A new environmental performance index based on the carbon footprint, VOC emissions, and waste in a printing house

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Abstract
An environmental performance index (EPI) is introduced to evaluate the activities of a printing house based on three impacts: carbon footprint, volatile organic compound emissions, and waste. As the main causes of environmental degradation are the operation of machinery and usage of materials, we aimed to integrate the three impacts to interpret the EPI or the environmental friendliness of printing houses. Our results demonstrate that environmental awareness increased with improvements to the EPI, following the modification of printing processes and choices of printing materials. Various scenarios, including pre-press, press, and post-press, as well as printing materials, are proposed to predict trends and the possibility of increasing the EPI. Press management and materials and equipment changes have the greatest influence on the improvement of the EPI.

KEYWORDS
environmental awareness, environmental performance index, print production, volatile organic compound emissions

1 INTRODUCTION
An environmental performance index (EPI) can serve as a tool to represent the quality of life across various activities. At global level, the global environmental performance index (GEPI) has been established, which includes comprehensive indicators for measuring and tracking the environmental performance of a country under two categories—ecosystem and health. Since 2006, the GEPI has been quantified and ranked regionally for both categories across 180 countries. Thailand ranked 91st and 121st globally in 2016 and 2018, respectively, reflecting the strain that economic growth imposes on the environment. The decline of Thailand’s GEPI performance has raised concerns from the government. For this reason, the Ministry of Industry has adopted a policy of encouraging all industries, including the printing industry, to manage their production in line with the goal of sustainable development.

The printing industry is one of the major sources of environmental pollution in Thailand due to its heavy energy and resource usages. Therefore, there is a need to adopt resourceful thinking regarding the print production activities so that they can contribute to environmental protection by adhering to a greener, more eco-friendly, and sustainable practices. Working processes, machine operations, and material usage within the framework of sustainable development are important subjects of research, as environmental actions often serve as value-drivers for companies. Key environmental issues in the printing industry are: air pollution (e.g., the release of volatile organic compounds [VOCs] into the atmosphere due to...
solvent usage) and energy usage from the printing process and transport, which contributes to greenhouse gas emissions (i.e., the carbon footprint [CFP]) and climate change. Additionally, a register of hazardous materials in the printing industry was proposed in a recent study as a tool for sustainable management. In their study, Kurski et al. presented various methods for data collection, the compilation of pollutants, and the classification of harmful substances generated during print production, and a database of hazardous substances and environmental impacts, such as VOCs and waste, in the printing industry was obtained.

A major return-on-investment from the development of proactive environmental programs is improved business efficiency. An increase in productivity often occurs when an operator works toward environmental compliance, such that the profitability of operations often increases significantly. An empirically demonstrated relationship has also been found between the economic and environmental performance of companies. The environmental impacts used in the studies of Wikina et al. and the United States Environmental Protection Agency (US-EPA) were categorized into events and environmental disclosures. However, it was noted that the jointly determined impacts were not considered in these studies. Based on the argument that overall impacts can affect the environmental performance of a company or corporation, an integrated analysis of the relationships among these environmental impacts was necessary. Moreover, determining the environmental performance of an organization requires an organizational structure for the component metrics, similar to how the EPI employs a hierarchical framework that groups environmental impacts within issue categories.

Unfortunately, we found very few studies that have been focused on integrating environmental impacts to improve the environmental performance of printing houses. In this study, our objective was to integrate the environmental impacts generated from print production to interpret the EPI of a printing house in the two categories used in the GEPI—ecosystem and health. This approach allowed us to confirm that the printing industry can damage both the environment and human health. Additionally, pre-press, press, and post-press scenarios were proposed to improve the EPI, and an actual trial and an extreme case, were studied.

We also revealed the contributions and importance of the chosen impacts on the EPI of a printing house based on an event study analysis for assessing the impacts of print production on pollutant concentrations.

2 | MATERIALS AND METHODS

2.1 | Research background

As mentioned in Section 1, there are many environmental issues related to the printing industry. These include but are not limited to air pollution, handling and disposing of hazardous materials, waste management, and energy use. More specifically, the printing industry contributes to air pollution by releasing VOCs from using inks, chemicals, and solvents. The increased amount of such hazardous materials poses a huge environmental risk that not only contributes to global climate change but may also lead to the destruction of the natural environment. Waste from this industry can be solid, liquid, or sludge-like and consists of chemicals and washed solvents. The energy used in material acquisition, production, delivery, recycling, and end-user usage can be interpreted as the CFP value. In prior studies, the print production process at Chulalongkorn University Printing house (hereafter, “CU Printing house”) was explored, resulting in the data compilation across three pollutants category: CFP, VOCs, and waste. The concepts of these processes were elaborated upon in this study.

2.1.1 | Carbon footprint identification

A pilot CFP project was launched in Thailand by the Thailand Greenhouse Gas Management Organization (TGO) and the National Metal and Materials Technology Center of Thailand (MTEC), wherein 25 producers applied for the first commitment period from April to November of 2009. The products were mainly foods and drinks. By this project, the product category rules for CFP calculations were published.

In 2011, the CU Printing house has launched its EcoPrint project in which its printed products were identified by their CFP values. The advantages inherent to this concept led us to improvement in the environmental friendliness of their products by reducing the environmental load of the book life cycle as shown in Figure 1.

The method employed for calculating the CFP of each book was based on the American National Standards Institute (ANSI) standard, ISO 16759, along with TGO recommendations. Calculations were completed by multiplying the data obtained for each component in the life cycle of a book by the relevant coefficients of the carbon dioxide emission equivalent (CO2-eq).
2.1.2 | VOC emissions

The air pollutants of most concerns in printing houses are VOCs. VOCs are those chemicals that are easily evaporated to form ozone in the atmosphere. The health effects of exposure to VOCs include eye irritation, headache, and damages to the liver, kidney, and central nervous system. The printers should monitor the amount of VOCs that are released during print production and the methods used to decrease them; however, the direct measurement of emissions is difficult and often impractical. Therefore, we calculated VOC emissions according to the amount of materials used, based on the recommendation of the Printers’ National Environmental Assistant Center (or PNEAC),\textsuperscript{18,19} which is a function of the consumption of each material in the production multiplied by its VOC content and release factor. For example, it was reported by the United States Environmental Protection Agency (US-EPA) that most offset printing ink have a VOC retention factor of 95%,\textsuperscript{18} which may be equated into a 5% release factor.

The CU Printing house began this project to evaluate its total VOC emissions since 2011, with the aim of developing guidelines for export as some print buyers in the US and European Union (EU) required this information.

2.1.3 | Waste management

Waste is one of the most important environmental issues in the printing industry today.

Therefore, we proposed that waste management activities be undertaken in cooperation with the Center of Excellence on Hazardous Substance Management (HSM), Chulalongkorn University, in 2016.\textsuperscript{17} All waste materials in the CU Printing house were first segregated and classified as either nonhazardous or hazardous waste. A waste code was applied and coded according to the Industrial Work Department of the, Ministry of Industry, Thailand.

Interestingly, recyclability played an important role in our waste management strategy; items that could be recycled included paper, cardboard, solvents, ink containers, printing plates, and pallets. However, minimizing the waste and managing the storage of waste was also important (Figure 2).

2.2 | Experimental and data collection

The CFP, VOC emissions, and waste impacts from print production were integrated to interpret the EPI of the CU Printing house. First, reference data for each impact was recorded and then improvements to each impact were introduced by dividing the study into two components: an actual trial and extreme case that would be expected in the future. The methodology chosen to contribute to the reduction of these three impacts was based on three scenarios: (a) machine
management, (b) material usage control, and (c) material and equipment changes. Finally, the EPIs of both cases under the ecosystem and health categories used in the GEPI were calculated.

To achieve accurate results, weighting ratios of these three impacts were generated by using an analytic hierarchy process (AHP) to assess data from our survey. The CU Printing house EcoPrint project was reviewed, and a specialist from the TGO was invited for verification and validation purposes. We compiled CFP data and the relevant contributors from short-run printing jobs of B5/A4 books with 120 to 180 pages throughout 2016. The average data were used as the reference values for the CFP output of a printed book (Table 1). Total production was counted at 735 000 copies/year, using a four-unit press and a two-unit press, with a perfecting unit and a perfect book binding machine.

To estimate waste and VOC emissions, measurements were taken under the same short-run printing in 1 year. We conducted a waste audit and measured the amount of waste generated from print production, as shown in Table 2. The wasted printing materials, excluding plates, accounted for 5% to 10% of the total usage. We obtained an overall waste as high as 76 352 kg/yr. We also noted that the contaminated water from computer-to-plate (CTP) processing was the major source of waste generated from the printing house.

Table 1: Average data of CFP/1000 books (B5/A4 format) at the CU Printing house in 2016

| Printing phase        | Material                          | Emission factor* (kg/kg) | C02 emission (kg) | CFP (%) | Total CO2 (kg) | Total CFP (%) |
|-----------------------|-----------------------------------|--------------------------|-------------------|---------|----------------|----------------|
| Procurement           | Papers                            | Cover; text papers (0.64; 0.97) | 248.60            | 31.92   | 399.56         | 51.30          |
|                       | Plates                            | 12.55                    | 136.65            | 17.54   |                |                |
|                       | Glue                              | 4.32                     | 8.64              | 1.11    |                |                |
|                       | Others                            | —                        | 5.67              | 0.73    |                |                |
| Production            | Design                            | Electric (0.56 kg/kwh)    | 2.10              | 0.27    | 340.56         | 41.15          |
|                       | Plate-making                      | CTP (2.90 kg/kwh)        | 24.76             | 3.18    |                |                |
|                       | Printing                          | 2-unit press, 4-unit press (12.60; 18.40 kg/kwh) | 66.61;154.99 | 27.17   |                |                |
|                       | Post-press                        | Folding; collating; perfecting machines (2.05; 1.60; 3.50 kg/kwh) | 81.98 | 10.53 |                |                |
| Delivery              | Delivery                          | —                        | 0.80              | 0.11    | 0.80           | 0.11           |
| Disposal and recycling| Waste disposal & recycling         | Landfilling; paper recycling; plate recycling (2.93; 0.17; 3.16) | 34.30 | 4.40 | 58.00 | 7.44 |
|                       | Wastewater treatment              | 0.136                    | 15.60             | 2.00    |                |                |
|                       | Solvent recovery                  | Distilling (1.25 kg/kwh)  | 8.10              | 1.04    |                |                |
| Total                 |                                   |                          | 778.80            | 100.00  |                |                |

Abbreviations: CFP, carbon footprint; CTP, computer-to-plate.

*http://thaicarbonlabel.tgo.or.th.
TABLE 2  Amount of waste generated at the CU Printing house in 2016

| Materials                      | Amount/year | Waste code |
|--------------------------------|-------------|------------|
| Coated paper                   | 260 kg      | 150 101    |
| Uncoated paper                 | 465 kg      | 150 101    |
| Cardboard                      | 89  kg      | 150 102    |
| Glue                           | 93 kg       | 150 106    |
| Used plates                    | 5495        | 191 203    |
| Washed ink + used solvents     | 19 tanks × 200 L | 150 110 HM |
| Isopropyl alcohol (IPA) + fountain solution | 1120 kg | 080117 HM |
| Inks                           | 267 kg      | 150 110 HM |
| Used cloth                     | 163 kg      | 150 202 HM |
| Paper dust                     | 20 sacks × 50 kg | 161 002   |
| Wastewater from CTP processing | 63 600 L    | 161 001 HM |

Abbreviations: CTP, computer-to-plate. HM: Hazardous waste – Mirror Entry;

TABLE 3  VOC emissions generated from print production in the CU Printing house

| Materials                  | Usage       | VOC content | Release factor | VOC emissions/yr |
|----------------------------|-------------|-------------|----------------|------------------|
| Inks                       | 2675 kg/yr  | 35%/kg      | 0.05           | 46.81 kg         |
| Fountain solution          | 893 L/yr    | 0.09 kg/L   | 1.0            | 80.37 kg         |
| IPA                        | 227 L/yr    | 0.80 kg/L   | 1.0            | 181.60 kg        |
| Solvent                    | 3800 L/yr   | 0.70 kg/L   | 0.5            | 1330.00 kg       |
| Overprint varnish          | 1210 kg/yr  | 75%/kg      | 0.8            | 726.00 kg        |
| Binding glue               | 1535 kg/yr  | 35%/kg      | 0.8            | 429.80 kg        |
| Total                      | 2794.58 kg  | 2.79 Tons   |

Abbreviation: VOC, volatile organic compound.

The data used to consider VOC emissions are given in Table 3. We surveyed the usage of printing materials containing VOCs, such as inks, fountain solutions, glues, coatings, and wash-up and cleaning solvents. The VOC emissions were then calculated according to the PNEAC method. We also interviewed printers about environmental improvements and found that most of them preferred changing inks to other materials. However, we found that only changing inks was not an effective means of significantly reducing VOC emissions in the press room.

Printers should manage press operations to decrease the amount of isopropyl alcohol (IPA) and solvents used. Another alternative is to use lower VOC materials. To determine the annual potential emission (APE) of the printing house, our calculations were based on the actual operating hours per year. The CU Printing house operates 350 days each year (i.e., 7 days/week for 50 weeks or 10 hours per day). Of these 10 hours, two are spent in make-ready activities, including machine cleaning, resulting in an actual crewed time of 2800 hours/yr (Equation (1)).

\[
VOC\text{ APE} = \frac{\text{Total VOC emissions} \times \text{actual operating hr/yr}}{8.760 \text{ hours (1 year)}}, \quad (1)
\]

\[
= \frac{2794.58 \text{ kg} \times 2800 \text{ hr/yr}}{8760 \text{ hr}} = 893.24
\]

The raw data were converted into new sets per 1000 printed books. Table 4 shows the reference data of the three impacts recorded in 2016. The alternatives and methods for reducing these impacts recommended by the invited printing experts are shown in Table 5. Three scenarios were proposed, as shown in Figure 3, based on machine management,
TABLE 4  Data for each environmental impact generated by the CU Printing house in 2016

| Impacts                  | Total amount/yr | Amount/1000 books |
|--------------------------|-----------------|-------------------|
| Carbon footprint (CFP)   | 579.8 t         | 778.80 kg CO₂     |
| VOC APE emissions        | 893.24 kg       | 1.21 kg           |
| Waste                    | 76,352 kg       | 103.88 kg         |

Abbreviations: APE, annual potential emission; VOC, volatile organic compound.

TABLE 5  Recommended guidelines to achieve best practices for environmental

| Printing phase         | Guidelines                  | CFP                      | VOCs                     | Waste                    |
|------------------------|------------------------------|--------------------------|--------------------------|--------------------------|
| Design and pre-press   | • Quick layout and imposition| • Process-less CTP       |                          |                          |
| Press                  | • Higher speed               | • Less inks              | • Fewer defects          |                          |
|                        | • Quick change over          | • Less alcohol           |                          |                          |
|                        | • Faster make-ready          | • Less wash up/cleaner   |                          |                          |
|                        | • Fewer defects              | • Less glue in binding   |                          |                          |
| Post-press             | • Quick process              |                          | • Non VOC or low VOC     |                          |
|                        | • Fewer defects              |                          | materials usage          |                          |
| Material usage         | • Less papers / inks         |                          | • Fewer defects          |                          |
|                        | • Lower weight papers        |                          |                          |                          |
|                        | • Vegetable inks             |                          |                          |                          |

Abbreviations: CFP, carbon footprint; CTP, computer-to-plate; VOC, volatile organic compound.

FIGURE 3  Three proposed scenarios to improve the environmental performance index of the CU Printing house

2.3  Actual trial

We applied overall equipment effectiveness (OEE) to Scenario I to manage Availability (A), Performance efficiency (P), and Quality rating (Q) of printing presses, as electrical usage was the major load contributing to the CFPs of printed books (Table 1). Using this concept, we reviewed the press operation relative to electricity usage and paper consumption during print production. We analyzed the press setup and make-ready time, as well as the amount of materials and energy used for the cover and black and white (b/w) printing presses during routine work, whereby the OEE factors (A, P, and Q) and OEE scores were calculated. The data were continuously collected every month and improvements to these factors were
expected to reduce the CFP. These factors may be described by the relationships shown in Equations (2) to (5).

\[
A = \frac{\text{Operating time}}{\text{planned production time}}, \quad (2)
\]
\[
P = \frac{\text{Operating speed}}{\text{maximum possible speed}}, \quad (3)
\]
\[
Q = \frac{\text{Acceptable printed sheets}}{\text{total printed sheets}}, \quad (4)
\]
\[
\text{OEE score} = A \times P \times Q. \quad (5)
\]

In a previous study, it was reported that the OEE score of the two-unit press for b/w text printing was at 15.33%, for which \(A\), \(P\), and \(Q\) were 42.00, 37.72, and 96.75, respectively. Meanwhile, the four color press for cover printing yielded a higher OEE score of 20.68% \((A = 44.14, P = 49.01, Q = 95.62)\).

We introduced a series of participative programs designed to increase the effectiveness of two presses, including the total preventive maintenance (TPM) program. Under this concept, it was assumed that all parts of the printing presses should be regularly examined, including maintenance. In theory, this should maintain press operations with minimized down-time losses. Maintenance specialists were invited to the CU Printing house to implement the TPM program every 2 months for 1 year. We then reanalyzed the OEE scores of the two presses and found that the improved OEE factors of the two-unit press were: \(A = 60.50\), \(P = 55.24\), and \(Q = 98.22\), by which an OEE score of 32.82% was obtained. Similarly, changes in the OEE of the four-unit press were the same direction (ie, positive) as those of the two-unit press. The OEE score of the four-unit press reached 40.03%, where \(A = 69.90\), \(P = 58.80\), and \(Q = 97.33\). The resultant CFP reduction after the press management of the two presses was then evaluated.

In Scenario II, material usage during print production affected the VOC emissions and waste in the pressroom. The materials that easily emit VOCs are fountain solutions, isopropyl alcohol (IPA), solvents, varnishes, and glues. Solvents accounted for the greatest contribution to VOC emissions. Thus, to minimize this impact in the press room, low-VOC solvents should be used, or printing methods should be modified to decrease their usage. We proposed a solvent dispenser (plunger) instead of using an open tank for cleaning the press, as shown in Figure 4. After 1 year, we collected data on ink-washing solvent usage to compare with the year before to determine the impact of this change on VOC emissions.

Scenario III, testing revealed that the usage of solvents (3800 L) and water (63 600 L) in the CTP processer was the main waste and VOC emission sources at the CU Printing house (Table 2). Changing the materials and equipment may, therefore, be an effective means of improving environmental conditions. The reduction in VOC emissions, waste, and CFP was clearly observed when we introduced an IPA substitute to reduce VOCs in the pressroom. We also proposed a process-less plate technology that allowed the printing house to save between 200 and 240 L/day of water, as well as the electricity use of the processor. Normally, in the conventional process of chemical development, one plate must be washed with water at least 3 L of water before drying.

The CU Printing house uses \(\sim 80\) printing plates per day for book production. After 1 year, we reconsidered the reduction in the amount of wastes, VOC emissions and CFP.

The values of CFP, VOC emissions (APE) and the amount of waste per 1000 books after the implementation of the three aforementioned scenarios were then be used to calculate the EPI based on the categories of ecosystem and health. Additionally, the effect of each scenario on each impact was evaluated.
FIGURE 5  Environmental impacts from print production

| Impact category | B   | VOCs | Waste | x     | y     | Weight |
|-----------------|-----|------|-------|-------|-------|--------|
| A               | CFP | 1    | 5     | 15    | 2.444 | 0.622  |
|                 | VOCs| 1/3  | 3     | 1     | 0.255 |        |
|                 | Waste| 1/3  | 1     | 0.11  | 0.483 | 0.123  |

Note: x, product of three impact categories.
Note: y, (category importance), 1/3 power of the product.
Note: Weight = y/total value of category importance.
Abbreviations: CFP, carbon footprint; VOC, volatile organic compound.

TABLE 6  Example of weighting ratio determined by an analytic hierarchy process

| Score of importance | Meaning         |
|---------------------|-----------------|
| 5                   | A is much more important |
| 3                   | A is more important   |
| 1/3                 | A is almost same as B |
| 1/5                 | A is less important  |

TABLE 7  Scores assigned to each category of impact based on the values in Table 6

2.3.1  Weighting ratio

A questionnaire based on AHP was used to analyze the weighting ratio of the three impacts (CPF, VOC emissions, and waste) relevant to the ecosystem and health categories, as shown in Figure 5. Fifty university students were involved in this analysis, 25 males and 25 females. The idea behind this survey was based on the ordering of impact categories determined by the student’s concern for the environment. Weighting each impact is a critical factor when consolidating environmental loads as an integrated indicator. Table 6 shows an example of the AHP used to determine the importance or weighting for each environmental impact. The scores of the importance of categories are further described in Table 7.

2.4  Extreme case

An extreme case was set as the target for improving environmental to impacts from possible trends. We followed the recommended guidelines shown in Table 5 by extending press management with possibly higher OEE values. Additionally, a low-VOC solvent was included.

To consider the trend in CO₂ reductions facilitated by press management, we proposed three possible OEE values (a, b, and c) under the curve representing the relationship between OEE factors and the amount of CO₂ emissions as shown in Figure 6 for the two-unit press under the approval of the advisor to the TPM program. Here, “a” represented the actual OEE score, while “b” and “c” were the expected OEE scores at 49.79% (A = 75.02, P = 67.50, Q = 98.32) and 59.77% (A = 80.20, P = 75.21, Q = 9.10), respectively. The data were based on the possible press performance achieved,
the number of the jobs, and workflow planning. These three cases affected the CO₂ emissions of printed products, with the A and P factors being the most effective. The curve shown in Figure 6 implies that the amount of CO₂ emissions in the cases of (B) and (C) of the two-unit press would be 43.00 and 33.32 kg CO₂e /1000 books with additional TPM activity in the future. Paper-savings of six or seven reams per year, respectively, could also be achieved.

From this finding, we could assume the same phenomenon for the four-unit press if it yielded the same percentage decrease in CO₂ emissions as that of the two-unit press (eg, 32.54% in case “c”). Accordingly, the CO₂ emissions of the four-unit press would be minimized to 66.91 kg CO₂e.

With respect to controlling material usage, using low-VOC solvents is necessary, as petroleum-based solvents contribute the highest load of VOC emissions in the printing house. Generally, commercial low-VOC solvents in Thailand have VOC contents ranging between 20% and 40%. Of course, the cost of low-VOC solvents is higher than that of conventional solvents. However, based on the extreme case, if the CU Printing house changed to using low-VOC solvents, a 380-kg/yr reduction in VOC emissions from such solvents could be achieved (Table 3).

Following our experiments, the EPI was recalculated from the new CFP, VOC emissions (APE), and waste values; and the items in each scenario of the actual trial and extreme case were compared to clarify any improvements to the EPI.

### 2.5 Determination of the EPI

To calculate the EPI, the obtained dataset for each impact required normalization. A “proximity-to-target” or “before/after” method was employed to normalize the data and to assess how closely the printing house was to an identified printing industry target or how improvements to the printing house had achieved environmental friendliness. Scores were then converted to a scale of 0 to 100 using simple arithmetic with 0 being the farthest from the target (ie, the worst observed value) and 100 being closest to the target (ie, the best-observed value).

#### 2.5.1 Data normalization

The collected data were normalized, as shown in Equation (6), with the results shown by positive and negative signs representing the worst and best scores, respectively,

\[ V_n = \frac{(V_{after} - V_{before}) \times 100}{V_{before}}, \]

where \( V_n \) is the normalized value of each impact, and \( V_{before} \) and \( V_{after} \) are the values before and after improvement, respectively. The obtained weighing ratio was then used to calculate the EPI of print production at the CU Printing house, as shown in Equation (7):

\[ \text{EPI (ecosystem/health)} = x(V_n - \text{CFP}) + y(V_n - \text{VOCs}) + z(V_n - \text{waste}), \]

where \( x, y, \) and \( z \) are the weighing ratios of each environmental impact.
3 | RESULTS AND DISCUSSION

The results of the AHP-based analysis indicated that the CFP was ranked first in the ecosystem category, while waste came second, and VOCs were ranked third place, with corresponding weighting ratios 0.48, 0.36, and 0.15, respectively. When the health category was considered, VOCs were viewed as much more important, followed by CFP and waste. The weighting ratios of these impacts were 0.63, 0.22, and 0.15, respectively.

3.1 | EPI improvements by scenario

Based on the actual trial, the downtime loss of the two-unit press was improved. The operating times for press set-up, job-changing, and plate-mounting were all reduced, and the printing speed was increased by 50%. The concomitant decrease in electric usage over 1 year led to a CO2 emission reduction in press operations of 25.86%, equivalent to 17.22 kg/1000 books. For the four-unit press, it was found that the decrease in electric usage could reduce the CO2 emissions of the press by 36.02% or 55.81 kg/1000 books. The decrease observed in the number of rejected papers from each press was ~3 to 4 sheets per job. Thus, for a total of 650 short-run jobs/year, we estimated the decrease in rejected papers to be ~2500 sheets or five reams for each press. Each ream (500 sheets) of B2 cover and text papers weighs 27 and 20 kg, respectively. Overall, these data demonstrated that press management of the two presses could reduce CO2 emissions by up to 73.03 kg/1000 books by decreasing electricity usage and 0.24 kg/1000 books by decreasing the number of rejected papers (0.11 kg CO2 for cover papers +0.13 kg CO2 for text papers).

Regarding the use of the plunger, it was found that up to 20% of washing solvents could be saved each day, which could also reduce the VOC emissions of the press. The estimated reduction in VOCs was 266 kg/yr. Using the IPA substitute, the VOC emissions were further reduced by 181.6 kg/yr. Thus, the total estimated reduction in VOCs was 447.6 kg/yr or 143.07 kg in APE.

In the case of a process-less plate, it was found that the printers accepted the quality of the print, but it took time when beginning a new print job with this plate system. The printers adapted well to this technology and the CU Printing house has now adopted process-less plates for printing. The key benefit provided by this change was that there was no longer a need for water to wash plates. Thus, including the decrease of rejected papers, the total waste was reduced by 83.53%, from 76 352 to 12 576 kg, indicating that it was the right decision to change the printing plates. After 1 year, the amount of waste should be 17.11 kg/1000 books. Interestingly, the electricity from the CTP machine (25%) and wastewater treatment were saved, which could account for the reductions of CFP by 6.19 and 15.6 kg CO2e, respectively, per 1000 books. From the actual experiment, we achieved new CFP, VOC emissions (APE), and waste values per 1000 books of 683.74 kg CO2e, 1.02 kg, and 17.11 kg respectively. We then calculated the EPI using the Equations (6) and (7).

\[
\text{CFP}(n) = \frac{(683.74 - 778.80) \times 100}{778.80} = -12.20%,
\]

\[
\text{VOCs}(n) = \frac{(1.02 - 1.21) \times 100}{1.21} = -15.70%,
\]

\[
\text{Waste}(n) = \frac{(17.11 - 103.88) \times 100}{103.88} = -83.53%.
\]

EPI (for ecosystem) = 0.48(−12.20) + 0.15(−15.70) + 0.36(−83.53) = (−5.85) + (−2.35) + (−30.07) = −38.27%.

EPI (for health = 0.22(−12.20) + 0.63(−15.70) + 0.15(−83.53) = (−2.68) + (−9.89) + (−12.53) = −25.10%.

The results showed that Scenario III was quite successful in decreasing the amount of waste by 83.53%. Meanwhile, the improvements to CFP and VOC emissions were only 12.20% and 15.70%, respectively, in all scenarios. This contributed to the EPI for the ecosystem (−38.27%) being higher than that for health (−25.10%).

3.2 | Actual trial vs extreme case

The reduction of achievements for the three impacts per 1000 books in the extreme case is shown in Table 8. We found that the obtained data from the environmental improvements during the actual trial still fell behind the possible target.
| Scenario                          | Measures                                      | CFP (kg CO₂e) | VOCs APE (kg) | Waste (kg) |
|----------------------------------|-----------------------------------------------|---------------|--------------|------------|
| Scenario 1: Machine management   | OEE + TPM of two-unit press                   | 33.29         |              |            |
|                                  | OEE + TPM of four-unit press                  | 88.08         |              |            |
|                                  | Decreased no. of rejected papers              | 0.34          | 0.24         |            |
| Scenario 2: Materials usage control | Solvent control using a plunger can           |              | 0.11         |            |
| Scenario 3: Materials and equipment change | Low-VOCS solvents using IPA substitute             | 0.41          | 0.08         |            |
|                                  | Process-less CTP                             | (4.95 + 15.6) | 86.53        |            |
| Total                            |                                               | 143.96        | 0.60         | 86.77      |

Abbreviations: APE, annual potential emission; CFP, carbon footprint; CTP, computer-to-plate; OEE, overall equipment effectiveness; TPM, Total Preventive Maintenance; VOC, volatile organic compound.

This means that there was still a gap between the real and desired management of print production to improve the environmental performance in the CU Printing house.

Press management could moderately reduce the amount of CFP, while low-VOCS solvents had a significant impact on the reduction of VOC emissions in the press room. We predicted the reductions of CFP, VOC emissions, and waste to be optimized at 18.48%, 49.59%, and 83.53%, respectively. This implies that we could solve the problem of VOC emissions if the appropriate measures were adopted. Accordingly, in the extreme case, the EPI for health was successfully improved by −47.78%, which was higher than the EPI for the ecosystem, −46.39%.

4 | CONCLUSIONS

The EPI can be used to quantify the environmental performance of the printing industry. The results from the CU Printing house demonstrated increased environmental awareness as the improvement of the EPI progressed within 1 year, according to the models of press management, material usage control, and material and equipment changes. Additionally, we were able to predict the EPI values with respect to the ecosystem and human health. The advantages of employing this methodology are not only improvements in environmental performance, but also the optimization of print production toward green printing. Furthermore, the EPI concept can be applied by Thai printing entrepreneurs in the future to ensure the sustainable development of the industry.

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CONFLICT OF INTEREST

The author declares no potential conflict of interest.

AUTHOR CONTRIBUTIONS

Aran Hansuebsai equally contributed to methodology, supervision, and writing-origin draft. Athima Kaosod equally contributed to methodology. Tanaporn Kanchanasing equally contributed to methodology.

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