Scheduling of a Paper Mill Process Considering Environment and Cost

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ABSTRACT

This study presents a new decision making method for scheduling paper mill processes, especially for the paper converting process. The optimal scheduling is analyzed with the multiobjective optimization programming (MOOP) using the summation of weighed objective functions (SWOF) [Ko and Moon, 2002]. In the production planning for the paper converting mill, making the strategy for the cutting paper is the bottleneck problem. In other words, how to cut papers efficiently with the raw paper reel is critical and this is called the trim loss problem. Environment (a waste amount) and energy cost are generally conflicting objectives. To reduce the environmental waste of the trim loss requires higher energy cost by moving the cutters. The MOOP is an applicable method to satisfy both objectives simultaneously.

The MOOP algorithm includes normalization, SWOF and Pareto point analysis steps. The amount of trim loss and production cost are considered objective functions under the concept of taking into account both economy and environmental impact in its scheduling. The constraints are to satisfy with order, minimum profit level, etc.. Here, the compromised solution set is identified based on Pareto points. The decision maker can select the practical solution for scheduling of paper mill process with the satisfaction of both environmental and economic requirement.

KEYWORD
Cost, Environment, MOOP, Scheduling, Trim loss

INTRODUCTION

The paper making process normally involves five units: paper machine, coater, rewinder, sheet cutter and roll ream wrapper. Paper mill process has adopted heuristic methods or database of previous cutting patterns to satisfy various demands. However, these methods may not reduce waste material efficiently. The trim loss problem is important on an aspect of environmental issue.

Generally it is impossible to have schedules which maximize environmental benefit (i.e., minimize waste) and minimize the operating cost simultaneously. In a conventional scheduling optimization problem, all process variables (for instance a waste amount) are converted into cost to find the minimum overall cost or the maximum profit. However in these days, environment is a vital issue and the importance of potential environmental impact is increasing. And trims are a problem themselves as wastes in environmental aspect. Moreover, inefficient use of raw material requires large storage capacity. Then pollutant generation increases. Hence, to minimize trim loss and cost simultaneously is very important in scheduling. This problem can be formulated MOOP problem, here, we represent a novel methodology using SWOF algorithm to seek optimal schedule in biobjective optimization problem and to find the ideal compromise solution set based on the Pareto point.

Multiobjective Optimization Programming (MOOP)

The general description for MOOP is as follows:

$$\min_{x\in\Omega} \; F(x) = [f_1(x), f_2(x), ..., f_n(x)] \tag{1}$$

subject to

$$h(x) = 0, \quad g(x) \le 0 \tag{2}$$

$$a \le x \le b$$

where, n ≥ 2 and Ω is the constraint set, which denotes the feasible set of equality constraints, *h(x)*, inequality constraints, *g(x)*, and explicit variable bounds. A vector $x^* \in \Omega$ such that $f_1(x) \le f_i(x^*)$ for all $i \in \{1,2, \ldots, n\}$. The characteristic of a noninferior solution set is that no decrease can be made in any of the objectives without causing a simultaneous increase in one or more of the other objectives [Ko and Moon, 2002].

There are several methods for MOOP, such as Summation of Weighted Objective Function (SWOF), ε-constraint method and Parameter Space Investigation Method(PSI), etc.. Among them SWOF method is used for MOOP in this study. The SWOF method minimizes a convex combination of objectives as following equations.

$$\min_{x\in\Omega} \; u(f_i, \alpha_i) = \sum_{i=1}^{n} \alpha_i f_i(x) \tag{3}$$

$$\sum_{i=1}^{n} \alpha_i = 1 \tag{4}$$

where, 0 ≤ α ≤ 1 and the utility function, $u(f_i, \alpha_i)$, is linearly combined with the objective functions (f_i) and the parametric weighting factors (α_i) under the constraint set (Ω).

PROBLEM STATEMENT

Trim loss problems are encountered in the paper mill process that was presented [Harjunkoski *et al.*, 1998]. The problem of minimizing the total cost of the trim loss and the knife changes was the objective function for trim loss problem. In this study, the objective function is modified to MOOP to consider environment and energy cost. There are the trim loss amount per product (T_p, objective function f_1) representing environment impact and energy cost per product (E_p, objective function f_2) representing energy costs as two objective functions. MINLP formulation of modified trim loss problem for MOOP is as follow;

$$\min \; \alpha_1 f_1 + \alpha_2 f_2 \tag{5}$$

Objective function f_1,

$$f_1 = \frac{\sum_{j=1}^{J} \left\{ m_j \cdot (W_{j,\max} - \sum_{i=1}^{I} n_{ij} \cdot w_i) \right\}}{\sum_{i=1}^{I} n_{ij} \cdot m_j} \tag{6}$$

Objective function f_2,

$$f_2 = \frac{\sum_{j=1}^{J} \left\{ P_m \cdot l_j / v_m + P_m \cdot t_j \cdot y_j \right\}}{\sum_{i=1}^{I} n_{ij} \cdot m_j} \tag{7}$$

subject to

$$\sum_{i=1}^{I} w_i \cdot n_{ij} - W_{j,\max} \le 0 \tag{8}$$

$$-\sum_{i=1}^{I} w_i \cdot n_{ij} - W_{j,\max} - e_j \le 0 \tag{9}$$

$$\sum_{i=1}^{I} n_{ij} - N_{\max} \le 0 \tag{10}$$

$$y_j - m_j \le 0 \quad (11)$$

$$m_j - M_j \cdot y_j \le 0 \quad (12)$$

$$j = 1, \ldots, J$$

$$n_{i,order} - \sum_{i=1}^{I} m_j \cdot n_{ij} \le 0 \quad (13)$$

$$\sum_{i=1}^{n} \alpha_i = 1.0$$

$$0 \le \alpha_i \le 1$$

$$i = 1, \ldots, I$$

$$m_j, n_{ij} \in Z^+$$

$$y_j \in \{0,1\}$$

f_1 minimizes the trim loss amount per product paper. It is significant in both waste of raw material and environmental waste aspects. f_2 minimizes energy costs per product paper including costs for the knife changes (changes of cutting pattern) (C_{change}). As both of objective functions increase in proportion to the production amount, we use the value divided by total number of products to take over-production into reasonable consideration. And parameteriztion algorithm is used to deal bilinear constraints presented by [Kim and Moon, 2001].

Constraints (8)~(9) are to prevent the patterns from exceeding the specified width limits. The maximum number of products that can be cut from one pattern is given in constraint (10). Note however that the total number of knives in the slitters is N_{max} + 1 since an edge cut needs to be made in both sides of the reel. This is owing to the fact that the quality of the paper near the edges is irregular and therefore a cut of 10mm from both edges is done. In constraints (11) and (12), the binary variable y_j is defined as zero if the cutting pattern j is inactive (m_j=0). Otherwise, it is equal to one. Bilinear constraint (13) is to satisfy the customer demand [Kim and Moon, 2001].

CASE STUDY

The following numerical example illustrates a daily production optimization problem in paper converting mill from [Harjunkoski et al., 1999]. An order is 98.74 tons (Table 1) and satisfies following general machine and raw material specific parameters: $i = 12$, $W_{j,\max} = 2100mm$, $l_j = 6500m$, $v_m = 260m/\min$, $P_m = 450kW$, $t_j = 10\min/change$ and density of the coated paper is $0.135kg/m^2$. And overproduction limits are specified 100% of total order size. 63 feasible patterns are produced from the parameterization.

The optimization for each objective function f1, f2 uses the given data and the result is presented in Table 2. And Figure 1 also presents Pareto points. Normalized values in Table 2 are calculated from point A,I; the minimum and the maximum of objectives by minimizing them independently of each other. According to weighting factor (α), the optimal schedule including values of cost and trim loss varies as shown in Table 2. The most efficient schedule can be taken with Table 2 when a decision maker to select the best compromise in scheduling process between improving economy considering environmental impact.

Table 1. The example order

Product (*i*)	Width (mm)	$N_{i,order}$
1	350	10
2	450	28
3	550	48
4	650	28
5	700	40
6	740	30
7	800	21
8	840	22
9	910	8
10	960	8
11	1010	9
12	1060	8

Table 2. The implemented results

Point	α_1	Trim Loss/product		Energy Cost/product		Schedules
		Normalized	Real [mm]	Normalized	Real [kWh]	Pattern number(number of times)
A	0	1.0000	7.52	0.0000	48.68	15(21), 26(9), 30(15), 32(30), 48(30), 51(19), 58(8), …
B	0.125	0.7143	5.50	0.0187	49.08	8(30), 32(30), 48(30), 42(30), 43(30), 54(19), 58(7), …
C	0.25	0.5714	4.49	0.0478	49.70	2(21), 36(9), 40(15), 42(30), 50(30), 54(19), 61(8), …
D	0.375	0.4201	3.42	0.1580	52.07	2(6), 16(9), 22(15), 32(30), 39(10), 44(19), 51(30), …
E	0.5	0.2857	2.47	0.1815	52.58	8(11), 36(9), 40(15), 44(10), 45(30), 50(19), 51(26), …
F	0.625	0.1429	1.46	0.4347	58.01	12(8), 36(22), 39(17), 42(18), 50(30), 54(19), 61(8), …
G	0.75	0.0722	0.96	0.6956	63.62	25(21), 36(9), 40(3), 42(19), 50(28), 54(10), 61(8), …
H	0.875	0.0000	0.45	0.9918	69.99	5(30), 16(8), 23(15), 27(30), 35(30), 38(19), 49(8), …
I	1	0.0000	0.45	1.0000	70.16	5(21), 18(16), 20(3), 26(15), 30(30), 38(19), 49(7), …

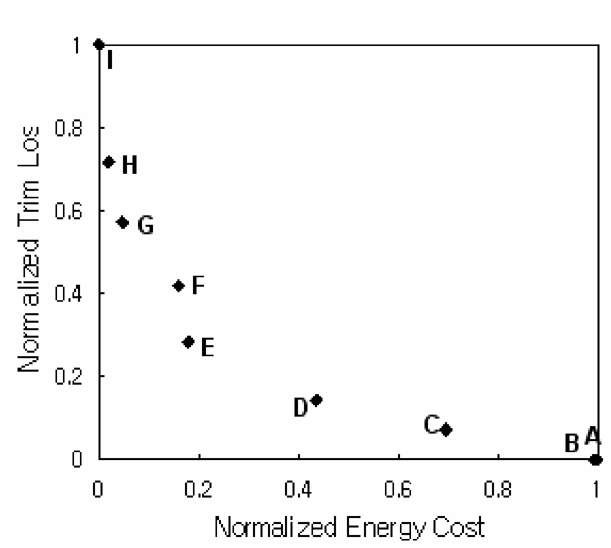

Figure 1. The Pareto points

CONCLUSIONS

In this study, the trim loss problem in the paper converting industry was analyzed in the aspect of environmental issue and energy cost. To analyze the optimization problem, we use the MOOP algorithm and represent the optimal solution by a set of Pareto points. By considering the resulting data, a decision maker can give weighting value of each objective function as case by case and make the optimal strategy.

If it is possible to formulate reasonable objective function considering fairly well both the energy cost and the environmental impact (trim loss), we could set a good schedule. This study provides a systematic scheduling method of considering both the environment and producing cost simultaneously. Hence, this study is meaningful in finding sustainable and environmentally benign solutions.

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