Applications of operations research techniques in paper industry : A review of the state of the art

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ABSTRACT

The paper industry is one of the earliest among the process industries in which Operations Research (OR) techniques were extensively used for management decision making. OR techniques have been used in three levels of planning, namely, mill level, regional level and national level. These applications are scattered throughout the literature and no single paper summarised these applications. This paper attempts to review some of the applications in pulp and paper industry, highlights two important applications and suggests a theoretical framework for a Decision Support System which can be used by managerial personnel for creating and experimenting with OR models.

Introduction :

OR is based on quantitative methods and mathematical modelling for arriving at decisions on complex problems in business, industry, agriculture, transportation, energy and other areas. Many OR techniques such as linear and non-linear programming, integer programming, dynamic programming, stochastic programming, etc., are available for solving the problems. In this paper OR applications for national/regional level planning are discussed in section 2. In section 3 applications within a mill level are reviewed. Section 4 highlights an 'energy optimisation model' and section 5 describes a 'production planning model'. In section 6, a theoretical framework for a 'decision support system' is suggested. The conclusion are given in section 7.

National/Regional Level Planning Models :

Some of the models used for decision making at national/regional level are as follows :

Plant Location Model

Selection of best (least cost) location for the establishment of a pulp and paper mill in a nation or region is a complex problem, because each location has its own advantages and disadvantages. Such problem is solved (14) using LP technique. This model decides whether to build a new mill at site or expand any existing mill to produce more so that fixed cost will be less,

Policy Evaluation Model :

In order to find the effectiveness of various policies (such as tax) of the government on the cyclical variation in the demand and supply of paper produced, pulp imported, waste paper recycled, continuous simulation (21) model has been used for the UK paper industry. LP has been used also [(5) & (9)] for analysing the tax policy specifically with respect to waste paper recycling.

Newsprint Industry Model :

Quadratic programming technique is applied for the North American Newsprint Industry (6), for forecasting newsprint production, consumption, manufacturing capacity and prices based on specific scenario for future economic and demographic growth. The objective function or the "net social pay off" is the value

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of newsprint to the consumer minus cost of production and transportation.

Mill Level Planning Models :

At a mill level, OR techniques are utilised for solving various problems such as trim minimisation, energy optimisation and production planning.

Trim Minimisation Model

The model most often discussed in the literature is the "trim minimisation" problem when meeting the demand for paper reels from different customers using LP (6) and heuristic techniques (0). When parent rolls are slitted into reels, a large number of jumbo roll slitting patterns exist, each resulting in a certain trim loss. The ideal slitting pattern is the one which suggests use of cutting patterns that produce minimum total trim loss while meeting the customer demand. Another application (19) in the 'finishing operation' is the use of General Purpose System Simulation (GPSS) for determining the efficiencies of rewinder, stencilling and weighing operations.

Energy Optimisation Models :

The energy models related to the paper industry are primarily focussed on solving the following types of decision problems :

(i) fuel allocation among boilers.

(ii) steam allocation among boilers.

(iii) process steam allocation among extraction and condensing stages of steam turbogenerators.

(iv) quantum of purchased power to be used and "in-house" power to be generated.

LP technique (1), (8), (10), (13) & (18) has been used for solving the above problems Subsequently mixed integer linear programming technique (3) was used with the objective was to minimise the quantity of steam generated in the boilers. Heuristic approaches are adopted (11) based on incremental cost analyses i.e. on equipment efficiencies (boiler, turbine, etc.,) under various load conditions.

Production Planning Models :

LP model is (13) used for examining feasibility of different production programmes, bottlenecks at different production programmes, feasibility of removing certain bottlenecks and most economical production programme. Also LP is used for solving (16) allocation of production among paper machines in a mill based on the economic advantages of various grades of paper made by these machines. Also it is used for the long term corporate planning for the expansion of production facilities (20). In addition to LP,' process simulation' models were also (22) used for improving the quality of decision making in the design and operation of pulp and paper manufacturing facilities.

Another area where LP is used (15) is for finding the optimum pulp ratio for a particular quality of paper, which is minimum interms of cost at the same time meeting the quality requirements. A time delay algorithm is used for [(12) & (23)] for optimisation of pulp mill process storage tanks with a quardratic objective function. The model considered five factors, viz., planned shut downs, steam balance, changes in production rate, intermediate storages and production schedules.

An energy optimisation model :

A short term energy optimisation model has been developed (2) using the Mixed Integer Linear Programming (MILP) technique to determine the optimal energy mix for the day-to-day operations. All the inputs of energy, process flow quantities and end use distribution of energy are defined as dicision variables in the model. The quantum of energy flow (steam as well as power) represents a variable in the MILP formulation The conceptual description of the short term energy optimisation model is given below:

Objective function

The objective is to minimise the total energy costs in a day comprising of the costs of purchased electrical energy as well as cost of steam generated in the fossil fuel boilers.

Constraints :

(a) balancing equations for various steam flows among the boilers, turbogenerators, process steam turbines and the proccess equipment.

(b) upper bounds on steam flow capacities of the boilers, turbogenerator's inlet, extraction and condensing flows

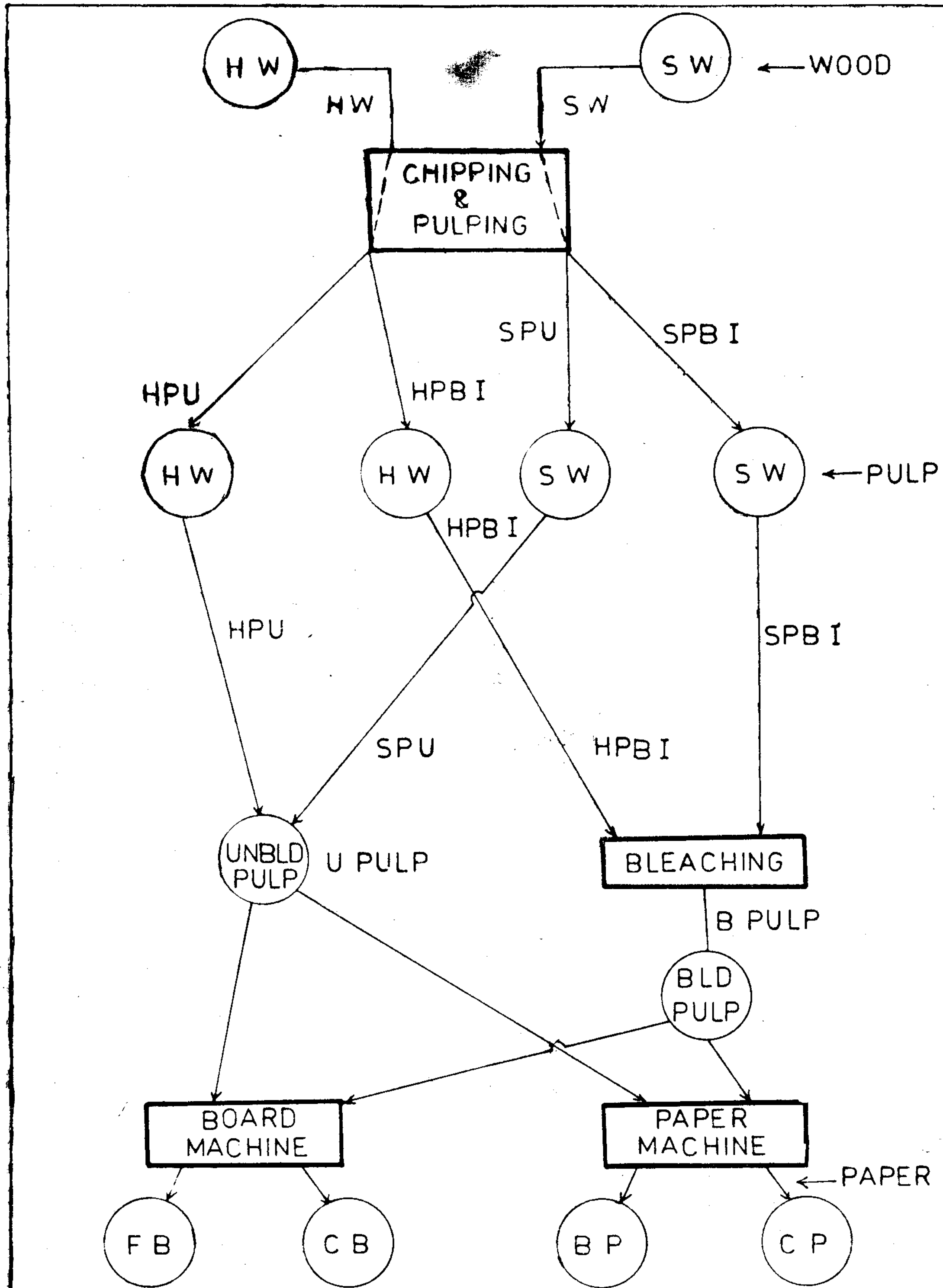

FIG:NO.1 SIMPLIFIED PROCESS FLOW DIAGRAM OF A PULP & PAPER MILL

(c) lower bound on steam condensation in turbogenerators

(d) steam to electrical conversion equations for turbogenerators

(e) electrical enery flow balance equations among the external grid, turbogenerator and process equipments

(f) upper bound on power flow from the grid, turbogenerators

(g) relationship between power and electrical energy

(h) integer variable restriction for representing the operation or otherwise of the turbogenerators

(i) non-negativity constraints on the decision variables

The short term model is further extended to incorporate the effects of varying "power cuts" imposed by the external electricity boards, on a mill's energy policy over a long time horizon. Both the short term and long term energy models are appropriatelly modified to form energy system performance evaluation models for different alternative energy system configurations. The other two models and demonstration of the appropriateness of the three models are discussed elsewhere (2).

A Production Planning Model

In this section, a production planning model using LP technique is described with an example.

Example

The production manager of a paper manufacturer must determine an optimal average daily product mix for a paper and board plant so as to maximize the total contribution from the manufacture and sale of the products. This plant can produce four products : food board, container board, book paper and coarse paper. The estimated maximum daily demand and sales prices shall be as follows :

ITEM	DEMAND	PRICE
Food Board	60 tons/day	Rs. 18450/ton
Container Board	120 tons/day	Rs. 9900/ton
Book Paper	25 tons/day	Rs. 15300/ton
Coarse Paper	30 tons/day	Rs. 13950/ton

The production process considered for the modelling is shown in the process flow diagram in Fig. 1.

Cost of Hardwood	=	Rs. 1650 per ton
Cost of Softwood	=	Rs. 1620 per ton
Hardwood available	=	200 tons per day
Softwood available	=	350 tons per day

Hardwood and softwood are chipped and pulped seperately. A single digester is available with total output capacity of 235 tons per day of pulp, regardless of the type of wood being processed, The yield on hardwood is 47% and on softwood is 45%. The chipping and pulping process incures a variable cost of Rs. 5400 per tonne of pulp produced.

Some pulp is directly usedtin producing the paper and some is bleached first. The stream of unbleached pulp going directly to the paper and board machine is composed of 60% hardwood and 40% softwood pulps. The stream of pulp going to bleaching is composed of 50% hardwood and 50% softwood pulps. Bleaching adds a variable cost of Rs. 900 per ton of bleached pulp produced. The bleaching yield is 98% and has a daily capacity of 80 tons. The bleached and unbleached pulps are mixed in fixed (iv) proportions for each of the final products. The quantity of bleached and unbleached pulp required to produce one ton of each of the final products are as follows :

	Tons of pulp per ton of product			
	Food Board	Container Board	Book Paper	Coarse Paper
Unbleached Pulp	—	0.10	0.70	0.90
Bleached pulp	1.10	0.95	0.40	0.15

A board machine is used to produce container board and food board A variable cost of Rs 450 results from producing a ton of either product and the output capacity of board machine is 190 tons per day. A paper machine is used to produce book paper and Coarse paper. A variable cost of Rs. 450 results from producing a ton of either product and the capacity of the paper machine is 60 tons per day.

Decision Variables :

The following decision variables are defined for formulating the Linear Programming model.

Let FB be the quantity of Food board produced in tons/day.

CB be the quantity of Container board produced in tons/day.

BP be the quantity of Book Paper produced in tons/day

CP be the quantity of Coarse Paper produced in tons/day;

UPULP be the quantity of unbleached pulp directly consumed by both the machines in tons/day.

BPULP be the quantity of bleached pulp directly consumed by both the machines in tons/day.

HPU be the quantity of unbleached hardwood pulp which directly goes to the machines in tons/day

SPU be the quantity of unbleached softwood pulp which directly goes to the machine in tons/day

HPBI be the quantity of unbleached hardwood pulp which directly goes to bleaching in tons/day

SPBI be the quantity of unbleached softwood pulp which directly goes to bleaching in tons/day

HW be the quantity of hardwood used in tons/day

SW be the quantity of softwood used in tons/day

Objective Function

The objective is to maximise the contribution from the products sold in Rs. per day. Contribution is defined as the difference between sales revenue and total variable cost.

Now for the example defined above,

Sales Revenue =

$$18450\ FB + 9900\ CB + 15300\ BP + 13950\ CP$$

Total Variable Cost = Sum of the variable costs at both machines. bleaching, chipping and pulping

$$= 450\ (FB+CB) + 450\ (BP+CP) + 900\ BPULP + 1650\ HW + 1620\ SW + 5400\ (SPU + HPU + HPBI + SPBI)$$

Hence the objective function is given by the expression

MAX Z =

$$18000\ FB+9450\ CB + 14850\ BP + 13500\ CP - 900\ BPULP - 1650\ HW - 1620\ SW - 5400\ SPU - 5400\ HPU - 5400\ HPBI - 5400\ SPBI \qquad (5.1)$$

Constraints

The constraints for the Lp model are given below;

(i) Demand Constraints

$$FB <= 60 \qquad (5.2)$$

$$CB <= 120 \qquad 5.3)$$

$$BP <= 25 \qquad (5.4)$$

$$CP <= 30 \qquad (5.5)$$

(ii) Raw Material Availability

$$SW <= 350 \qquad (5.6)$$

$$HW <= 200 \qquad (5.7)$$

(iii) Chipping and Pulping Capacity

$$SPU + HPU+HPBI+SPBI <= 235 \qquad (5.8)$$

(iv) Input/Output Relation at Chipping and Pulping

$$0\ 47\ HW - HPU - HPBI = 0 \qquad (5.9)$$

$$0.45\ SW - SPU - SPBI =0 \qquad (5.10)$$

(v) Composition of Unbleached Pulp

$$HPU - 0.60\ UPULP = 0 \qquad (5.11)$$

$$SPU - 0.40\ UPULP = 0 \qquad (5.12)$$

$$0.98\ HPBI - 0\ 50\ BPULP = 0 \qquad (5,13)$$

$$0.98\ SPBI - 0.50\ BPULP = 0 \qquad (5.14)$$

(vi) Bleach plant capacity

$$BPULP <= 80 \qquad (5.15)$$

(vii) Input/Output Relation at Machines

For unbleached pulp,

$$0.10\ CB+0.70\ BP+0\ 90\ CP-UPULP=0 \qquad (5.16)$$

For bleached pulp

$$1.10\ FB+0\ 95\ CB+0.40\ BP+0.15\ BPULP=0 \qquad (5.17)$$

(viii) **Machine Capacities**

$FB + CB <= 190$ (5.18)

$BP + CP <= 60$ (5.19)

(ix) **Non-negativity Constraints**

All the decision variables ≥ 0. (5.20)

Results & Discussions

The model is run in PC-AT with a standard LP software. The solution is summarised in Table 1. As can be seen in Table 1 the maximum contribution that can be achieved is Rs. 6,46,908 per day when the pro-indiducts are produced as per the optimum product-mix eated in Table 1. Further the LP model can determine the revised optimum product mix, for example, (i) if the variable production cost of machines increases from Rs. 450 per ton to Rs. 550 per ton, (ii) if the cost of hardwood raises by Rs. 200 per ton, (iii) if the availability of softwood gets reduced by 50 tons/day, if the bleach plant capacity is increased by 10 tons/day, etc.

TABLE—1

OPTIMUM SOLUTION FOR THE PRODUCTION PLANNING PROBLEM

S.No.	Description	Unit	Optimum Values
1.	Maximum Contribution	RS/DAY	6,46,908
2.	**Optimum Product Mix**		
	Food Board	Tons/Day	60
	Container Board	Tons/Day	0
	Book paper	Tons/Day	25
	Coarse Paper	Tons/Day	30
3.	Bleached Pulp	Tons/Day	80
4.	Hardwood	Tons/Day	144
5.	Softwood	Tons/Day	130
6.	Unbleached Softwood Pulp to Machine	Tons/Day	17.80
7.	Unbleached Hardwood Pulp to Machine	Tons/Day	26.70
8.	Unbleached Hardwood Pulp to Bleaching	Tons/Day	40.82
9.	Unbleached Softwood Pulp to Bleaching	Tons/Day	40.82
10.	Unbleached Pulp to Machine	Tons/Day	44.50

Though only basic model is presented, the following factors can also be included in the model by suitably defining additional decision variables. The chemical recovery section can be represented in the model with suitable constraints and decision variables.

(i) difference in the energy (steam and power) consumption for the same product when made in different machines.

(ii) Difference in the energy consumption for the production of different type of pulps.

(iii) Difference in the energy consumption for refining a various pulps for making a specific type of paper.

(iv) Availability of different plants for production.

(v) Chemical consumption at various section of the mill.

Further the model will be of great use for evaluating a new technology or modernising a part of the production plant. Also the computer software prints out the report relating to 'Sensitivity Analysis'.

Decision Support Systems

Management information system (MIS) has been successful in providing information for routine, structured, and anticipated types of decisions. In addition, it has been successful in acquiring & staring large quantities of detailed data concerning transaction processing. MIS has been less successful in supporting complex decision situations The main payoff has been in improving efficiency by reducing costs, turnaround time, and so on, and by replacing clerical personnel. The relevance for manager's decision making has mainly been indirect, for example, by providing reports and access to data.

On the other hand in Operations Research (OR), the impact has been mostly on structured problems (rather than tasks). where the objective, data and constraints can be prespecified. The payoff has been in generating better solutions for given type of problems. The relevance for managers has been the provision of detailed recommendations and new methodologies for handling complex problems,

In Decision Support Systems (DSS) the impact is on decisions in which there is sufficient structure for computer and analytic aids to be of value but where manager s judgement is essential. The payoff is in extending the range and capability of computerised managers' decision process to help them improve their effectiveness. DSS has been defined as an interactive, flexible, and adaptable Computer Based Information System that utilises decision rules, models and model base coupled with a comprehensive database and the decision maker's own insights, leading to a specific, implementable decisions in solving problems.

Composition of DSS for the production planning problem

A DSS consists of three modules, the data management module, the model management module and the dialogue management module.

(i) Database Management : The data management includes number of databases for storing, retrieving and updating various input data for the problem. These include costs of input materials such as hardwood, softwood, steam, power and chemicals, prices of products manufactured and sold, yield data for various production processes, demand for products, requirements of various inputs for each production process and production and consumption data. The data bases are managed by a software called database management System (DBMS)

(ii) Model Management : A software package. containing the solution procedure for the statistical technique, linear programming technique, etc., which provide the system's analytical capabilities, and an appropriate software management

(iii) Communication subsystem : The subsystem (dialogue) through which the user can communicate with and command the DSS and fully exploit its potential.

Conclusion :

The applications of operations research techniques in paper industry have been reviewed. OR techniques have been used for efficient decision making at national, regional and mill level planning. However, very few mills in India use OR technique. There may be many reasons for this slow growth. These include (i) management unaware of OR capabilities, (ii) management donot want to reveal their data, (iii) lack of communication skills with the OR analysts and (iv) the production manager donot understand how to formulate the problem. But some of these problems can be overcomed by suitably designing, developing, testing and installing Decision Support Systems, so that even if the production manager does not know the problem formulation and OR method, he can simply get the support from the DSS by merely interacting with it. Also DSS make it possible to do timely (mostly less than 30 minutes), adhoc and quick analysis which will take many days in other computer systems.

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