blast furnace, it will be cooled first using an inert gas in the coke dry quenching. And finally, the sinter machine produces the sinter cake by mixing various raw materials with solid fuels.

The recycle unit considered to be integrated to the existing iron plant includes separation processes that will sort the scrap iron to the light and heavy residues from the scrap metal. This integration will lower the...
carbon emission of the iron manufacturing plant as well as lowering the needed raw material requirements to obtain the optimal plant capacity.

3. Results and Discussion

The product stream generated by the optimization model is shown in Table 1. The streams that are significantly affected by the integration of the recycling unit to the iron manufacturing plant are the consumption of coal and power. While it is noteworthy that the carbon dioxide production is reduced from 1067.58 ton/hr to 962.70 after the integration of the recycling unit. The resulting carbon emission compared to the study conducted by Ubando et al. (2020) is 23% lower. Hence, an iron manufacturing plant integrated with a recycling unit has a lower carbon footprint compared to the iron manufacturing plant integrated with a biomass-based poly-generation system.

Table 1. Optimal streams for iron manufacturing plant with recycling unit and without recycling unit.

| Process Unit             | With Recycling Unit | Without Recycling Unit |
|--------------------------|---------------------|------------------------|
| Coal                     | -661.12             | -945.92                |
| Converter Off Gas        | -46.56              | -46.56                 |
| Liquified Petroleum Gas  | -4.24               | -4.24                  |
| Oxygen                   | -15.36              | -15.36                 |
| Air                      | -1660.48            | -1660.49               |
| Scrap Metal              | -320.00             | 0                      |
| Iron Ore                 | -660.40             | -990.40                |
| Limestone                | -94.40              | -94.40                 |
| Lime                     | -35.68              | -35.68                 |
| Recycled Coke Oven Gas   | -35.20              | -35.20                 |
| Recycled Sinter Cake     | -128.00             | -128.00                |
| Power                    | 303.20              | 353.87                 |
| Heat                     | -111.20             | -111.20                |
| Hot Metal                | 800.00              | 800.00                 |
| Slag                     | 229.60              | 229.60                 |
| Blast Furnace Gas        | 828.80              | 828.80                 |
| Sinter Cake              | 240.00              | 240.00                 |
| Coke Oven Gas            | 233.12              | 233.12                 |
| Scrap Iron               | 0.00                | 0.00                   |
| Cooled Coke              | 0.00                | 0.00                   |
| Blast Gas                | 0.00                | 0.00                   |
| Light Scrap Metal Residue| 23.47               | 0                      |
| Heavy Scrap Metal Residue| 3.20                | 0                      |
| Coke                     | 0.00                | 0.00                   |
| Cooled Fine Coke         | 0.00                | 0.00                   |
| Carbon Dioxide           | 962.70              | 1067.58                |

The coal consumption was reduced (Figure 2) due to the integration of the recycling unit. The raw materials used in the production of iron was reduced and replaced with the scrap iron produced by the recycling unit. The scrap iron had lowered the requirements of the manufacturing plant in terms of raw
materials (iron ore) that cascaded its effect to the lowering of heating requirement of the process hence lowering the coal and power requirement of the production. This also affects the carbon footprint generation of the whole production due to lesser fresh materials being used in the production.

Figure 2. Coal and Carbon dioxide streams after the integration of recycling unit.

4. Conclusion
In the study, an iron manufacturing plant with an integrated recycling unit was evaluated. The generated model to optimize the iron manufacturing plant indicated that the carbon emission of the plant decreased by 10.35% when the recycling unit was introduced. It was also observed that the coal requirement as a raw material was also reduced significantly by 35.44%. The model had identified that the optimal operational capacity of the iron production plant integrated with a recycling unit is at 80% capacity. The total power consumed in the production was also decreased by 15.44% however a detailed analysis on energy consumption and can be conducted in the future studies specifically on the reduction of energy requirement on each process unit after the incorporation of the recycling unit. The cumulative energy demand for energy environment consideration can also be considered for further analysis of the model. This can also include the embodied carbon emissions especially on the consumption of coal in the iron manufacturing plant.

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