

ENERGY CONSUMPTION MANAGEMENT IN TEXTILE FINISHING PLANTS: A COST EFFECTIVE AND SEQUENCE DEPENDENT SCHEDULING MODEL

TEKSTİL TERBİYE TESİSLERİNDE ENERJİ TÜKETİMİ YÖNETİMİ: MALİYETE DUYARLI VE SIRALAMAYA BAĞLI BİR ÇİZELGELEME MODELİ

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Received: 23.08.2016

Accepted: 16.12. 2016

ABSTRACT

This study focuses on managing energy consumption and reducing energy costs in textile finishing plants with an effective scheduling approach, which consists of sequence dependent set-up times, sequence dependent set-up energy usages and time-of-use energy tariff. The finishing plants are typical examples of the flexible job shops. Therefore, a novel energy saving mixed-integer linear programming model is proposed for the sequence dependent flexible job shop scheduling problems in this study. The proposed model comprises an extended cost function that has a quaternary structure for tackling actual scheduling problems. The capability of the developed model is evaluated with actual manufacturing data.

Keywords: Textile finishing, flexible job shop scheduling, sequence dependent set-ups, time-of-use energy tariff, energy costs

ÖZET

Bu çalışmada tekstil terbiye işletmelerinde, etkin bir çizelgeleme yaklaşımıyla, enerji tüketimi yönetiminin sağlanması ve enerji maliyetlerinin azaltılması amaçlanmaktadır. Bu çizelgeleme yaklaşımında, sıralamaya bağlı hazırlık işlemleri süreleri, sıralamaya bağlı hazırlık işlemleri enerji tüketimleri ve zamana bağlı elektrik enerjisi tarifi bir bütün halinde ele alınmaktadır. Tekstil terbiye işletmeleri, esnek atölye tipi üretim ortamlarının tipik örnekleridir. Bu yüzden, yapılan çalışmada sıralamaya bağlı esnek atölye tipi üretim ortamları için yeni bir enerji tasarruflu, karma tam sayılı doğrusal programlama modeli önerilmektedir. Önerilen model aktüel çizelgeleme problemlerini karşılayabilen dört bileşenli bir maliyet fonksiyonunu içermekte olup, modelin yeterliliği gerçek zamanlı üretim verileriyle sınanmıştır.

Anahtar Kelimeler: Tekstil terbiye, esnek atölye tipi çizelgeleme, sıralamaya bağlı hazırlık işlemleri, zamana bağlı enerji tarifi, enerji maliyetleri.

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1. INTRODUCTION

Efficient energy use is crucial and essential for a sustainable world. Looking at the macro level, there are three basic eco-friendly and energy efficient concepts: energy efficient equipment, insulation and recovery systems and renewable energy. Furthermore, area of decision support systems should be emphasized for efficient energy use and it can be the fourth energy efficient concept.

Scheduling is an important decision making process since it is vital for energy consumption and cost management, particularly for production units that have high product variety. Set-up costs such as energy, labour and equipment are usually variable due to sequence dependency of production schedule. Furthermore, reducing energy costs with an effective production schedule is possible under time-of-use (TOU) electricity pricing model that has been adopted in some countries such as Austria, Canada, South Korea,

Turkey [1,2,3,4]. For cost reduction, high electricity consuming operations may be processed during off-peak periods (low-priced periods) and relatively less energy consuming operations may be processed during on-peak periods (high-priced periods).

On the one hand, a number of studies have focused on the issues of energy consumption and scheduling because of the raised energy awareness and the importance of cost management in recent years. In that context, Mouzon proposed to create unified idle times on schedule and turn off machines in non-processing times for single machine and parallel machine systems [5]. Liu et al. saved energy in a flow shop manufacturing system with a similar assumption [6]. Luo et al. reduced energy costs with TOU electricity pricing model and right shift on schedule by speed adjustment for the flow shop manufacturing systems [7]. Likewise, Gong et al. reduced energy costs with demand balancing and turning off approach under TOU and real time pricing models for a single machine [8]. Turning off a machine and deceleration of a line are smart solutions but not applicable for bottleneck and full capacity machines. In the argument of Liu et al. a multi-objective scheduling method was proposed for minimising energy consumption in job shops, however they neglected set-up operations and parallel machines [9]. Likewise, Dai et al. optimised energy consumption and makespan with selectable parallel machines by an improved heuristic algorithm, however, they neglected set-up operations [10].

On the other hand, companies constantly introduce new products for keeping their market share and increasing their profit in the competitive textile market. Moreover, the evolving machine technology has increased the flexibility of the finishing machines so flexible job shops spread in the textile industry. Furthermore, the flexible job shop scheduling (FJSS) problem is the extended version of the classical job shop scheduling (JSS) problem. In a flexible job shop, machines can process more than one operation type, and single or parallel machines can be located in a machine shop [11]. There are relatively few studies about the FJSS problem due to its complexity and modelling challenge.

Set-up times are usually used sequence independent form within process times or set-up times are neglected for the JSS problems. Allahverdi et al. provided broad explanation on the set-up issue [12]. In the same manner, Hershauer [13], Flynn [14], Patterson [15], Kim and Bobrowski [16] mentioned that using sequence dependent set-up times improves the performance of schedules.

In addition to the set-up matter, makespan or due date related objectives are usually preferred in the JSS and FJSS studies. Indeed, makespan is vital for on time production but the important point is both on time and cost effective production. Therefore, this study aims to develop a novel, energy conservative and cost effective mixed integer linear programming (MILP) model for green and clean world. As seen in Table 1, the proposed model in this study is compared with the relevant JSS/FJSS models that were reviewed in Karacizmeli and Ogulata [17].

2. PROBLEM DESCRIPTION AND THE PROPOSED MODEL

The shop floor is outlined for the FJSS problem and the proposed mathematical model is described in this section.

1.1. Problem description

There are a set of n jobs (products) and a set of m machines in a flexible job shop. The main objective is, assigning jobs to machines without disrupting the delivery date in order to ensure the cost effective schedule. Jobs (j) can have various numbers of processes (l) and each process corresponds to an operation type (OT_{jl}). The described flexible job shop floor is similar to the finishing shop floor and it is illustrated in Fig.1.

Other major working conditions of the problem are provided below:

- Set-up times and set-up costs are variable dependent on scheduled operation sequence.
- TOU electricity pricing model is used for electric energy costs of processes and there are certain number of periods for every planning day in TOU tariff (Generally, three periods are used that are off-peak, mid-peak and on-peak).
- Other energy resources such as coal, fuel oil or natural gas have flat prices during a planning day.

Energy and labour costs are usually the most important cost items for set-up operations since they may vary depending on the overall scheduling situation. Therefore, the sum of labour and energy costs is used as the set-up cost in the proposed model. Allahverdi et al. explained that durations and costs of setups are used as an alternative to each other in various studies [30]. However, these two criteria can move independently in the finishing processes. If labour/machine time is the sole cost distribution key for the set-up costs then incorrect cost accounting is inevitable, particularly in terms of energy costs. For example, a stenter machine consumes energy and a certain time passes in heating but in cooling, the machine can be cooled by itself without energy consumption and a certain time passes too, except standby energy [31]. Energy consumption in the standby mode is neglected in this study.

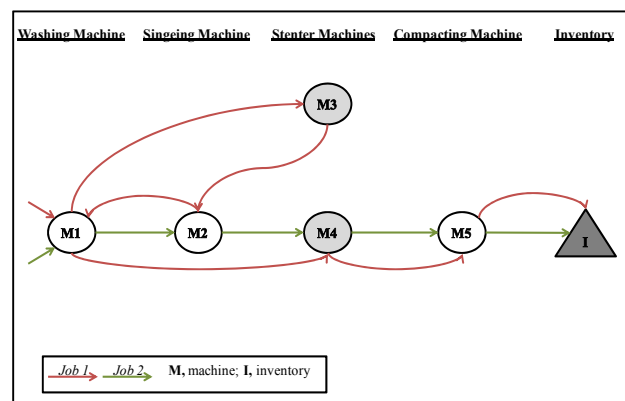


Fig. 1. A flexible job/finishing shop

Table 1. Comparison of the models in the literature and the proposed model

Model	Problem Type	Model Characteristics					
		Setups			Processes	Objective(s)	
		SeqD	T	EU	PEU	MS/DD	C
The proposed model	FJSS	✓	✓	✓	✓	✓	✓
[9]	JSS				✓	✓	✓
[18]	JSS					✓	✓
[19]	JSS					✓	
[20]	FJSS	✓	✓			✓	
[21]	FJSS	✓	✓			✓	
[22]	FJSS					✓	
[23]	JSS		✓			✓	
[24]	JSS		✓				✓
[25]	FJSS		✓			✓	
[26]	FJSS	✓	✓			✓	
[27]	FJSS					✓	
[28]	JSS					✓	
[29]	JSS					✓	

Denotes: SeqD, sequence dependency; T, times; EU, energy usages; PEU, energy requirements of the processes; MS, makespan related; DD, due date related; C, cost related.

1.2. Proposed Mathematical Model

An integrated MILP model is developed for handling the outlined FJSS problem. The objective function is designed like a quaternary cost function, as shown in Fig.2. Constraints are grouped to three parts that are sequencing constraints, periodization constraints and integration constraint. The equations and necessary notations can be seen in Appendix-A.

1.2.1. Objective Function

The objective function has four cost components. Eq. (1) is the total tardiness cost (TC). Eq. (2) is the energy costs of set-up operations (SuEC). Eq. (3) is the labour costs of set-up operations (SuLC). Eq. (4) is the energy costs of processes (PEC). As it is shown in the Eq. (5), the integrated objective function involves, minimising the total of these four costs.

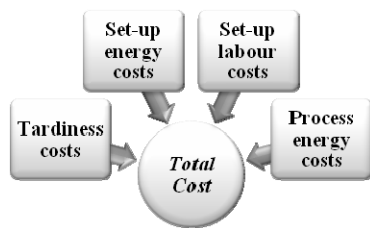


Fig.2. The components of the cost function

1.2.2. Sequencing Constraints

This part contains sequencing constraints on the FJSS MILP model of Mousakhani [26]. However, set-up durations are constructed depending on consecutive operations, unlike the model of Mousakhani. In some flexible job shop manufacturing facilities, set-up operations can be associated with the consecutive jobs. Nevertheless, in many flexible job shop manufacturing facilities, required set-up

operations between two consecutive jobs, depend on operation types (OT_{ji}) of their relevant processes. In these kinds of flexible job shops, machines can process more than one operation type and required setting information of a machine such as temperature, speed, pressure etc. are carried by operation types. Constraint set (6) guarantees that each process is scheduled only once and each process has only one preceding process. Constraint set (7) provides that each process is scheduled to one of its eligible machines. Constraint set (8) ensures that each process has at most one succeeding process. (9) is the dummy process constraint. Initial set-up process is necessary for each used machine so a dummy job is defined that has only one process and dummy process must be assigned at time zero. Constraint set (10) specifies that only processes assigned to same machines can be consecutive. Constraint set (11) ensures that a job cannot be assigned on more than one machine at the same time. Similarly constraint set (12) provides that more than one job cannot be scheduled on the same machine at the same time. The starting times of processes are calculated with (13). (14) is the tardiness calculation constraint, tardiness of a job is difference between the completion time of its last process and its due date. Constraint set (15) assures that completion times of processes and tardiness of jobs must be nonnegative. Constraint set (16) defines the binary variable of process assignment.

1.2.3. Periodization Constraints

This part deals with constraints related to assigning processes to the TOU electricity periods. A functional structure with additional one binary variable established for the FJSS problem. Constraint sets (17), (18) and (19) determine the period of processes. Constraint set (20) ensures that each process is assigned to periods only once. Constraint set (21) provides right and eligible machine selection when assigning a process to a period. Constraint set (22) defines the binary variable.

1.2.4. Integration constraint

This constraint part has a task for integrating the sequencing and periodization constraints whereby whole model can run perfectly together. Thus, when assigning each process to machines, also integration constraint ensures assigning processes to periods (23).

2. RESULTS AND DISCUSSION

Initially, the duration-energy consumption relationship is analysed for set-up operations. Then the capability of the proposed model is proved with real time manufacturing data, which was collected from the finishing department (washing, singeing, stenter and compacting machines) of an integrated textile company. Finally, benchmark problems are evaluated in Section 3.

Randomly collected set-up data has been analysed. There are two different reactions between set-up energy costs and set-up durations. Therefore, set-up operations are split in two groups that are start-up set-up operations and set-up operations between two processes. As seen in Fig.3, set-up energy costs are highly and positively correlated with set-up durations during start-up. Both energy and time are required to reach operating conditions when a machine is in the off position. However, as seen in Fig.4, a significant relationship is not observed between set-up energy costs and set-up durations for set-up operations between two processes. Since set-up operations for cooling require less or no energy. Thus, the assertion mentioned in Section 2 is justified.

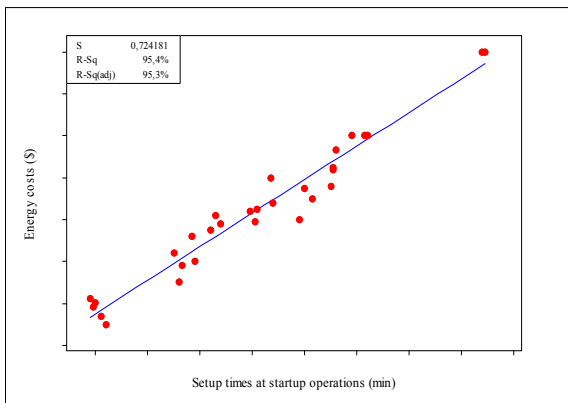


Fig.3. Fitted line plot for start-up set-up operations

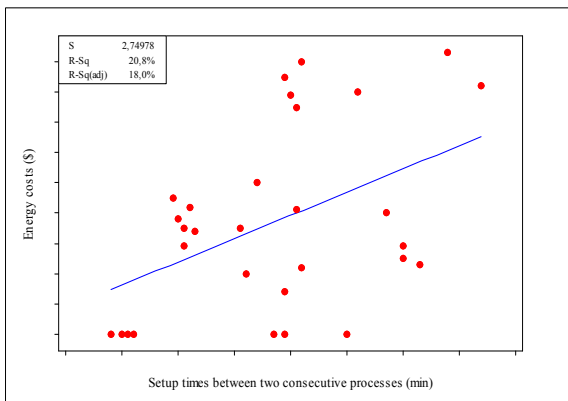


Fig.4. Fitted line plot for set-up operations between two processes

The proposed model has been coded in GAMS (23.5.1)/CPLEX (12.0) and an actual scheduling problem has been solved on a Core(TM) i5-M460 CPU 2.53 GHz personal computer. In the sample problem, two semi-finished products (one of them has 8 processes and the other 9), five machines as shown in Fig.1 and three manufacturing periods (TOU periods) are used for a daily schedule. The scheduling results regarding process sequencing are shown in Fig.5 and process flow can be seen in Appendix-B. Two stenter machines are available in the system, the solver prefers only one of them, which has the highest energy efficiency ratio. Likewise, although three different TOU periods are available, the solver prefers the cheapest two periods for assignments.

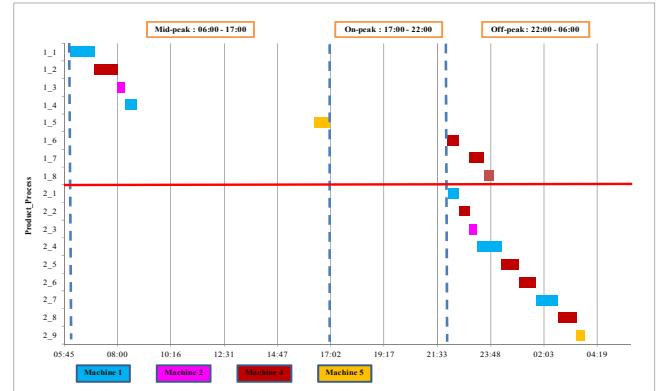


Fig.5. Gantt chart

Furthermore, two different scenarios have been created for indicating the success of the MILP model. In the first scenario, the objective function "minimises the total tardiness cost" and in the second scenario, the objective function "minimises the total tardiness and set-up labour costs.

As known, in the standard three-shift system, there is only one start-up operation for a machine in a week, except failure and maintenance conditions. Moreover, in the 7-day shifting model, machines are not shutdown unless failure or maintenance conditions, so any start-up operations are not required especially for bottleneck and full capacity machines. Therefore, the costs of the scenarios and the proposed model are evaluated without start-up set-ups (Fig.6).

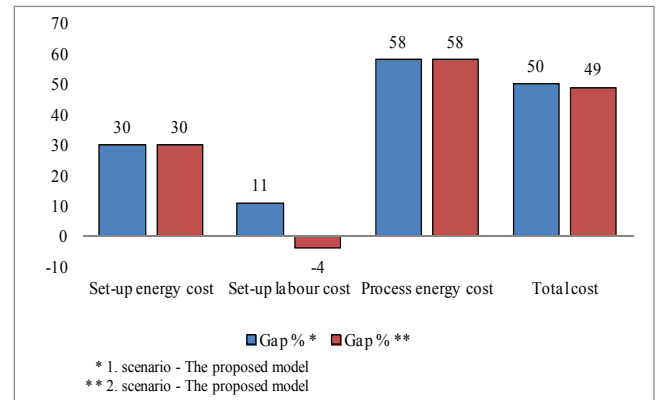


Fig.6. The cost gaps between the scenarios and the proposed model

Furthermore, the different sized benchmark problems were prepared with the real time data and the solver performances have been evaluated for determining the limitations of the model. As shown in Table 2, optimal values can be found within acceptable times up to 20 processes.

4. CONCLUSION

Energy is one of the most important production requirements for most states, particularly for the countries that have limited energy resources and have to consume relatively expensive energy. It is fact that the world's reserves of fossil fuels are running out at an alarming rate and humankind has usually destroyed the environment for energy production [17]. In this study, an energy saving, integrated MILP model is presented for the FJSS problems and particularly for the scheduling of the textile finishing processes.

The characteristics of the set-up operations have been analyzed with an in-depth logic.

As seen in Fig.6, the total cost reaches high values of 50% and 49% in the first and second scenarios, respectively, compared to the proposed model. Managers should use different cost distribution keys for accurate cost accounting and proper scheduling because using only machine or labour time based cost distribution keys may be insufficient in some manufacturing environments as evidenced by this study. The energy costs of processes are higher by 58% in the first and second scenarios, compared to the proposed model. The high electricity consuming operations can be scheduled during off-peak periods (low-priced periods) and

relatively less energy consuming operations can be scheduled during on-peak periods (high-priced periods).

The advantages of the proposed model are as follows. The proposed model,

- has a modular and flexible structure for different real world situations.
- takes into account costs that have impact on schedule.
- reduces energy consumption and energy costs without increasing total schedule cost.
- reduces energy consumption without investment.

In fact, the proposed MILP model brings a different perspective for scheduling problems and it can easily be used in SMEs and customized shops of large facilities for optimum solutions. The performance of the model can be evaluated with metaheuristics for the large scheduling problems.

ACKNOWLEDGEMENTS

This work was supported by Research Fund of Cukurova University under project number FDK-2016-5566. The authors express their special thanks to the engineers and operators of the textile company for their kindly supports in the data collection phase. The authors would like to thank the anonymous referees for their valuable comments and suggestions that have improved the organisation of the paper.

Table 2. Computational results of the benchmark problems

J	P	DP	M	Var	I	CPU time (h:min:sec)	OV
2	10	4	5	719	1,958	00:00:02	135.4
3	15	4	5	1,450	51,759	00:00:07	166.5
4	20	4	5	2,431	4,877,120	00:05:08	203.4
5	25	-	5	-	-	-	N/A
10	50	-	5	-	-	-	N/A

Denotes: J, number of jobs; P, number of processes; DP, number of used dummy processes; M, number of available machines; Var, number of variables; I; number of iterations; OV, optimal values.

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APPENDIX-A

Model notations

	Notation	Definition
Indices	j, k	Index of jobs $j, k = \{0, 1, 2, \dots, n\}$
	l, b	Index of processes $l = \{1, 2, \dots, v_j\}$ and $b = \{1, 2, \dots, v_k\}$
	i	Index of machines, $i = \{1, 2, \dots, m\}$
	p	Index of periods, $p = \{1, 2, \dots, a\}$
	V_j	Process set of job j , $ V_j = v_j$
Parameters	$SuD_{j kbi}$	Set-up time, when OT_{ji} is assigned after OT_{kb} on machine i
	$EU_{j kbi}$	The amount of natural gas consumption, when OT_{ji} is assigned after OT_{kb} on machine i
	UTC_j	Tardiness unit cost of job j
	PE	Unit price of natural gas
	UP_p	Unit price of electricity
	PL	Unit labour cost
	PEU_{ji}	The amount of electricity consumption, when OT_{ji} is assigned on machine i
	OEU_{ji}	The amount of natural gas consumption, when OT_{ji} is assigned on machine i
	d_j	Due date of job j
	e_{ji}	Equals to 1 if machine m is eligible for OT_{ji} , 0 otherwise
	t_{ji}	Processing time of OT_{ji} on machine i
	S_p	Starting time of period p
	B_p	Finishing time of period p
	M	A very large number ($M > 0$)
Decision variables	$Y_{j kbi}$	Equals to 1 if OT_{ji} is assigned after OT_{kb} on machine i , 0 otherwise
	$X_{j ip}$	Equals to 1 if OT_{ji} is completed in period p on machine i , 0 otherwise
	F_{ji}	Completion time of OT_{ji} ($F_{ji} \geq 0$)
	St_{ji}	Starting time of OT_{ji}
	T_j	Tardiness of job j ($T_j \geq 0$)

Objective Function

$$TC = \sum_{j=1}^n T_j \times UTC_j \quad (1)$$

$$SuBC = \sum_{j=1}^n \sum_{l=1}^{v_j} \sum_{b=1}^{v_k} \sum_{i=1}^m Y_{j|lkb} \times PE \times EU_{j|lkb} \quad (2)$$

$$SuLC = \sum_{j=1}^n \sum_{l=1}^{v_j} \sum_{b=1}^{v_k} \sum_{i=1}^m Y_{j|lkb} \times PL \times SuD_{j|lkb} \quad (3)$$

$$PEC = \sum_{j=1}^n \sum_{i=1}^m \sum_{p=1}^a X_{j|ip} \times (UP_p \times PEU_{ji} + PE \times OEU_{ji}) \quad (4)$$

$$\text{Minimise}(TC + SuBC + SuLC + PEC) \quad (5)$$

Sequencing Constraints

$$\sum_{k=0}^n \sum_{b=1}^{v_k} \sum_{i=1}^m Y_{j|kbi} = 1 \quad \forall j \geq 1, l \in V_j \quad (6)$$

$$\sum_{k=0}^n \sum_{b=1}^{v_k} Y_{j|kbi} \leq e_{ji} \quad \forall j \geq 1, l \in V_j, i \quad (7)$$

$$\sum_{j=1}^n \sum_{l=1}^{v_j} \sum_{i=1}^m Y_{j|lbi} \leq 1 \quad \forall k \geq 1, b \in V_k \quad (8)$$

$$\sum_{j=1}^n \sum_{l=1}^{v_j} Y_{jlkdt} \leq 1 \quad \forall i \quad (9)$$

$$\sum_{j=1}^n \sum_{l=1}^{v_j} Y_{jlkdt} \leq \sum_{k=0}^n \sum_{b=1}^{v_k} Y_{kdbjt} \quad \forall k \geq 1, b \in V_{k,t} \quad (10)$$

$$F_{jlt} F_{j,t-1} + \sum_{k=0}^n \sum_{b=1}^{v_k} \sum_{l=1}^m Y_{jlkdbt} \times (t_{jlt} + SuD_{jlkdbt}) \quad \forall j \geq 1, l \in V_j \quad (11)$$

$$F_{jlt} F_{kbt} + \sum_{l=1}^m Y_{jlkdbt} \times (t_{jlt} + SuD_{jlkdbt}) - M \times \left(1 - \sum_{l=1}^m Y_{jlkdbt} \right) \quad \forall j \geq 1, l \in V_j, k, b \in V_k \quad (12)$$

$$St_{jlt} = F_{jlt} - \sum_{k=0}^n \sum_{b=1}^{v_k} \sum_{l=1}^m Y_{jlkdbt} \times (t_{jlt} + SuD_{jlkdbt}) \quad \forall j \geq 1, l \in V_j \quad (13)$$

$$T_j \geq F_{jv_j} - d_j \quad \forall j \quad (14)$$

$$F_{jlt}, T_j \geq 0 \quad \forall j \geq 1, l \in V_j \quad (15)$$

$$Y_{jlkdbt} \in \{0,1\} \quad \forall j \geq 1, l \in V_j, k, b \in V_k, t \quad (16)$$

Periodization Constraints

$$M \times (1 - X_{jltsp}) \geq S_p - F_{jt} \quad \forall j \geq 1, l \in V_j, t, p \quad (17)$$

$$M \times (1 - X_{jltsp}) \geq F_{jt} - B_p \quad \forall j \geq 1, l \in V_j, t, p \quad (18)$$

$$St_{jlt} \geq S_p \times X_{jltsp} \quad \forall j \geq 1, l \in V_j, t, p \quad (19)$$

$$\sum_{l=1}^m \sum_{p=1}^a X_{jltsp} = 1 \quad \forall j \geq 1, l \in V_j \quad (20)$$

$$\sum_{p=1}^a X_{jltsp} \leq e_{jlt} \quad \forall j \geq 1, l \in V_j, t \quad (21)$$

$$X_{jltsp} \in \{0,1\} \quad \forall j \geq 1, l \in V_j, t, p \quad (22)$$

Integration Constraint

$$\sum_{p=1}^a X_{jltsp} - \sum_{k=0}^n \sum_{b=1}^{v_k} Y_{jlkdbt} = 0 \quad \forall j \geq 1, l \in V_j, t \quad (23)$$

APPENDIX-B

Process Nr.	Product 1	Product 2
1	Washing	Washing
2	Drying	Drying
3	Singeing	Singeing
4	Washing	Washing
5	Drying	Drying
6	Fixation	Fixation
7	Chemical finishing	Washing
8	Sanforising	Chemical finishing
9		Sanforising