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ÇOK ÇEŞİTLİ/AZ HACİMLİ ELEKTRONİK KART ÜRETİMİ YAPAN BİR FİRMANIN ÜRETİM ÇİZELGELEMESİNİ GERÇEKLEŞTİREN KARMA-TAMSAYI PROGRAMLAMASI

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AN OPTIMAL MIXED INTEGER PROGRAM FOR SCHEDULING IN A HIGH MIX-LOW VOLUME PRINTED WIRING BOARD PRODUCTION COMPANY

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Emre Özgenç Ekici tarafından hazırlanan "Çok Çeşitli/Az Hacimli Elektronik Kart Üretimi Yapan bir Firmanin Üretim Çizelgelemesini Gerçekleştiren Karma-Tamsayı Programlaması" başlıklı bu çalışma, [16.07.2013] tarihinde yapılan savunma sınavı sonucunda başarılı bulunarak jürimiz tarafından Yüksek Lisans Tezi olarak kabul edilmiştir.

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TEŞEKKÜR

Öncelikle eğitimim konusunda beni her zaman destekleyen ve yüksek lisans fikrini hep aklımda tutan anneme, tez yazılımı hazırlamak ve tez yazmak için zaman yaratmam konusunda bana yardımcı olan ve beni hep mutlu eden eşime, ayrıca tez konusu seçimi, tez yazım ve sonuçlandırma aşamasında beni yönlendiren, destekleyen, ve hep özgür bırakarak yaratıcı olmamı sağlayan sayın hocalarım Prof. Dr. Ş. Armağan TARIM ve Dr. Roberto ROSSI'ye çok teşekkür ediyorum.

ÖZET

EKİCİ, Emre Özgenç. Çok Çeşitli/Az Hacimli Elektronik Kart Üretimi Yapan bir Firmanin Üretim Çizelgelemesini Gerçekleştiren Karma-Tamsayı Programlaması, Yüksek Lisans Tezi, Ankara, 2013.

Çok Çeşitlilik/Az hacimli üretim yapan, birden fazla üretim safhası bulunan, her safhada birden fazla paralel kaynağı olan Hibrit Akış Atölye (HAA) alanlarında optimum üretim çizelgesi yapmak gerçek hayatta rutin ve zor bir problemdir. Bu tür üretim alanlarının optimum üretim çizelgelemeleri için literatürde bir çok özel karma-tamsayı programları mevcuttur. Bu tezde ise, çok değişkenlik/az hacimli üretim yapan, birden fazla safhası bulunan, her safhada paralel kaynakları bulunan, safhalar arasında bekleme zaman/hacim sınırı olmayan, parti bölmeye izin veren, her işin birbirinden bağımsız kurulum süresinin olduğu gerçek bir firmanın Elektronik Kart Üretim Çizelgelemesi için geliştirilen Karma-Tamsayı Modeli yer almaktadır. Bu modelde, amaç fonksiyonu; geç kalan işlerin maliyeti ve her safhadaki kapasite artırım maliyet toplamını minimum hale getirmek olarak belirlenmiştir.

Anahtar Sözcükler

Hibrit Akış Atölye, Karma-Tamsayı Programlama, Çizelgeleme, Elektronik Kart Üretim

ABSTRACT

EKİCİ, Emre Özgenç. An Optimal Mixed Integer Program for Scheduling in a High Mix - Low Volume Printed Wiring Board Production Company, Master's Thesis, Ankara, 2013.

Finding optimum schedules for High Mix / Low Volume, multistage Hybrid Flow Shop (HFS) areas, is regular and hard problem. For these kinds of production areas, there are many specific Mixed Integer Programs in literature. In this thesis, another Mixed Integer Program is demonstrated for a real Printed Wiring Board Production Company with specific features: High Mix / Low Volume, multistage production with parallel units, Unlimited Interstate Buffer, Allowed Lot-Splitting, Independent set-up times of each job. Objective Function of the model is minimizing sum of costs of tardy jobs and capacity increment at each stage.

Key Words

Hybrid Flow Shop, Printed Wiring Board Production, Scheduling, Mixed Integer Programming

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INTRODUCTION

The company that this thesis is about is ASELSAN A.Ş. Defense Systems Technologies Division Electronics Production Department and it is working according to High Mix/low Volume Production Type.

4 main stages exist for Printed Circuit/Wiring Board (PCB) assembly at Electronics Production Department;

1. SMD Assembly

At this stage, SMD components such as resistors, diodes, capacitors, transistors, integrated circuits are mounted.

2. Through Hole Component Assembly and Rework

All electronic through-hole components and electromechanical components such as connectors, heat sinks, screws, RF screens are fixed and soldered on PCB's by using different kind of soldering methods.

3. Functional Test

PCB's are checked if they are functioning properly in accordance with their documented specifications by using special test setups, and test equipments.

4. Conformal Coating and Gluing

The conformal coating process is applied to protect PCBs from degradation caused by dust, dirt, moisture, thermal cycling and exposure to solvents.

At each stage, there are parallel sources, and owing to nature of electronic production, each production order follows same routing. (From stage1 to Stage 4) In literature, these kinds of productions types are called Hybrid Flow Shop (HFS) (Gupta, 1988; VoX, 1993). This production type is frequently-used in electronic industry and it has multi-stage, parallel resources in each stage and jobs having same production flow. Therefore, this scheduling problem easily can be regarded as Hybrid Flow Shop scheduling problem with its own additional special features. Each job has its own due-dates; each stage has its own capacity. And there are costs that company pays for tardy jobs and capacity increment.

Also, because of high variety, various Printed Wiring Board Assembly production orders come to Electronics Production Department. All of these production orders includes different release date, due date, quantity, material name, routing, documents needed, sub-materials needed. After that, capacity constraints are included manually by Shop Floor Engineer. During Manufacturing Execution stage, in line with due-dates, release-dates, and capacity min/max borders, Shop Floor Engineer schedules each production order by splitting/not splitting the batches, increasing/decreasing capacity of each stage. This process is not cost affective and totally manual. Therefore, in this thesis mainly this scheduling problem is examined, a Mixed Integer Model is developed, solved and demonstrated.

Company Information

As a developer of state of the art Land, Air, Naval and Space technology, ASELSAN is Turkey's leading defense industry company. Since the day it was founded, ASELSAN has attached the utmost importance to R&D activities as well as the advancement of technology, and endeavors to achieve its goal of increasing its share in the international market by taking part in international projects.

For the last four years, ASELSAN sustained its position in the world as being in the list of Top 100 Defense Companies. ASELSAN's objective is to become one of the top 50 companies in the world through the development of original and national opportunities and talents of the highest level.

ASELSAN operates under four divisions:

Communications and Information Technologies,

Radar, Electronic Warfare and Intelligence Systems

Defense Systems Technologies

Microelectronics, Guidance & Electro-Optics Division.

ASELSAN operates in the fields of the design, development, production, system integration, and after-sales services of

1. Military Communications Systems
2. Radar Systems
3. Electronic Warfare Systems
4. Electro-Optic Systems
5. Navigation and Avionic Systems
6. Weapons Systems
7. Command Control Communication Computer Intelligence, Reconnaissance and Surveillance Systems
8. Naval Systems
9. Unmanned Systems
10. Traffic and Toll Collection Systems.

Production and engineering activities are realized in Macunköy and Akyurt facilities, all of them are located in Ankara.

The Communications and Information Technologies Division, Defense Systems Technologies and Radar, Electronic Warfare and Intelligence System Divisions and the headquarter are situated in Macunköy Facilities which is established on a total area of 187.000 m2, of which 110.000 m2 is closed area.

Microelectronics, Guidance and Electro optics Division is situated in Akyurt Facilities, which is nearby Ankara Esenboğa Airport, is established on a total area of 232.000 m2, of which 54.000 m2 is closed area.

Some part of the overall R&D activities with respect to Communications and Information Technologies Division are carried out in Aselsan Teknokent, a premise in Middle East Technical University, which is established on a total area of 4,500 m2, of which 4,000 m2 is closed area, which is also located in Ankara.

This research is done in Defense Systems Technologies Division and focused on Electronics Production Department Scheduling Problems.

Due to defense systems market conditions, ASELSAN Defense Systems Technologies Division is an Engineer-To-Order Company and it has High Mix/Low Volume Production type.

After ASELSAN Defense Systems Technologies Division has got sales contracts, engineering activities begins. For each “Sales contract”, a “Project Name” is given. During and after engineering activities, Bill of Materials is stabilized and fixed. Master Production Schedules are created and Material Resource Planning algorithms are run according to master plans. Consequently, purchase orders and production orders are created in batches. Lot-Sizing procedure is made by ERP system. All of materials are procured or produced during these stages. For instance, during this research, company has got approximately totally different 25 projects running.

Electronic Production Department and Printed Wiring Board Assembly

In Electronic Production Department, Printed Circuit/Wiring Boards (PCBs), modules, LRU’s and cables are produced by certified technicians. All personnel are trained in ESD and safety transportation. According to working shops, respected operators are certified periodically by authorized trainer regarding IPC-A-610, J-STD-001, IPC-A-620, IPC-7721/7711 standards. The production area with air conditioning and the floor completely covered with conductive dissipative material against ESD. The internal atmospheric pressure is held above that of outside to insure a dust free work place. All the work benches are covered with ESD dissipative mats.

All of multi-layer, double-sided PCBs which have surface mounted (SMD) and through-hole (leaded) components are produced according to IPC-A-610 standard.

In addition, the work benches in PCB assembly, visual inspection and repair touch up areas are equipped with overhead ionizing neutralizers. The effectiveness of the ESD preventive hardware is periodically checked using electrostatic field tester, surface resistivity tester, ground tester and wrist strap tester.

Additionally; According to the volume of production and test measurement complexity, different types of functional test methods are applied to the cable, harness, PCB, LRU and subsystems as known as manual tests methods or automated test methods. Automated test methods can be performed with general purpose or special to type automated test equipments. There are many standard test devices working between DC and up to 50 GHz frequency.

Briefly, 4 main stages exist for Printed Circuit/Wiring Board (PCB) assembly;

1. SMD (Surface Mounted Devices) assembly
2. Through-hole (leaded) components assembly and rework
3. Functional Test
4. Conformal Coating and Gluing

Therefore, this scheduling problem easily can be regarded as Hybrid Flow Shop scheduling problem with its own additional special features. As it is mentioned, each job has its own due-dates; each stage has its own capacity. And there are costs that company pays for tardy jobs and capacity increment.

Research Objectives:

The aim of this thesis is to study real company scheduling restrictions and Hybrid Flow Shop scheduling models and combine them together to design a decision support tool for scheduling jobs. Therefore objectives of this thesis can be regarded as following:

1. Analyzing Hybrid Flop Shop Scheduling Problem and special features of the company.
2. Developing a suitable model for scheduling problem of the company.
3. Evaluating the research results and making this model a part of the decision support tools of the company.

1. PROBLEM STATEMENT

1.1. PRINTED WIRING BOARD ASSEMBLY ENVIRONMENT IN THE COMPANY

In Electronic Production Area, all electronic through-hole and SMD components such as resistors, diodes, capacitors, transistors, integrated circuits are mounted and electromechanical components such as heat sinks, screws, and RF screens are fixed on PCB's.

All of these assemblies are made simply through 4 main stages.

1. SMD Assembly

2. Through Hole Component Assembly and Rework

3. Functional Test

4. Conformal Coating and Gluing

Because of High Mix/Low Volume production structure, each stage is not fully automated and some stage usually encounters labor-intensive jobs. Except SMD assembly, remaining 3 stages can be regarded as labor intensive. Regarding this situation; for 3 stages, scheduling and capacity planning is done due to labor restrictions and for SMD Assembly stage scheduling and capacity planning is done due to machine restrictions. Each stage has parallel labor and machine resources. Because of High Mix, set-up times are inevitable for this case.

Additionally, approximately 1.000 PCBs of 80 different types are produced per month in this production area.

1. SMD (Surface Mounted Devices) Assembly

SMD components such as resistors, diodes, capacitors, transistors, integrated circuits are mounted. There are 2 parallel SMD machines in production line. Materials are prepared and put into feeders, trays and tubes before assembly and before machine run, an assembly program which is showing the exact locations of materials on PCB’s, should be prepared. Except setup activities, this stage can be considered as machine-intensive stage. Capacity planning, scheduling is done due to SMD Machines restrictions.

Figure -1: One of SMD Machine used in SMD Assembly Process

2. **Through Hole Component Assembly and Rework**

All electronic through-hole components and electromechanical components such as connectors, heat sinks, screws, RF screens are fixed and soldered on PCB’s by using different kind of soldering methods such as wave soldering system, Selective Soldering System or manual soldering.

Additionally there is an extra stage called “Component Forming, Potting and Preparing” which can be regarded as setup of this stage. In this extra stage, Component leads are cut and formed, some small mechanical parts such as pins, rivets, carriers are formed and placed on pcb, peel able solder mask material applied to PCB’s prior to PCB assembly. Therefore, this stage is a setup for “Through Hole Component Assembly and Rework” stage.

This stage can be considered as labor-intensive stage. Capacity planning, scheduling is done due to labor resource restrictions.

Figure-2: Wave-Soldering Machine

Figure-3: Selective-Soldering Machine

3. Functional Test

PCB's are checked if they are functioning properly in accordance with their documented specifications by using special test setups, and test equipments. The PCB's that pass the test, go on the consequent stage. But the PCB's that cannot pass, are sent to previous stage for repair/rework.

This stage can be considered as labor-intensive stage. Capacity planning, scheduling is done due to labor resource restrictions.

Figure-4: Sample Test Setup (1)

Figure-5: Sample Test Setup (2)

4. Conformal Coating and Gluing

The conformal coating process is applied to protect PCBs from degradation caused by dust, dirt, moisture, thermal cycling and exposure to solvents. This process is applied manually or by special automatic machine

Also, In order to stabilize the large components subject to mechanical shock in operation, gluing process is applied to fix the components to each other or prevent the leakage.

This stage also can be considered as labor-intensive stage. Capacity planning, scheduling is done due to labor resource restrictions.

Figure-6: Gluing Process

Figure-7: Conformal Coating Machine

The flow of PCBs can be demonstrated briefly as at Figure-8:

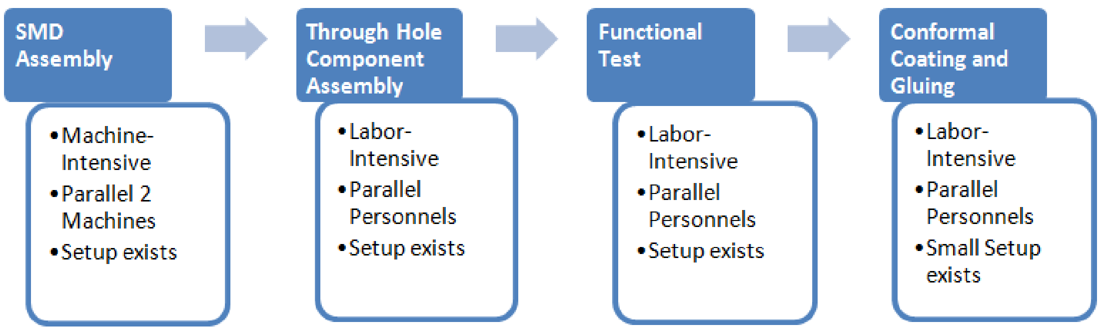

Figure-8: Flow of PCB Production

1.2. PRINTED WIRING BOARD ASSEMBLY PLANNING AND SCHEDULING PROBLEM

Due to various Project Plans and Master Production Schedules (MPSs), Engineering Departments fix and freeze Bill of Materials (BOMs) data of Materials. Afterward, Production Planning Department runs Material Resource Planning, explodes BOMs and creates production and purchase orders regarding Project Plans and MPSs.

Lots and batches are determined during this activity. There is not a methodic lot-sizing strategy in the company. “Lot-for-Lot” Lot-Sizing method is used usually. For the cases, “Lot for Lot” method is not used, Production Planning Engineers decide the lots for each material type without regarding a common algorithm.

After material procurement activities, various production orders come to Electronics Production Department in High Mix/low Volume type.

Each production order includes a release date, due date, quantity, material name, routing, documents needed, sub-materials needed. Subsequent to production orders arrival, capacity constraints are included manually by Shop Floor Engineer. During Manufacturing Execution stage, in line with due-dates, release-dates, and capacity min/max borders, Shop Floor Engineer schedules each production order by splitting/not splitting the batches, increasing/decreasing capacity of each stage.

As it’s seen, this scheduling problem has its own additional special features and can be regarded as Hybrid Flow Shop scheduling problem.

Therefore, this scheduling problem has;

Assumptions:

1. For each stage, setup time of each job is independent from other jobs’ setup times. (Sequence – independent).

   Because of Engineer to Order and High Mix/low Volume production type of company, there is no product line and grouping of products, so one type of product do not resemble another. This causes totally different setups for each product and totally different and independent setup times for each product.

2. Some obligatory wait-times just like oven, cleaning etc. are not managed.

   Wait-times are assumed that they are occurred after work-hours. These kinds of waiting times for each product make the schedules totally unmanageable. So as to manage these wait-times, the company put them often after work-hours.

3. Material handling times are not managed.

   In the ASELSAN Defense Systems Technologies Division PCB Production Area, there is at most 15 meters distance and it takes at most 2 minute walk between stages. Therefore, the company neglects these material handling times in their schedules.

4. All of parallel labor and machine resources that are at the same stage are identical.

   In order to formulize and calculate the capacity of each stage, company makes their schedules by neglecting differences of each resource.

5. Processing times of each job is deterministic.

   In scheduling studies hold during and before production in company, process times are determined previously and if they are changed during production, all of scheduling studies are redone.

6. Lot splitting is allowed in each stage.

   Lots for each production order are not determined via common algorithm. Frequently, while scheduling production orders, lots of production orders are divided into sub-lots because of capacity constraints of stages or different urgency conditions of sub-lots.

7. Raw material, tooling or infrastructure availability is not managed.

As in all scheduling problems, in order to take healthy solutions from scheduling methods, these kinds of availability problems are neglected by the company.

8. Processed units are always satisfactory.

   In order to handle Reworks/Fail Processes for jobs, the company chooses to re-schedule them as another job.

9. Some sub-lots of customer order can have different due date than remaining part of customer order.

   The company uses the way of re-scheduling these Sub-lots with different due dates as another job.

10. Unlimited buffer between stages.

    The company has no determined space limit between and in stages.

Given Data:

1. Release date of each job.

   Every production order is coming to production area after kitting process at warehouse. Therefore, each production order has a release date. On the other hand, same date can be named as completion date of kitting process of that production order at warehouse. These release dates are determined by Production Planning Engineers in the company.

2. Due date of each job.

   Production Planning Engineers determine due date of each job according to Master Production Plan and MRP.

3. Min/max capacity borders in each stage during a time period.

   As a result of labor-intense stages, capacity of each stage can be changed by managers due to capacity constraints. Minimum and maximum level of capacity for a time period is determined and capacity decisions are made due to these borders.

4. Process time and setup time of each job.

   Every production order has pre-determined, deterministic process time and setup time for each stage.

5. Costs of each tardy jobs and capacity increment.

   In order to make meaningful schedules, unit costs for tardy jobs and capacity increment are predetermined by managers.

Constraints:

1. Capacity of each stage has minimum and maximum borders for labor and machine resources.
2. Every job or part of the batch has due date and release date.

Decision Variables:

1. Start time of each stage for each job
2. Finish time of each stage for each job
3. Can batches be divided to sub-lots? Or will whole batch be processed?
4. How many capacity units used in each stage for a time-period

Objectives:

1. Minimizing total cost of tardy jobs.
2. Minimizing total cost of capacity increments at each stage.

A small Example of Problem:

In order to illustrate ASELSAN Defense Systems Technologies Division PCB Production Scheduling Problem, a small example with 6 production order can be examined.

Production Order #	Stock Number	Amount (Unit)	Relase Date	Due Date
1	A	10	01.01.2014	08.01.2014
2	B	5	02.01.2014	08.01.2014
3	C	1	03.01.2014	06.01.2014
4	D	12	01.01.2014	08.01.2014
5	E	8	01.01.2014	07.01.2014
6	F	4	01.01.2014	08.01.2014

These 6 production orders come to PCB production area, and then process times and setup times of these production orders are determined such as:

	Stage #			
Process Time Matr	1	2	3	4
	20	10	25	10
	5	40	10	0
	8	3	20	4
	32	80	64	16
	0	32	27	26
	16	20	12	8

	Stage #			
Setup Time Matrix	1	2	3	4
	8	2	4	1
	4	3	3	0
	4	1	2	1
	12	3	4	2
	0	1	2	3
	8	2	1	1

Then minimum and maximum borders for capacity of each stage for each time period are determined.

Stage #	Capacity Borders (hr)	
	Minimum	**Maximum**
1	8	32
2	30	80
3	20	50
4	10	20

After all, according to capacity, due date, release date constraints, a feasible schedule is found and executed manually by Shop Floor Control Engineer as following: (Please note that setup times are not included in this demonstration.)

Time t = 01.01.2014 → Time Horizon = 08.01.2014 (8 days)

Job #	Stage #	1	2	3	4	5	6	7	8	Process Times Of Each Job
1	1	20								20
	2		10							10
	3			15	10					25
	4					10				10
2	1		5							5
	2			40						40
	3						10			10
	4									0
3	1			8						8
	2				3					3
	3					20				20
	4						4			4
4	1	12	20							32
	2		70	10						80
	3			30	34					64
	4					10	6			16
5	1									0
	2	32								32
	3		27							27
	4			10	16					26
6	1				16					16
	2					20				20
	3							12		12
	4								8	8

Capacity Usage	1	2	3	4	5	6	7	8	**Normal**	**Max**
S1	32	25	8	16					**8**	**32**
S2	32	80	50	3	20				**30**	**80**
S3		27	45	44	20	10	12		**20**	**50**
S4			10	16	20	10		8	**10**	**20**

Although it is a small example, you can see capacity-usage imbalance over time periods in the schedule. Regarding that the company schedules from 80 to 110 jobs daily, it is not hard to see the complexity of this problem. During scheduling and manufacturing execution, company faces periodically many due-date and capacity violations.

This research focuses on this complex problem and aims to develop a decision support tool for scheduling from 80 to 110 jobs for ASELSAN Defense Systems Technologies Division.

2. LITERATURE REVİEW

2.1. HYBRID FLOW SHOP SCHEDULING PROBLEM

Hybrid Flow Shop (HFS) (Gupta, 1988; VoX, 1993) is a frequently-used production type with multi-stage, parallel resources in each stage and jobs having same production flow. The queues between the various stages may be managed by various disciplines (First In First Out, Earliest Due Date etc.). HFS is named also as “Flexible Flow Shop” or “Multi-Processors Flow Shop” in literature. (M. Pinedo, 2002) A machine/labor can process at most one job at a time and a job can be processed by at most one machine/labor at a time. (Tam_as Kis, Erwin Pesch , 2005) In real world, this special production type has been used generally by the companies that have Low Volume/High Mix production. In Electronics, Foods, Textile Industries, this type can be seen broadly.

HFS production type can be demonstrated mathematically as: (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

3. There should be more than one stage for production. $s > 1$
4. Each stage can have more than 1 parallel resource. $K > 0$
5. Each job should follow same routing. stage1-> stage2 -> stage3-> …

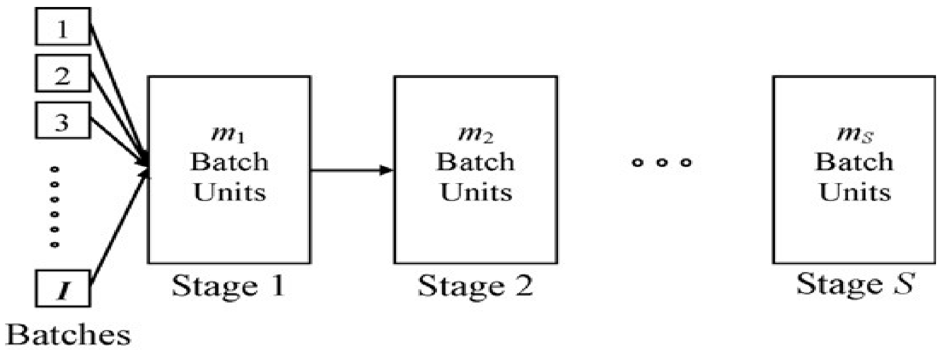

Figure – 9: Schematic of Hybrid Flow Shop with identical parallel units. (Yu Liu, I.A. Karimi, 2008)

HFS scheduling problem can be defined as; finding an optimal or near-optimal schedule of all jobs due to a given objective. However, HFS scheduling problem in most cases NP-Hard. (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

HFS scheduling problems vary because of different industry applications and manufacturing environments. This carries different assumptions, constraints, variables, parameters and objectives to HFS scheduling problem.

In literature, for solving different kinds of HFS scheduling problem, several exact methods and heuristics methods are proposed. Additionally, for stochastic type of this problem, there are some special heuristics (metaheuristics) just like Simulated Annealing, Genetic Algorithms and Tabu Searchs etc.

Commonly, scheduling problems are classified according to shop-configuration (α), set of constraints and assumptions (β), objective functions (ɣ) and are denoted simply as α| β | ɣ. (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

Shop-configuration (α)

Shop-configuration (α) identifies the number of stages, number of machines in each stage and characteristics of machines. Parameter (α) is composed of 4 characteristics that are defined in Table 1.

Set of constraints and assumptions (β)

This parameter described in Table 1, demonstrates special features, constraints and assumptions of manufacturing area.

Objective functions (ɣ)

This parameter depicts the objective function type that is used for that specific scheduling problem.

Parameters of Scheduling Problems
Shop-configuration (α)

α1	General type of Manufacturing Area. Flow-Shop, Job-Shop, Open-Shop etc. Example: FH = Hybrid Flow Shop
α2	Number of Stages
α3 and α4	Properties of Machines in each stage Example: α3 Є {Ø, P,Q,R} P = identical parallel machines Q = uniform parallel machines R = unrelated paralel machines Ø = single machine
Set of constraints and assumptions (β) (Most common parameters)	
r_j	job j cannot start processing before its release date rj
prmu	jobs are processed in every stage in the same order
prec	there are precedence constraints between operations from different jobs.
M_j	the processing of job j is restricted to the set of machines Mj at stage k. This is known as eligibility.
S_{sd}	the setup times are dependent on the sequence of operations.
prmp	preemptions are permitted.
block	the buffer capacities between stages are limited. The jobs must wait in the previous

	stage until sufficient space is released.
recrc	jobs are allowed/required to be processed more than once in the same stage.
unavail	machines are not available at all times.
no – wait	jobs are not allowed to wait between two successive stages.
$p_j = p$	all processing times are equal to p.
Split	if batches of jobs can be devided into parts. (Larysa Burtseva, Rainier Romero, Salvador Ramirez, Victor Yaurima, Félix F. González-Navarro and Pedro Flores Perez (2012))
Objective functions (ɣ)	
C_{max} = maxj C_j	maximum completion time
F_{max} = maxj(C_j – r_j)	maximum flow time
L_{max} = maxj(L_j)	maximum lateness
T_{max} = maxj(T_j)	maximum tardiness
E_{max} = maxj(Ej)	maximum earliness
$C = \sum C_j$	total/average completion time
$C^w = \sum w_jC_j$	total/average weighted completion time
$F = \sum F_j$	total/average flow time
$F^w = \sum w_jF_j$	total/average weighted flow time
$T = \sum T_j$	total/average tardiness
$T^w = \sum w_jT_j$	total/average weighted tardiness
$U = \sum U_j$	number of late jobs
$U^w = \sum w_jU_j$	total/average weighted number of late

	jobs
$E = \sum E_j$	number of earliness
$E^w = \sum w_j E_j$	total/average weighted earliness

Table-1 (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

Therefore, as an example, a HFS scheduling problem that has;

- m stage
- parallel uniform machines at each stage
- unlimited buffer between stages
- preemption-forbidden
- release dates of all jobs
- set-up times independent from each other
- allowed-lot-splitting
- objective function that is sum of number of earliness and number of tardy jobs

α1 α2 α3&α4 β γ

can be denoted simply as **FHm $(PM^{(k)})^m{}_{k=1}$ | r_j, split, S_{nsd} | U + E. (Table-1)**

For solving different kind of HFS scheduling problems, there are two ways proposed in literature;

1. Exact methods such as; Integer Programming and Branch & Bound
2. Heuristics and metaheuristics such as; Complicated Dispatching Rules, Simulated Annealing, Genetic Algorithms and Tabu Search Algorithms etc.

2.2. SOLVING METHODS FOR HFS SCHEDULING PROBLEM

2.2.1. Exact Methods:

In literature, for solving HFS Scheduling problem, different type Branch and Bound (B&B) Based Algorithms and Integer Programming Models are used widely.

B&B Based Algorithms are briefly concentrates on canceling non-promising solutions as far as possible during the run. This decreases the branches of search tree and it helps to find optimum much easier (Ahmet Bolat, Ibrahim Al-Harkan, Bandar Al-Harbi , 2005). In literature, from easier version of HFS scheduling problem (2 or 3 stages and 5-10 jobs) to hardest ones (n stages and m jobs), various B&B based Algorithms can be be found.

Integer programming is also often used to formulate and solve this HFS scheduling problem. Again, there are different types of Integer Programming Models for different types of HFS's. However, general HFS scheduling problem that has negligible setups, no release dates, not allowed preemption, unlimited buffer between stages, identical machines in each stage, can be formulated such as: (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

Index:

j = job number

k = stage number

l = machine number

Parameters:

p_{jk} = processing time required by job j in stage k

Q = Big Number

Decision Variables:

c_{jk} = completion time of job j in stage k. cj0 = 0.

Y_{jkl} = 1 if job j on stage k is assigned at machine l

0 otherwise

X_{jrk} = 1 if job j precedes job r on stage k

0 otherwise

$$\text{minimize } Z \quad (1)$$

$$s.t.$$

$$Z \geq c_{jm}, \forall j \quad (2)$$

$$\sum_{l=1}^{M^{(k)}} Y_{jkl} = 1, \forall (j,k) \quad (3)$$

$$c_{jk} - c_{j,k-1} \geq \sum_{l=1}^{M^{(k)}} Y_{jkl} p_{jk}, \forall (j,k) \quad (4)$$

$$Q(2 - Y_{jkl} - Y_{qkl} + X_{jqk}) + c_{jk} - c_{qk} \geq p_{jk}, \forall (j,k,l,q) \text{ such that } j < r \quad (5)$$

$$Q(3 - Y_{jkl} - Y_{qkl} - X_{jqk}) + c_{qk} - c_{jk} \geq p_{qk}, \forall (j,k,l,q) \text{ such that } j < r \quad (6)$$

$$Y_{jkl} \in \{0,1\}, \forall (j,k,l) \quad (7)$$

$$X_{jrk} \in \{0,1\}, \forall (j,q,k) \quad (8)$$

$$c_{jk} \geq 0, \forall (j,k). \quad (9)$$

Figure – 10: Basic of Hybrid Flow Shop Mixed Integer Programming Model (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

Z is restricted to be greater or equal to the completion time of the last operation to finish its processing, i.e., the makespan. Several other criteria will be discussed in Section 3. The set of constraints (3), guarantees that all operations are assigned strictly to one machine at each stage. Constraint set (4), restrict the starting time of operation ojk to be greate ror equal to its release time from the previous stage. Constraint sets (5) and (6) prevent any two operations from overlapping in a common machine. Constraint sets (7), (8) and (9) define the domains of the decision variables (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009).

Furthermore, in literature, there are Mixed Integer Programming applications for PCB Production Companies. In (Tadeusz Sawik, Andreas Schaller, Thomas M. Tirpak, 2002 and Tadeusz Sawik, 2001), there are convenient MIP applications for HFSs which have no storage or limited-storage between stages, no setup, no lot-splitting, medium to high volume and SMT (Surface Mount Technology) machines-intense features. In (Tadeusz Sawik, 2000), there is a suitable MIP application for HFS that has jobs having different routes, limited-storage between stages, no setup, no lot-splitting, medium to high volume and SMT machines-intense features. In (Tadeusz Sawik, 2002), there is a fitting MIP application for HFS that has batches of different type of units, limited-storage between stages, no setup, no batch-splitting, medium to high volume and SMT machines-intense features. Additionally, a hierarchically MIP approach to HFS scheduling problem exists in (Tadeusz Sawik, 2006). Two MIP models are demonstrated, by first MIP model, which sub production lots of customer orders has to be scheduled in the periods of time-horizon, is determined, by second MIP model, which machines in each stage are assigned to each sub production lot of customer orders, is determined. Over again, this model is created for HFSs that have no setup times, predetermined production lots for each customer order (therefore no lot-splitting via MIP modeling), medium to high volume and SMT machines-intense characteristics. Another MIP Approach and reactive scheduling algorithms exists in (Tadeusz Sawik, 2007) for HFSs that have predetermined production lots, limited-lot-splitting (lot splitting allowed only for specific pre-determined customer orders and only for two subsequent periods), no setup, often-rescheduling environment, make to orger, medium to high volume traits. Different rescheduling algorithms (REALL, REMANT, RENON etc.) are compared via computational results.

Additional to PCB Production Application, there are other MIP applications for different HFS types. In (Yu Liu, I.A. Karimi, 2008), there are slot-based and sequence based MIP approaches for HFSs that have Zero wait between stages/No Inter-stage buffer, no setup times, parallel non-identical resources/units, weighted Just In time objectives, sequence-dependent batches/jobs, no lot-splitting traits.

A convenient MIP approach for real steel company applications exists in (Stefan Voss, Andreas Witt, 2007). Similar to ASELSAN HFS Problem, this MIP application models a steel company HFS problem with characteristics; parallel identical machines, unlimited inter-stage buffer, sequence-dependent setup times, lot-splitting, minimum weighted set-up times and tardiness objectives.

Special lot-splitting MIP model for reed switch manufacturing exists in (Larysa Burtseva, Rainier Romero, Salvador Ramirez, Victor Yaurima, Félix F. González-Navarro and Pedro Flores Perez (2012)). This MIP application has traits; two stations with parallel identical machines (FH2), at first station allowed lot-splitting, sequence independent-setup times, unlimited inter-stage buffer, high-volume. Besides MIP application, lot-splitting issue is comprehensively examined.

2.2.2. Heuristics and Meta-Heuristics

For every type of scheduling problem in different type of industries, -from simplest to complex- heuristics and algorithms can be found in literature. Simplest heuristics in literature are dispatching rules for HFS problems. These rules are easy to use and do not need hard computational effort. They are designed for finding near-optimal solutions. As example, Johnson's rule, Kusiak's Rule, Gupta's Heuristic, Palmer's Heuristic, CDS and RA Heuristics for Flow Shop Scheduling, Earliest Due Date, Shortest Process Time Dispatching Rules are simplest ones.

By development of computer technology, some stochastic and variable elements are started to be included in algorithms. These kinds of algorithms and heuristics are called "Metaheuristics". Complicated Dispatching Rules, Simulated Annealing, Genetic Algorithms and Tabu Search Algorithms can be given as examples for this kind. (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009)

3. APPROACH AND MODEL PROPOSED

3.1. APPROACH

In order to formulate and develop a HFS Mixed Integer Programming Model for ASELSAN Defense Systems Technologies Division Production Area, the model that is proposed should have assumptions, constraints, given data and objective function such as:

Assumptions:

1. HFS should have 4 stages. However, it is good to remember that an m-stage model can handle this problem.
    a. SMD Assembly
    b. Through Hole Component Assembly and Rework
    c. Functional Test
    d. Conformal Coating and Gluing
2. Each stage has parallel labor and machine resources
3. Because of High Mix/low Volume, set-up times are inevitable and setup time of each job is independent from other jobs' setup times. (sequence – independent)
4. Material handling times are not managed
5. Some obligatory wait-times just like oven, cleaning etc. are not managed. Wait-times are assumed that they are occurred after work-hours.
6. Material handling times are not managed.
7. All of labor and machine resources that are at the same stage are identical.
8. Processing times of each job is deterministic.

9. Lot splitting is allowed in each stage.
10. Raw material, tooling or infrastructure availability is not managed.
11. Processed units are always satisfactory. Reworks/Fail Processes for jobs should be re-scheduled as another job.
12. Some sub-lots of customer order can have different due date than remaining part of customer order. Sub-lots that have different due dates should be re-scheduled as another job.
13. Unlimited buffer between stages.

Given Data:

1. Release date of each job
2. Due date of each job
3. Min/max capacity borders in each stage during a time period
4. Process time and setup time of each job
5. Unit Costs of each tardy job and capacity increment

Constraints:

1. Capacity of each stage has minimum and maximum borders for labor and machine resources.
2. Every job or part of the batch has due date and release date.

Decision Variables:

1. Start time of each stage for each job
2. Finish time of each stage for each job
3. Can batches be divided to sub-lots? Or will whole batch be processed?
4. How many capacity units used in each stage for a time-period

Objectives:

Minimizing total cost of tardy jobs.

Minimizing total cost of capacity increments at each stage.

Therefore for simple notation, this kind of HFS scheduling problem, can be denoted simply as;

FHm $(PM^{(k)})^{m}{}_{k=1}$ | r_j, split, S_{nsd} | U + Total Capacity

And ASELSAN Defense Systems Technologies Division simply waits from this research to adopt a decision support tool that is finding optimal schedules in line with due dates and release dates of all jobs **(from 80 up to 110)** at four stages via using lot-splitting and capacity increase/decrease decisions.

MIP model that is included in (Stefan Voss, Andreas Witt, 2007) an be considered as a fit model for ASELSAN's HFS Scheduling Problem because the model has traits; parallel identical machines, unlimited inter-stage buffer, sequence-dependent setup times, lot-splitting, minimum weighted set-up times and tardiness objectives. The MIP model proposed in (Stefan Voss, Andreas Witt, 2007) includes sequence-dependent setup times and lot-splitting by using model approach in (Haase, K., 1994), minimum weighted set-up times and tardiness objectives different to the MIP model that is proposed in (Talbot, F.B., 1982). This model is prepared for a steel company HFS problem.

On the other hand, it is good to remember that, different from the model in (Stefan Voss, Andreas Witt, 2007), ASELSAN Defense Systems Technologies Division HFS Scheduling problem has sequence-independent setup times and allowed-capacity decrease/increase attribute.

The model in (Stefan Voss, Andreas Witt, 2007) is;

FHm $(PM^{(k)})^{m}{}_{k=1}$ |split, S_{sd} | T^{w} (Stefan Voss, Andreas Witt, 2007)

Index:

j = job number j = 1,……J+1

t = each time period $t = 1, \ldots..T$

m = stage number $m = 1, \ldots.M$

r = resource number in each stage $r = 1, \ldots..R$

a = setup state of resource r $a = 1, \ldots.A_r$

Parameters (Given Data):

$d_{j,m}$ = process time of job j in stage m

$d_{j,}$ = total process time of job j

P_j = immediate predecessors of a job j

S_j = immediate successors of a job j

T = Time Horizon

dd_j = due date of job j

$wt_{h,m}$ = waiting time for predecessor job h of job j in mode m

Earliest Start Time

$EST_j = 0$ if $P_j = \{0\}$;

$\quad$ $Max((EST_h + d_h)\ h\ \epsilon\ P_j)$ otherwise

Latest Start Time

$LST_j = T - d_j$ if $j\ \epsilon\ P_{j+1}$

$\quad$ $Min((LST_k - d_j)\ k\ \epsilon\ S_j)$ otherwise

$c_{j,m,r,a}$ = capacity consumption of job j in stage m at resource r of setup state a

$scr_{r,b,a}$ = setup cost matrix from b setup state to a setup state for resource r

scr_r^{max} = maximum setup cost that is incurred at resource r

$st_{r,a}$ = minimal time that setup state a requires at resource r

Decision Variables:

$C_{r;t}$ = 1 if r resource is working at period t

0 not-working or break-down

$x_{j;m;t}$ = 1; if job j is completed in period t in mode m;

0; otherwise

$SC_{r,,t}$ = setup cost incurred at resource r in time period t

$Y_{r;a;t}$ = 1; if resource r is setup in state a in period t;

0; otherwise

Total Model: (Stefan Voss, Andreas Witt, 2007)

$$\text{Minimize} \sum_{r=1}^{R}\sum_{t=1}^{T} SC_{r,t} + \lambda * \sum_{t=EFT_{j+1}}^{LFT_{j+1}} t * x_{j+1,1,t} + (1-\lambda) * \sum_{j \in P_{j+1}} \sum_{m=1}^{M_j} \sum_{t=\max(EFT_{j+1}, dd_j)}^{LFT_j} w_j * (t - dd_j) * x_{j,m,t}$$

Subject to

$$\sum_{m=1}^{M_j}\sum_{t=EFT_j}^{LFT_j} x_{j,m,t} = 1 \qquad j = 1,.....J+1 \qquad (1)$$

$$\sum_{m=1}^{M_h}\sum_{t=EFT_h}^{LFT_h} (t + wt_{h,m}) * x_{h,m,t} \le \sum_{m=1}^{M_j}\sum_{t=EFT_j}^{LFT_j} (t - d_{j,m}) * x_{j,m,t} \qquad j = 1,.....J+1, h \in P_j \qquad (2)$$

$$\sum_{j=1}^{J}\sum_{m=1}^{M_j} \sum_{\tau=\max(t, EFT_j)}^{\min(t+d_{j,m}-1, LFT_j)} c_{j,m,r,a} * x_{h,m,\tau} \le C_{r,t} * y_{r,a,t} \qquad r = 1,.....R \quad t = 1,...T \quad a = 1,.....A_r \qquad (3)$$

$$\sum_{a=1}^{A_r} y_{r,a,t} = 1 \qquad r = 1,.....R \quad t = 1,...T \qquad (4)$$

$$SC_{r,t} - sc_r^{\max} * y_{r,a,t} + \sum_{b=1}^{A_r} (sc_r^{\max} * y_{r,b,t-1} - sc_{r,b,a} * y_{r,b,t-1}) \ge 0 \quad r = 1,.....R \quad a = 1,.....A_r \quad t = 1,...T \qquad (5)$$

$$\sum_{v=t}^{t+st_{ra}-1} y_{r,a,v} \ge st_{r,a}(y_{r,a,t} - y_{r,a,t-1}) \qquad r = 1,.....R \quad a = 1,.....A_r \quad t = 1,...T \qquad (6)$$

$$SC_{r,a,t} \ge 0 \qquad r = 1,.....R \quad a = 1,.....A_r \quad t = 1,...T \qquad (7)$$

$$y_{r,a,t} \in \{0,1\} \qquad r = 1,.....R \quad a = 1,.....A_r \quad t = 1,...T \qquad (8)$$

$$x_{j,m,t} \in \{0,1\} \qquad j = 1,.....J+1 \quad m = 1,.....M_j, \quad t = 1,...T \qquad (9)$$

$$0 \le \lambda \le 1$$

It's seen that; objective function of the model composes of three elements. First one is, total setup change cost in each resource at each time period. Second one is, weighted total completion time of each job therefore makespan. Third one is weighted total tardy jobs. (Stefan Voss, Andreas Witt, 2007)

First constraint (1) is providing each job is completed exactly once during time horizon (T). Second constraint (2) ensures precedence relation of each job with other jobs and adding a waiting time to each job's process time for cooling time of heated materials. Third constraint (3) prohibits capacity violations in each time period for each resource and each setup state. Fourth constraint (4) assures every resource to have only one setup state in each period. Fifth constraint (5) provides that a variable setup cost occurs if a resource (r) changes its setup state from a to b from the period t-1 to t. Sixth constraint (6) is about a special case for steel company which is;" if a resource change its setup state from 1 to 3 than there is no job of transition 2 state available. Therefore, whenever this kind of case occurs, this constraint implies setup times with duration of zero or minimum $st_{r,a}$." (Stefan Voss, Andreas Witt, 2007)

As a result, this model decides each time period that each job is completed and each time period that each resource at each stage changes its setup state by minimizing sum of total setup cost, weighted total completion time and weighted total tardy jobs. (Stefan Voss, Andreas Witt, 2007)

This model is most approximate proposed-model in literature for ASELSAN Defense Systems Technologies Division HFS Scheduling problem. **Also, it should be mentioned that the model in (Stefan Voss, Andreas Witt, 2007) is more comprehensive than model that is demonstrated in this thesis. And it includes a complicated solution for a harder scheduling problem than ASELSAN has.** However, regarding two primary points, it is clear that this model cannot be directly applied to ASELSAN Defense Systems Technologies Division. It should be converted for special case of the company. First thing to change is, the company's HFS problem has setup-independent trait which means each job has independent setup time from other jobs in each stage because of company's High Mix / Low Volume issue. Second one is; the company has three labor-intensive stages (Through Hole Component Assembly and Rework, Functional Test and Conformal Coating and Gluing) and one machine-intensive stage (SMD Assembly). Therefore, ASELSAN Defense Systems Technologies Division wants to schedule all jobs due to labor-intense constraints too. And capacity increase/decrease in each stage is allowed, probable and frequently used.

For that reason, a new model approach is needed for this special case and this is what this research is all about.

3.2. MODEL PROPOSED

As mentioned before, simply ASELSAN Defense Systems Technologies Division waits from this research to adopt a decision support tool that is finding optimal schedules in line with due dates and release dates of all jobs **(from 80 up to 110)** at four stages via using lot-splitting and capacity increase/decrease decisions.

This Hybrid Flow Shop Scheduling Problem starts with arrival of various production orders to Electronics Production Department in High Mix/low Volume type. Each production order includes a release date, due date, quantity, material name, routing, documents needed, sub-materials needed. Subsequent to production orders arrival, capacity constraints are included manually. During Manufacturing Execution stage, in line with due-dates, release-dates, and capacity min/max borders, each production order in time horizon (T) is scheduled by splitting/not splitting the batches, increasing/decreasing capacity of each stage.

In order to comprehend all these assumptions, constraints and objectives of ASELSAN Defense Systems Technologies Division Hybrid Flow Shop Scheduling Problem, we start with dividing scheduling time horizon (T) to equal time periods as it is mentioned in (Stefan Voss, Andreas Witt, 2007). This equal time periods can be regarded as 1 work-day, 1 work-hour or 4 work-hours etc. and it should be determined before. For ASELSAN’s case, 4 work-hours time period and 60 X 4 Work – Hours = 30 Days Time Horizon will be used. This will ease to handle entire HFS problem.

Additionally, for the company's case, it will be good to think of process times of each job for all stages in terms of pre-determined equal time periods. Therefore, process time matrix is converted from hour or second based process time to this pre-determined time periods based process times. For instance;

First matrix is converted to second one by rounding up values as it is demonstrated below.

Process Time Matrix (Hour-Based)	**Stage #**			
Job #	**1**	**2**	**3**	**4**
1	8	12	16	4
2	4	2	4	6
3	8	9	6	4

→

Process Time Matrix (Pre-determined Time Period = 4-hours)	**Stage #**			
Job #	**1**	**2**	**3**	**4**
1	2	3	4	1
2	1	1	1	2
3	2	2	2	1

This process-time conversion and pre-determined time periods provides our model to handle the capacity and lot-splitting notion. In order to understand this special scheduling problem easily, the Figure-11 can be used. As it's seen, there are four important assumptions to make the problem easier.

1. Every job has process times at each stage in terms of pre-determined time-periods.

2. In each period, there is capacity limits for all stages and if these capacity limits are exceeded, capacity-cost occurs.

3. At all stages, batches of jobs can be divided into minimum sub-lots and sub-batches which's total process time at that stage should be equal to pre-determined time period.

4. At every lot-split occasion, setup time occurs again. Therefore, for our new model, setup cost will balance lot-splitting occasions.

It is important to add that same should be applied to setup times and setup times should be converted from hour or second based setup time to this pre-determined time periods based setup times.

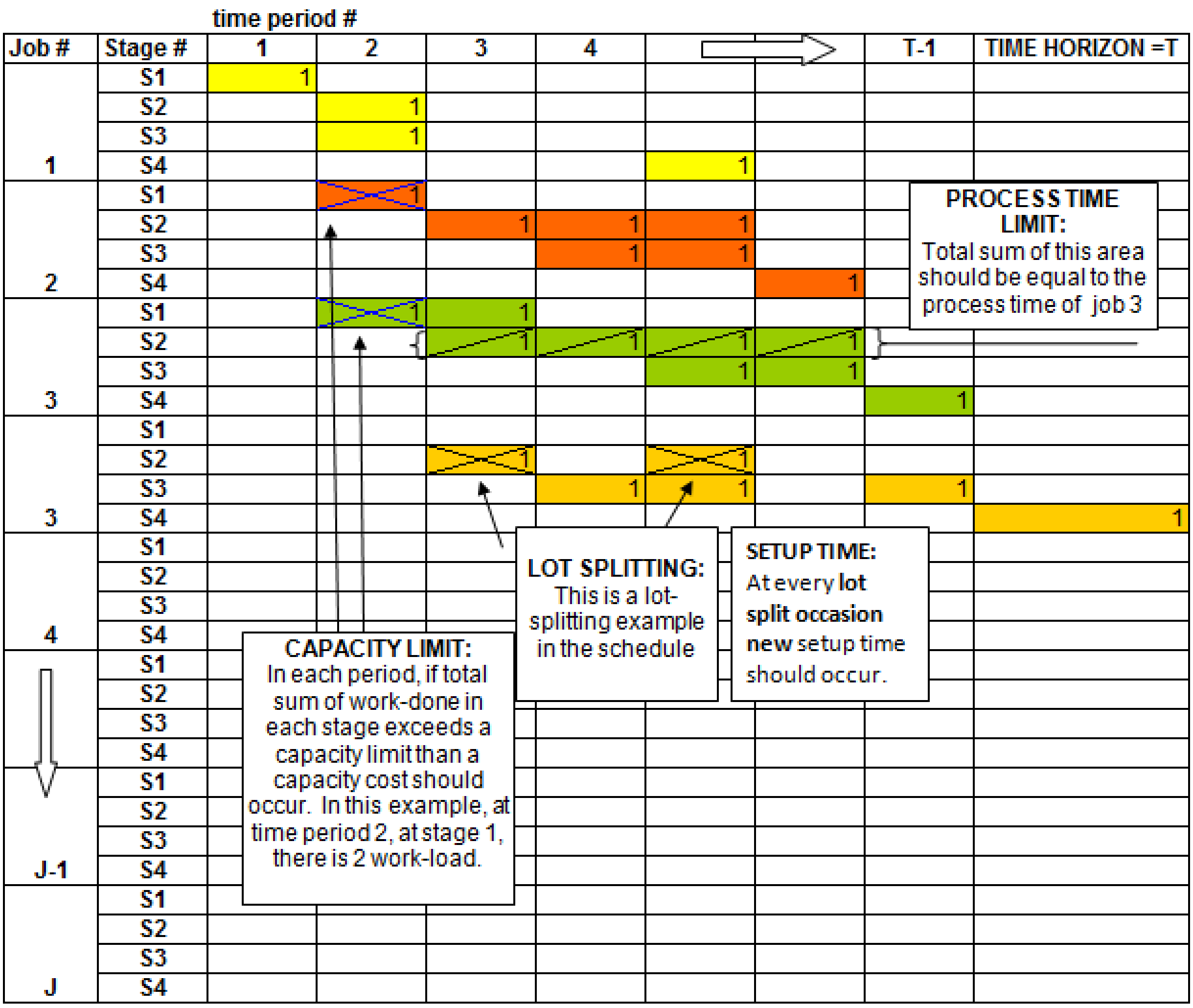

Figure- 11: Easy schematic of ASELSAN Defense Systems Technologies Division Hybrid Flow Shop Scheduling Problem

It is easy to see that these assumptions make it easier to develop a Mixed Integer Programming Model for ASELSAN Defense Systems Technologies Division Hybrid Flow Shop Scheduling Problem, solve it and obtain optimal schedules of all jobs (from 80 to 110 jobs).

Considering ASELSAN Defense Systems Technologies Division Hybrid Flow Shop Scheduling Problem as whole, major indexes in the proposed model are:

j = job number j = 1,……J+1

t = each time period t = 1, …..T

s = stage number s = 1,….S

There are parameters (given-data) given by the company and used in the model and they are:

$p_{j,s}$ = process time of job j in stage s

$ST_{j,s}$ = setup time of job j in stage s

T = Time Horizon

rd_j = release date of job j

dd_j = due date of job j

$minC_{s,t}$ = minimum capacity level at each stage and in each time period

$maxC_{s,t}$ = maximum capacity level at each stage and in each time period

$pbin_{j,s}$ = 1 if there is a process time of job j at stage s

0 otherwise

TH = Time Horizon

CC= Capacity cost for each increment

TJC = Cost paid for each Tardy job

BigM = Big number

The model that is proposed in this research begins with finding decision variables. Most important decision variable is;

$X_{j,s,t}$ = 1; if s th stage of job j is being done in period t ;

0; otherwise

This decision variable is used mainly for capacity limitations, process time limitations, setup costs determination and lot-splitting. If $X_{j,s,t}=1$, this means ***"one time period part"*** of process time of s th stage of job j is done during the period t. If $X_{j,s,t}=0$, then there is not work-done in the period t for sth stage of job j.

Another important decision variable is;

$S_{j,s,t}$ = 1; if a setup occurs at s th stage of job j is completed in period t

0; otherwise

This acts like balancing variable for lot-splitting or not decisions. By adding setup cost for each lot-splitting event to objective function will force the model to balance these lot-splitting events. For each stage of each job, If $X_{j;s;t-1}$ equals to 0 and $X_{j;s;t}$ equals to 1 then $S_{j;s;t}$ will be 1. Else $S_{j;s;t}$ will be 0 in the model.

Capacity decision variable is another positive integer decision variable;

$C_{t,s}$ = capacity at each stage in t th time period.

In each time period, there is a minimum level of capacity for each stage, and maximum level of capacity of each stage. This variable cannot exceed maximum level for each stage and each time period. And if this variable takes a value bigger than minimum level, company is paying capacity increment cost for the amount of ($C_{t,s}$ – minimum $level_{t,s}$).

Finish time positive integer decision variable is:

F_j = Completion time of j th job.

This is exact time of completion time of each job.

Tardy Job decision variables are:

TA_j = 1; if Finish time is greater than due date of each job. ($F_j>dd_j$)

0; otherwise

These binary variables act for balancing costs of tardy jobs.

As mentioned before ASELSAN Defense Systems Technologies Division aims to minimize total cost of tardy jobs and minimize total cost of capacity increments at each stage. Therefore, proposed model in this research has an objective function contains three of them but weights them using different costs for them. (CC and TJC.)

First one is for total cost of tardy jobs;

$$\sum_{j=1}^{J} TJC * \mathrm{TAj}$$

Second one is for total cost of capacity increments;

$$\sum_{j=1}^{J} \mathrm{CC} * (\mathrm{C}_{\mathrm{t,s}} - \mathrm{minC}_{\mathrm{t,s}})$$

For third one, this part also forces the model for using 0 resources (below the minimum capacity border) as much as possible at each stage and in each time period.

Therefore; our exact objective function is:

$$Z = \sum_{j=1}^{J} TJC * \mathrm{TAj} + \sum_{j=1}^{J} \mathrm{CC} * (\mathrm{C}_{\mathrm{t,s}} - \mathrm{minC}_{\mathrm{t,s}})$$

In order to achieve real-life assumptions and obstacles of ASELSAN Defense Systems Technologies Division Hybrid Flow Shop Scheduling Problem, model has important constraints such as following.

1. Every job has to be finished before time horizon T+1.

This is handled easily by;

$$F_j \leq T \qquad j = 1,....,J \quad (1)$$

2. Completion time of each job is calculated by finding biggest time period which has the value of $X_{j,s,t}$ = 1. And also if there is a setup time (if $S_{j,s,t}$=1) at that time period, it should be added to found value.

This is formulated as;

$$(X_{j,t,s} * t) + (S_{j,t,s} * ST_{j,s}) \leq F_j \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (2)$$

3. Process times of each job at each stage should be matched with given process time values. For each job and each stage, this is ensured by equalizing sum of $X_{j,s,t}$ from beginning of time period (t=1) to time horizon(T) to given process times.

$$\sum_{t=1}^{T} X_{j,t,s} = p_{j,s} \qquad j = 1,....,J \quad s = 1,....,S \quad (3)$$

4. If a lot-splitting event occurs in the schedule, a setup time should occur in that time period when a divided sub-lot begins its work. Assume that there is a work in a period of a job's stage, $X_{j,s,t}$ = 1. If there is not a work in one period before that time period (t-1) of that job's stage ($X_{j,s,t-1}$ = 0.) then there is a setup cost in that period (t) $S_{j,s,t}$=1. For all other cases, setup time will not occur. (Otherwise, $S_{j,s,t}$=0)

So as to understand easily, the following table can be examined.

$X_{j;s;t-1}$	$X_{j;s;t}$	$\mathbf{S_{j;s;t}}$
1	1	**0**
1	0	**0**
0	1	**1**
0	0	**0**

Table 2: Setup Cost Table

And this is handled by the model as following:

$$X_{j,t,s} - X_{j,t-1,s} \leq S_{j,t,s} \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (4)$$

5. Given release dates of all jobs should be met. If there is a process time at jth job's sth stage ($pbin_{j,s}$=1), all of $X_{j,s,t}$'s should be 1 after release dates of jobs (t ≥ rd_j).

This is assured by:

$$pbin_{j,s} * X_{j,t,s} * rd_j \leq t * X_{j,t,s} \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (5)$$

6. Maximum border of capacity ($maxC_{t,s}$) for each stage (s) and in each time interval (t) should be met.

This is assured by:

$$C_{t,s} \leq \max C_{t,s} \qquad t = 1,....T \quad s = 1,....S \quad (6)$$

7. If finish time of a job (F_j) is bigger than due date of a job (dd_j), then a tardy job occurs and for that job, tardy job variable (TA_j) should be 1. Due to this is a minimization problem, this is handled by using Big M method as following:

$$F_j - dd_j \leq BigM * TA_j \qquad j = 1,....J \qquad (7)$$

8. Variable Capacity of each stage in each period should be bigger than or equal to work-load of total jobs on that stage during that period. Work-load is calculated with total sum of $X_{j,s,t}$'s (Process Time-Load) and $S_{j,s,t}$ X $ST_{j,s}$ (if setup occurs ($S_{j,s,t}$=1) then setup-time load occurs) for every job at each stage and in each period.

This is ensured by:

$$\sum_{j=1}^{J} (X_{j,t,s} + (S_{j,t,s} * ST_{j,s}) \leq C_{t,s} \qquad t = 1,....,T \quad s = 1,....,S \quad (8)$$

9. Because of lot-splitting issue, stages of jobs have different prerequisite conditions. There are S-1 different conditions and constraints for a start of a stage. In this research for ASELSAN Defense Systems Technologies Division, it is considered that S=4 is enough. Therefore, mainly 3 different conditions are examined and added.

    a. If a job has process time at current stage (s) and following stage (s+1). (If $pbin_{j,s}$=1 and $pbin_{j,s+1}$=1) The subsequent stage of current stage cannot start before a sub-lot of job finishes its work at current stage. Therefore, subsequent stage looks for only if some part of preceding stage finishes. In order to see easily, figure in the below demonstrates that (s+1)st stages (in red marks) do not wait for accomplishment of total work at preceding stage and do not start before preceding stage.

time period #

Job #	Stage #	1	2	3	4			T-1	TIME HORIZON =T
	S1	1			1				
	S2								
	S3			1		1			
1	S4					1	1		
	S1		1		1				
	S2			1			1		
	S3								
2	S4					1			1
	S1		1	1					
	S2			1	1	1	1		
	S3					1	1		
3	S4							1	
	S1								
	S2			1		1			
	S3				1	1		1	
3	S4						1		1
	S1								
	S2								
	S3								
J-1	S4								
	S1								
	S2								
	S3								
J	S4								

Figure-12: Simple Examples for Constraint 9.a

In order to formulize this condition ($pbin_{j,s}$=1 and $pbin_{j,s+1}$=1 case), for each job, partial work at preceding stage (s) should be done at least one period before s+1st stage starts. For instance, imagine that at time period t+1, in order to start s+1st stage ($X_{j,s+1,t+1}$ = 1), at least one of $X_{j,s,1}$, $X_{j,s,2}$, $X_{j,s,3}$…., $X_{j,s,t-1}$, $X_{j,s,t}$ should be equal to 1. Therefore this can be visualized as following:

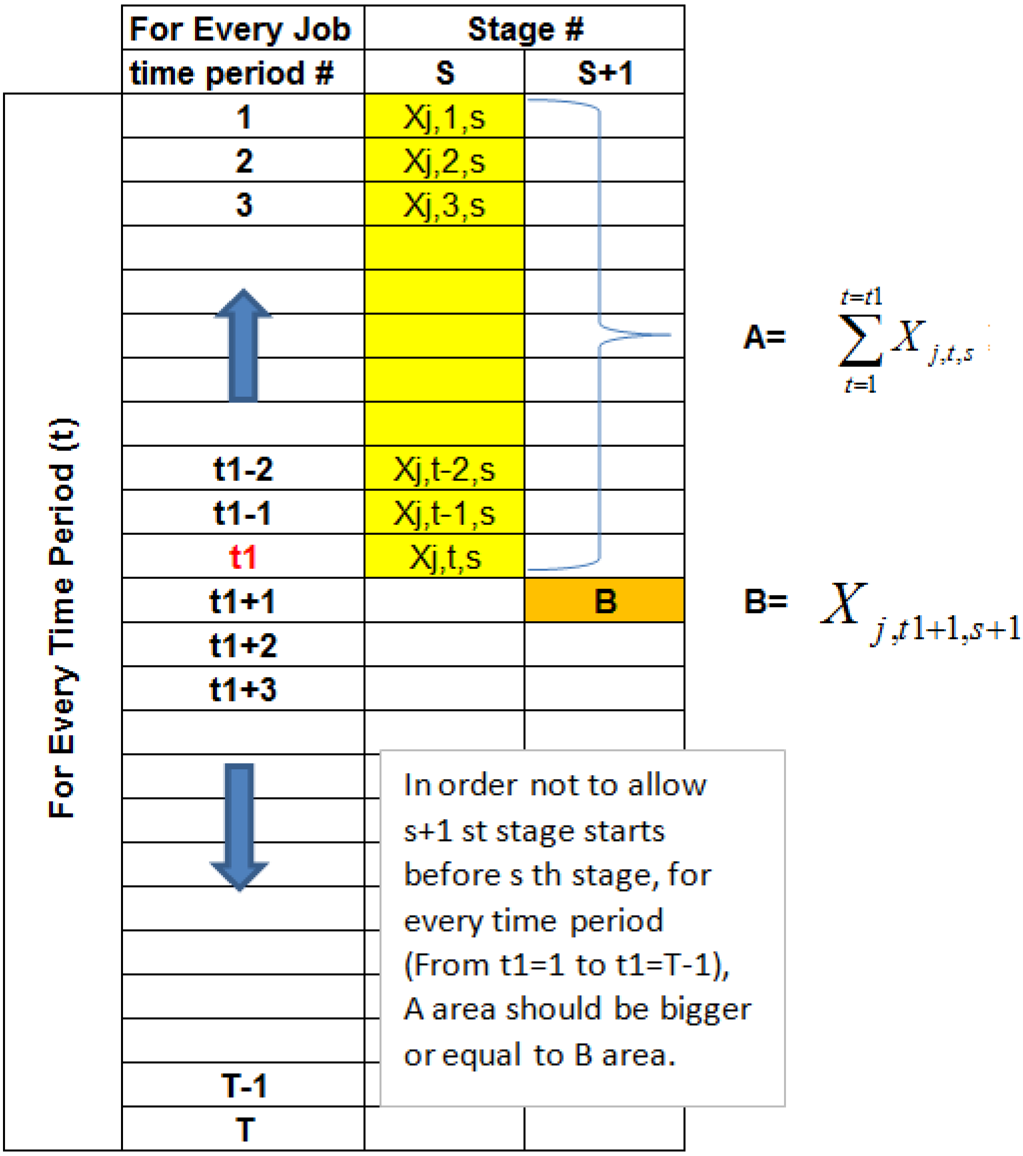

Figure-13: Visualization Of Constraint 9.a

Consequently, this constraint can be added to the model easily as following:

$$\sum_{t=1}^{t=t1} X_{j,t,s} \geq pbin_{j,s} * X_{j,t1+1,s+1} \quad j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (9.a)$$

b. If a job has process time at current stage (s) and following (s+2)nd stage. (If $pbin_{j,s}$=1 and $pbin_{j,s+2}$=1). This constraint is added in order to handle a special case that if (s+1)st stage has not a process time. By this constraint, start of (s+2)nd stage before a sub-lot of job finishes its work at sth stage is forbidden. In order to see easily, figure in the below demonstrates that (s+2)nd stages (in red marks) do not start before partial finish of sth stage and do not wait for accomplishment of total work at sth stage.

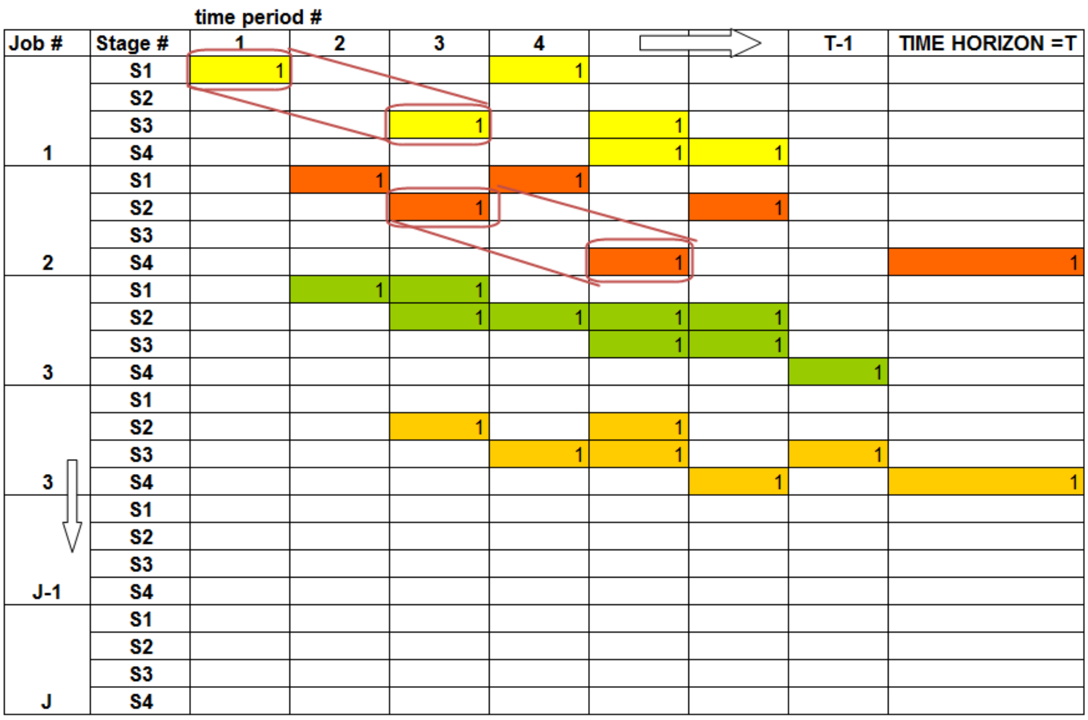

Figure-14: Simple Examples for constraint 9.b

As visualized in Figure 13 for Constraint 9.a, similarly this constraint is constructed such as:

$$\sum_{t=1}^{t=t1} X_{j,t,s} \geq pbin_{j,s} * X_{j,t1+1,s+2} \quad j=1,....,J \quad t1=1,...,T-1 \quad s=1,....,S \quad (9.b)$$

c. If a job has process time at current stage (s) and following (s+3)rd stage. (If $pbin_{j,s}$=1 and $pbin_{j,s+3}$=1). This constraint is added in order to handle a special case that if (s+1)st and (s+2)nd stage have not process times. By this constraint, start of (s+3)rd stage before a sub-lot of job finishes its work at sth stage is forbidden. In order to see easily, figure in the below demonstrates that (s+3)rd stages (in red marks) do not start before partial finish of sth stage and do not wait for accomplishment of total work at sth stage.

Job #	Stage #	time period # 1	2	3	4			T-1	TIME HORIZON =T
	S1	1			1				
	S2								
	S3								
1	S4		1			1	1		
	S1		1		1				
	S2			1			1		
	S3								
2	S4					1			1
	S1		1	1					
	S2								
	S3								
3	S4				1			1	
	S1								
	S2			1		1			
	S3				1	1		1	
3	S4						1		1
	S1								
	S2								
	S3								
J-1	S4								
	S1								
	S2								
	S3								
J	S4								

Figure-15: Simple Examples for constraint 9.c

As visualized in Figure 13 for Constraint 9.a, similarly this constraint is constructed such as:

$$\sum_{t=1}^{t=t1} X_{j,t,s} \geq pbin_{j,s} * X_{j,t1+1,s+3} \quad j=1,....,J \quad t1=1,...,T-1 \quad s=1,....,S \quad (9.c)$$

These three constraints strictly arrange starting periods of each stage of every job. In order to visualize it, these constraints force the schedule to be like in Figure 16. Constraints construct an imaginary line such as red lines in the Figure 16 for each stage of every job which works as a minimum border of starting points of each stage.

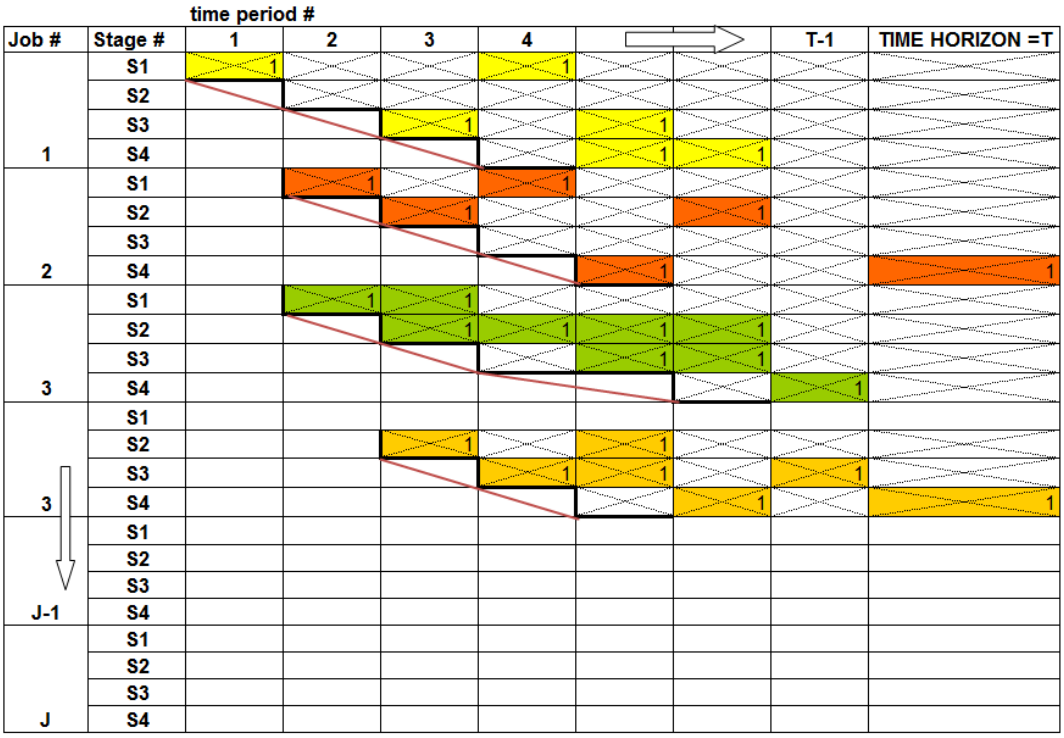

Figure-16: Schedule Visualization after Constraints 9.a, 9.b and 9.c.

10. For finishing of process times at each stage, there are also S-1 different conditions and constraints. And, in this research for ASELSAN Defense Systems Technologies Division, it is considered that S=4 is enough. Therefore, mainly 3 different conditions are added.

    a. If a job has process time at current stage (s) and following stage (s+1). (If $pbin_{j,s}=1$ and $pbin_{j,s+1}=1$) The subsequent stage cannot end before current stage finishes all of job's work. Therefore, subsequent stage ends after all work of preceding stage finishes. In order to see easily, figure in the below demonstrates that $(s+1)^{st}$ stages (in red marks) do waits for accomplishment of total work at preceding stage and do not end before preceding stage.

Job #	Stage #	1	2	3	4	→		T-1	TIME HORIZON =T
	S1	1			1				
	S2								
	S3			1		1			
1	S4					1	1		
	S1		1		1				
	S2			1			1		
	S3								
2	S4					1			1
	S1		1	1					
	S2			1	1	1	1		
	S3					1	1		
3	S4							1	
	S1								
	S2			1		1			
	S3				1	1		1	
3	S4						1		1
	S1								
	S2								
	S3								
J-1	S4								
	S1								
	S2								
	S3								
J	S4								

Figure-17: Simple Examples for constraint 10.a

In order to formulize this condition ($pbin_{j,s}$=1 and $pbin_{j,s+1}$=1 case), for each job, all of work at preceding stage (s) should be done at least one period before s+1st stage ends. For instance, think that at time period t+1, in order to finish s+1st stage (total sum of $X_{j,s+1,1}$,$X_{j,s+1,2}$, ,$X_{j,s+1,3}$….,$X_{j,s+1,t}$,$X_{j,s+1,t+1}$ = $P_{j,s+1}$, total sum of $X_{j,s,1}$, $X_{j,s,2}$, $X_{j,s,3}$…., $X_{j,s,t-1}$, $X_{j,s,t}$ should be equal to $P_{j,s}$) at least one period before. Therefore, in order to finish s^{th} stage at t^{th} time period, at least one of $X_{j,s+1,t+1}$,$X_{j,s+1,t+2}$, ,$X_{j,s+1,t+3}$….,$X_{j,s+1,T-1}$,$X_{j,s+1,T}$ equals to 1. Because s+1th stage always should finish after than s^{th} stage. This can be visualized as following:

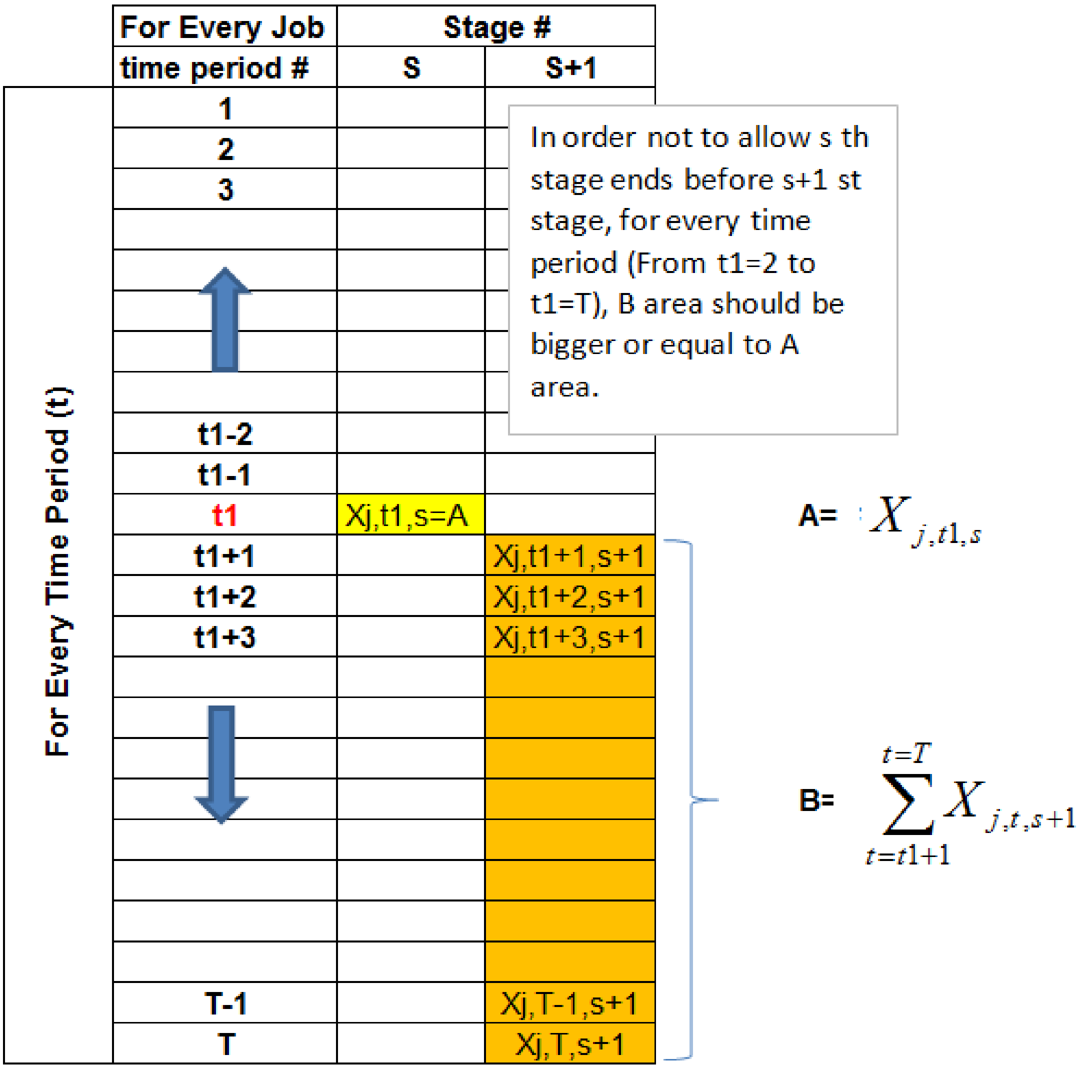

Figure-18: Visualization Of Constraint 10.a

Consequently, this constraint can be added to the model easily as following:

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+1} \geq pbin_{j,s+1} * X_{j,t1,s} \quad j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (10.a)$$

b. If a job has process time at current stage (s) and following stage (s+2). (If $pbin_{j,s}$=1 and $pbin_{j,s+2}$=1) This constraint is added in order to handle a special case that if $(s+1)^{st}$ stage has not a process time. The $(s+2)^{nd}$ stage cannot end before current stage (s^{th} stage) finishes all of job's work. Therefore, $(s+2)^{nd}$ stage ends after all work of s^th^ stage finishes. In order to see easily, figure in the below demonstrates that (s+2)^nd^ stages (in red marks) do waits for accomplishment of total work at s^th^ stages and do not end before s^th^ stages.

time period #

Job #	Stage #	1	2	3	4	⇨		T-1	TIME HORIZON =T
	S1	1			1				
	S2								
	S3								
1	S4		1			1	1		
	S1		1		1				
	S2			1			1		
	S3								
2	S4					1			1
	S1		1	1					
	S2								
	S3								
3	S4				1			1	
	S1								
	S2			1		1			
	S3				1	1		1	
3	S4						1		1
	S1								
	S2								
	S3								
J-1	S4								
	S1								
	S2								
	S3								
J	S4								

Figure-19: Simple Examples for constraint 10.b

As visualized in Figure 18 for Constraint 10.a, similarly this constraint is constructed such as:

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+2} \geq pbin_{j,s+2} * X_{j,t1,s} \quad j=1,....,J \quad t1=1,...,T-1 \quad s=1,....,S \quad (10.b)$$

c. If a job has process time at current stage (s) and following stage (s+3). (If $pbin_{j,s}$=1 and $pbin_{j,s+3}$=1) This constraint is added in order to handle a special case that if (s+1)^st^ and (s+2)^nd^ stages have not process times. The (s+3)^rd^ stage cannot end before current stage (s^th^ stage) finishes all of job's work. Therefore, (s+3)^rd^ stage ends after all work of s^th^ stage finishes. In order to see easily, figure in the below demonstrates that (s+3)^rd^ stages (in red marks) do waits for accomplishment of total work at s^th^ stages and do not end before s^th^ stages.

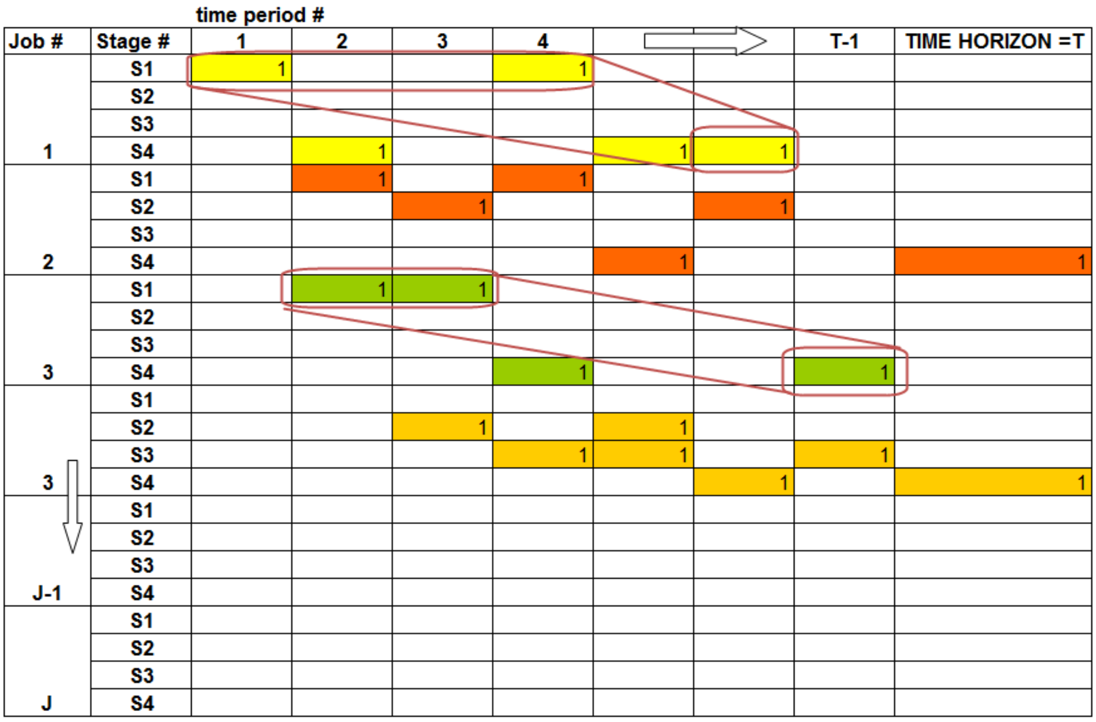

Figure-20: Simple Examples for constraint 10.c

As visualized in Figure 18 for Constraint 10.a, similarly this constraint can be added as:

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+3} \geq pbin_{j,s+3} * X_{j,t1,s} \quad j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (10.c)$$

These six constraints (9.a, 9.b, 9.c, 10.a, 10.b and 10.c) strictly arrange starting and finishing periods of each stage of every job. In order to visualize it, these constraints force the schedule to be like in Figure 21. Constraints construct two imaginary lines such as red lines in the Figure 21 for each stage of every job. One works as a minimum border of starting points of stages and the other works as a maximum border of finishing points of each stage. By these constraints, model forces the schedules to be between these imaginary lines.

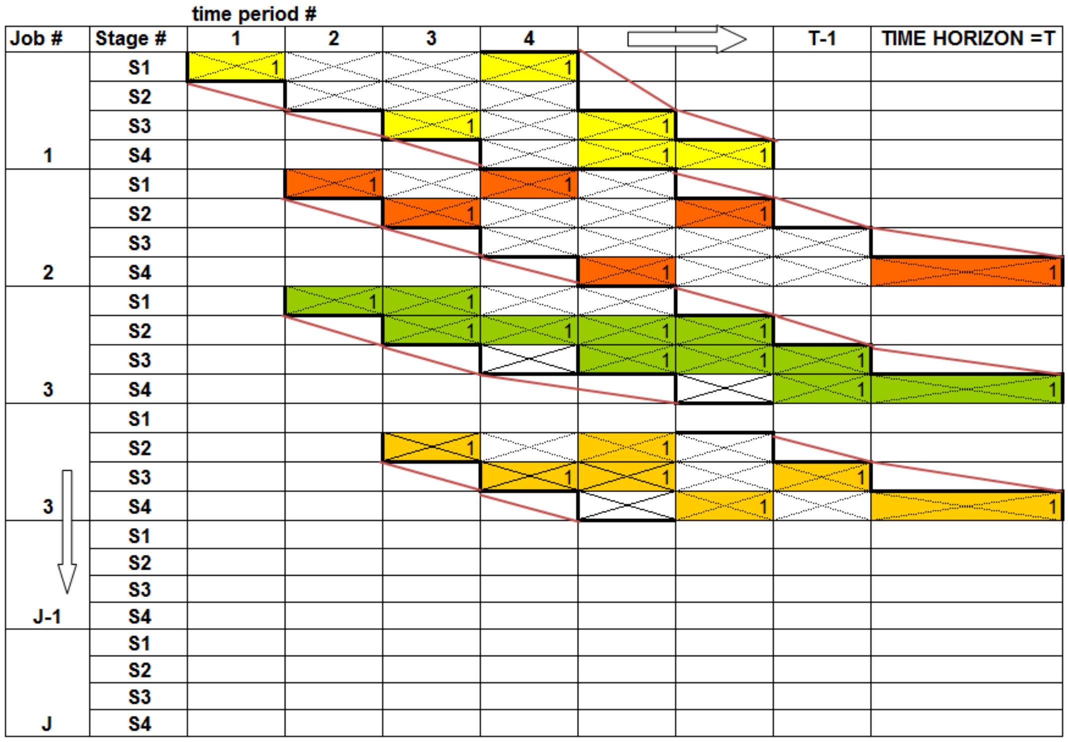

Figure-21: Schedule Visualization after Constraints 9.a, 9.b, 9.c, 10.a, 10.b and 10.c.

11. Additionally, three special cases for time period =1 should be handled. These constraints ensures not to start s+1st , s+2 nd and s+3 rd stages of each job at time period =1 if there is a process time at stage s. They are easily added to model as following:

$$pbin_{j,s} * X_{j,1,s+1} = 0 \quad j = 1,....,J \qquad s = 1,....,S \quad (11.a)$$

$$pbin_{j,s} * X_{j,1,s+2} = 0 \quad j = 1,....,J \qquad s = 1,....,S \quad (11.b)$$

$$pbin_{j,s} * X_{j,1,s+3} = 0 \quad j = 1,....,J \qquad s = 1,....,S \quad (11.c)$$

12. Also, there are three special cases for time period =60 that should be handled. These three constraints ensures s th stage of each job not to end at time period = 60 before s+1st , s+2 nd and s+3 rd stages if there are process times at s+1st , s+2 nd or s+3 rd stages. Here are these constraint:

$$pbin_{j,s+1} * X_{j,60,s} = 0 \quad j = 1,....,J \qquad s = 1,....,S \quad (12.a)$$

$$pbin_{j,s+2} * X_{j,60,s} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (12.b)$$

$$pbin_{j,s+3} * X_{j,60,s} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (12.c)$$

After detailed demonstration of parameters, decision variables, constraints and objective function, whole proposed model for ASELSAN Defense Systems Technologies Division HFS Scheduling Problem seems like following:

Index:

j = job number j = 1,……J+1

t = each time period t = 1, …..T

s = stage number s = 1,….S

Parameters (Given-Data)

$p_{j,s}$ = process time of job j in stage s

$ST_{j,s}$ = setup time of job j in stage s

T = Time Horizon

rd_j = release date of job j

dd_j = due date of job j

$minC_{s,t}$ = minimum capacity level at each stage and in each time period

$maxC_{s,t}$ = maximum capacity level at each stage and in each time period

$pbin_{j,s}$ = 1 if there is a process time of job j at stage s

0 otherwise

TH = Time Horizon

CC= Capacity cost for each increment

TJC = Cost paid for each Tardy job

BigM = Big number

Decision Variables:

$X_{j,s,t}$ = 1; if s th stage of job j is being done in period t ;

0; otherwise

$S_{j,s,t}$ = 1; if a setup occurs at s th stage of job j is completed in period t

0; otherwise

$C_{t,s}$ = capacity at each stage in t th time period.

F_j = Completion time of j th job.

TA_j = 1; if Finish time is greater than due date of each job. ($F_j > dd_j$)

0; otherwise

Complete Proposed Model for T=60 and S=4:

$$Minimize \qquad Z = \sum_{j=1}^{J} TJC * \mathrm{TA}_j + \sum_{j=1}^{J} \mathrm{CC} * (\mathrm{C}_{t,s} - \mathrm{minC}_{t,s})$$

$Subject\ to:$

$$F_j \le T \qquad j = 1,....,J \quad (1)$$

$$(X_{j,t,s} * t) + (S_{j,t,s} * ST_{j,s}) \le F_j \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (2)$$

$$\sum_{t=1}^{T} X_{j,t,s} = p_{j,s} \qquad j = 1,....,J \quad s = 1,....,S \quad (3)$$

$$X_{j,t,s} - X_{j,t-1,s} \le S_{j,t,s} \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (4)$$

$$pbin_{j,s} * X_{j,t,s} * rd_j \le t * X_{j,t,s} \qquad j = 1,....,J \qquad t = 1,....T \quad s = 1,....S \quad (5)$$

$$C_{t,s} \le \max C_{t,s} \qquad t = 1,....T \quad s = 1,....S \quad (6)$$

$$F_j - dd_j \le BigM * TA_j \qquad j = 1,....J \qquad (7)$$

$$\sum_{j=1}^{J} (X_{j,t,s} + (S_{j,t,s} * ST_{j,s}) \le C_{t,s} \qquad t = 1,....,T \quad s = 1,....,S \quad (8)$$

$$\sum_{t=1}^{t=t1} X_{j,t,s} \ge pbin_{j,s} * X_{j,t1+1,s+1} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (9.a)$$

$$\sum_{t=1}^{t=t1} X_{j,t,s} \ge pbin_{j,s} * X_{j,t1+1,s+2} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (9.b)$$

$$\sum_{t=1}^{t=t1} X_{j,t,s} \ge pbin_{j,s} * X_{j,t1+1,s+3} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (9.c)$$

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+1} \ge pbin_{j,s+1} * X_{j,t1,s} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (10.a)$$

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+2} \ge pbin_{j,s+2} * X_{j,t1,s} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (10.b)$$

$$\sum_{t=t1+1}^{t=T} X_{j,t,s+3} \ge pbin_{j,s+3} * X_{j,t1,s} \; j = 1,....,J \quad t1 = 1,...,T-1 \quad s = 1,....,S \quad (10.c)$$

$$pbin_{j,s} * X_{j,1,s+1} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (11.a)$$

$$pbin_{j,s} * X_{j,1,s+2} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (11.b)$$

$$pbin_{j,s} * X_{j,1,s+3} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (11.c)$$

$$pbin_{j,s+1} * X_{j,60,s} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (12.a)$$

$$pbin_{j,s+2} * X_{j,60,s} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (12.b)$$

$$pbin_{j,s+3} * X_{j,60,s} = 0 \; j = 1,....,J \qquad s = 1,....,S \quad (12.c)$$

$$X_{j,t,s} = \{0,1\} \qquad S_{j,t,s} = \{0,1\} \qquad \mathrm{TA}_j = \{0,1\} \qquad EA_j = \{0,1\}$$

$$F_j \ge 0$$

$$C_{t,s} \ge 0$$

4. COMPUTATIONAL RESULTS AND DISCUSSION

The MIP model, developed in this research for ASELSAN Defense Systems Technologies Division HFS Scheduling Problem, is programmed at GAMS Integrated Development Environment 23.7.3 version. With real-data acquired from the company, it is ran in PC that has Windows 7 Home Premium 64-Bit Operating System, Intel Core i3 2.53 GHz CPU, 3 GB RAM and it is solved with CPLEX Solver in GAMS. The written MIP program is updatable from Microsoft Excel therefore many real scenarios developed for the company are tried and solved easily in the program. And also program is able to screen results to Microsoft Excel.

In order to evaluate the scalability of the program, from easiest to hardest 9 numerical examples has been created and tried to solve such as:

	Stage #	Job #	Time Horizon
1	2	4	4
2	3	6	8
3	4	6	8
4	4	15	20
5	4	30	20
6	4	60	60
7	4	110	60
8	4	152	60
9	4	160	60

Table 3: Properties of Solved Examples

During solving hard examples, best possible solutions so far at time 5, 10 and 20 minutes are taken and demonstrated in this research in order to evaluate at what time and at which percentage that proposed MIP model get closer to objective function. Also, characteristics and run-times of examples are demonstrated in this research so as to test speed of the proposed MIP model.

After solving these imaginary cases for testing proposed-MIP model, a real scheduling case is solved depending on real-data taken from ASELSAN Defense Systems Technologies Division.

For all of these examples, in order to simulate realistic cases, coordinated with the company, tardy job cost has been determined as TJC = 20.000 $, and capacity increment cost has been determined as CC = 100 $. Additionally, capacity level and maximum capacity borders for all periods have been determined such as:

	Stage 1		Stage 2		Stage 3		Stage 4	
Time Period	**Normal Limit**	**Max.**	**Normal Limit**	**Max.**	**Normal Limit**	**Max.**	**Normal Limit**	**Max.**
1→ t	8	12	20	40	5	11	2	8

But as mentioned before, for the proposed model, different capacity level for each period and for each stage can be determined due to different production environments and conditions.

This is a minimization problem therefore all of objective values can be less than 0 (-) too. That negative amount can be regarded as positive profit that is gained from the optimal schedules.

Run-Results of 10 Numerical Examples:

1. **Numerical Example:**

For 2 stages, 4 jobs and 4 time horizon; process times and setup times are determined such as:

			Process Times		Setup Times	
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 1**	**Stage 2**
j1	0	5	0	2	0	2
j2	1	5	3	1	2	0
j3	0	4	0	3	0	1
j4	0	4	2	1	3	1

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS	17	SINGLE EQUATIONS	169
BLOCKS OF VARIABLES	6	SINGLE VARIABLES	81
NON ZERO ELEMENTS	423	DISCRETE VARIABLES	68

OBJECTIVE VALUE = -9.100

Run Time = 0.05 Sec

Proposed MIP model results an optimal schedule just like following:

OPTIMAL SCHEDULE			
Job#	**Time #**	**Stage 1**	**Stage 2**
j1	**t1**	0	1
j1	**t2**	0	1
j2	**t1**	1	0
j2	**t2**	1	0
j2	**t3**	1	0
j2	**t4**	0	1
j3	**t2**	0	1
j3	**t3**	0	1
j3	**t4**	0	1
j4	**t1**	1	0
j4	**t2**	1	0
j4	**t3**	0	1

Completion times and due dates of each job are like this:

Job #	Completion Time	Due Dates
j1	3	5
j2	4	5
j3	4	4
j4	4	4

As it is seen no tardy jobs occur in optimal schedule.

For optimal schedule, capacity level for each stage at each time period has been like this:

CAPACITY LEVEL AT EACH TIME PERIOD		
Time #	**Stage 1**	**Stage 2**
t1	7	3
t2	2	3
t3	1	3
t4	0	2

2. Numerical Example:

For 3 stages, 6 jobs and 8 time horizon; process times and setup times are determined such as:

			Process Times			Setup Times		
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 1**	**Stage 2**	**Stage 3**
j1	0	8	0	0	2	0	0	0
j2	1	7	0	0	5	0	0	1
j3	0	8	0	3	3	0	1	1
j4	0	9	2	1	0	3	1	0
j5	0	9	2	0	1	1	0	1
j6	1	9	1	3	2	2	1	1

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS 57 SINGLE EQUATIONS 1,033

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 325

NON ZERO ELEMENTS 3,579 DISCRETE VARIABLES 290

OBJECTIVE VALUE = -7.900

Run Time = 0.02 Sec

Proposed MIP model results an optimal schedule just like following:

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t1**	0	0	1	0
j1	**t2**	0	0	1	0
j2	**t1**	0	0	1	0

j2	**t2**	0	0	1	0
j2	**t3**	0	0	1	0
j2	**t4**	0	0	1	0
j2	**t5**	0	0	1	0
j3	**t1**	0	1	0	0
j3	**t2**	0	1	1	0
j3	**t3**	0	1	1	0
j3	**t4**	0	0	1	0
j4	**t2**	1	0	0	0
j4	**t3**	1	0	0	0
j4	**t8**	0	1	0	0
j5	**t5**	1	0	0	0
j5	**t7**	1	0	0	0
j5	**t8**	0	0	1	0
j6	**t1**	1	0	0	0
j6	**t2**	0	1	0	0
j6	**t5**	0	1	1	0
j6	**t6**	0	1	0	0
j6	**t7**	0	0	1	0

Completion times and due dates of each job are like this:

Job #	Completion Time	Due Dates
j1	2	8
j2	5	7
j3	4	8
j4	9	9
j5	9	9
j6	8	9

As it is seen no tardy jobs occur in optimal schedule.

For optimal schedule, capacity level for each stage at each time period has been like this:

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	3	2	3	0
t2	4	3	4	0
t3	1	1	2	0
t4	0	0	2	0

t5	2	2	3	0
t6	0	1	0	0
t7	2	0	2	0
t8	0	2	2	0

3. Numerical Example:

For 4 stages, 6 jobs and 8 time horizon; process times and setup times are determined such as:

			Process Times				Setup Times			
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	0	8	3	3	5	3	2	1	1	1
j2	1	7	1	3	2	1	1	1	1	0
j3	0	8	1	1	1	1	1	1	1	1
j4	0	9	0	1	0	1	3	1	1	1
j5	0	9	0	0	1	1	0	1	1	1
j6	1	9	1	3	2	1	2	1	1	1

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS 57 SINGLE EQUATIONS 1,485

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 429

NON ZERO ELEMENTS 5,481 DISCRETE VARIABLES 390

OBJECTIVE VALUE = -8.700

Run Time = 0.01 Sec

Proposed MIP model results an optimal schedule just like following:

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t1**	1	0	0	0
j1	**t2**	1	1	0	0
j1	**t3**	1	1	1	0

j1	**t4**	0	1	1	0
j1	**t5**	0	0	1	0
j1	**t6**	0	0	1	1
j1	**t7**	0	0	1	1
j1	**t8**	0	0	0	1
j2	**t1**	1	0	0	0
j2	**t2**	0	1	0	0
j2	**t3**	0	1	0	0
j2	**t4**	0	1	0	0
j2	**t5**	0	0	1	0
j2	**t6**	0	0	1	0
j2	**t7**	0	0	0	1
j3	**t3**	1	0	0	0
j3	**t5**	0	1	0	0
j3	**t6**	0	0	1	0
j3	**t7**	0	0	0	1
j4	**t1**	0	1	0	0
j4	**t6**	0	0	0	1
j5	**t1**	0	0	1	0
j5	**t5**	0	0	0	1
j6	**t1**	1	0	0	0
j6	**t2**	0	1	0	0
j6	**t3**	0	1	0	0
j6	**t4**	0	1	0	0
j6	**t6**	0	0	1	0
j6	**t7**	0	0	1	0
j6	**t8**	0	0	0	1

Completion times and due dates of each job are like this:

Job #	**Completion Time**	**Due Dates**
j1	8	8
j2	7	7
j3	8	8
j4	7	9
j5	6	9
j6	9	9

As it is seen no tardy jobs occur in optimal schedule.

For optimal schedule, capacity level for each stage at each time period has been like this:

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	8	2	2	0
t2	1	6	0	0
t3	3	3	2	0
t4	0	3	1	0
t5	0	2	3	2
t6	0	0	6	4
t7	0	0	2	4
t8	0	0	0	3

4. Numerical Example:

For process times and setup times of 4 stages, 15 jobs and 20 time horizon, please look at Appendix-1 Table 1- Process times and Setup times of 4^{th} Numerical Example

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS	129	SINGLE EQUATIONS	9,116
BLOCKS OF VARIABLES	6	SINGLE VARIABLES	2,511
NON ZERO ELEMENTS	64,795	DISCRETE VARIABLES	2,415

OBJECTIVE VALUE = -59.000

Run Time = 0.23 Sec

For optimal schedule output, please look at Appendix-1 Table 2- Optimal Schedule Output
For Completion times and due dates of each job, please look at Appendix-1 Table 3- Completion times and Due Dates Output

As it is seen no tardy jobs occur in optimal schedule.

For capacity level for each stage at each time period, please look at Appendix-1 Table 4- Capacity Level for Each Stage Output

5. **Numerical Example:**

For process times and setup times of 4 stages, 30 jobs and 20 time horizon, please look at Appendix-2 Table 1- Process times and Setup times of 5^{fh} Numerical Example

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS 129 SINGLE EQUATIONS 18,064

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 4,941

NON ZERO ELEMENTS 129,485 DISCRETE VARIABLES 4,830

OBJECTIVE VALUE = -48.400

Run Time = 0.48 Sec

For optimal schedule output, please look at Appendix-2 Table 2- Optimal Schedule Output

For Completion times and due dates of each job, please look at Appendix-2 Table 3- Completion times and Due Dates Output

As it is seen no tardy jobs occur in optimal schedule.

For capacity level for each stage at each time period, please look at Appendix-2 Table 4- Capacity Level for Each Stage Output

6. **Numerical Example:**

For process times and setup times of 4 stages, 60 jobs and 60 time horizon; please look at Appendix-3 Table 1- Process times and Setup times of 6^{fh} Numerical Example

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS 369 SINGLE EQUATIONS 108,316

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 29,161

NON ZERO ELEMENTS 2,073,541 DISCRETE VARIABLES 28,860

OBJECTIVE VALUE = -164.400

Total Run-Time = 47,42 Seconds

For optimal schedule output, please look at Appendix-3 Table 2- Optimal Schedule Output

For Completion times and due dates of each job, please look at Appendix-3 Table 3- Completion times and Due Dates Output

As it is seen no tardy jobs occur in optimal schedule.

For capacity level for each stage at each time period, please look at Appendix-3 Table 4- Capacity Level for Each Stage Output

7. Numerical Example:

For process times and setup times of 4 stages, 110 jobs and 60 time horizon; please look at Appendix-4 Table 1- Process times and Setup times of 7^{fh} Numerical Example

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS	369	SINGLE EQUATIONS	198,076
BLOCKS OF VARIABLES	6	SINGLE VARIABLES	53,261
NON ZERO ELEMENTS	3,800,719	DISCRETE VARIABLES	52,910

OBJECTIVE VALUE = -129.200

Total Run-Time = 169.28 Seconds

For optimal schedule output, please look at Appendix-4 Table 2- Optimal Schedule Output

For Completion times and due dates of each job, please look at Appendix-4 Table 3- Completion times and Due Dates Output

As it is seen no tardy jobs occur in optimal schedule.

For capacity level for each stage at each time period, please look at Appendix-4 Table 4- Capacity Level for Each Stage Output

It is seen that for 110 jobs, model can find optimal schedule in 170 Sec. Therefore, no additional solution is taken during execution.

8. **Numerical Example:**

For process times and setup times of 4 stages, 152 jobs and 60 time horizon; please look at Appendix-5 Table 1- Process times and Setup times of 8^{fh} Numerical Example

Execution Statistics has been just like this:

BLOCKS OF EQUATIONS 369 SINGLE EQUATIONS 273,554

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 73,505

NON ZERO ELEMENTS 5,249,831 DISCRETE VARIABLES 73,110

OBJECTIVE VALUE = -100.400

Total Run-Time = 1.289,53 Seconds / 20 Min. 89 Sec.

For optimal schedule output, please look at Appendix-5 Table 2- Optimal Schedule Output

For Completion times and due dates of each job, please look at Appendix-5 Table 3- Completion times and Due Dates Output

As it is seen no tardy jobs occur in optimal schedule.

For capacity level for each stage at each time period, please look at Appendix-5 Table 4- Capacity Level for Each Stage Output

As mentioned before, additional to optimal schedule, at time 5, 10 and 20 minutes best solutions so far are saved. These solutions that are taken from model have been:

	300 Sec	600 Sec.	1200 Sec.	Optimal Solution

Best Objective So Far	-110.711	-107.420	-104.118	Obj.Value= -100.400
	% 10	% 7	% 3,7	Run Time= 1.290 Sec.

9. Numerical Example:

For process times and setup times of 4 stages, 160 jobs and 60 time horizon; please look at Appendix-6 Table 1- Process times and Setup times of 9[fh] Numerical Example

After execution, it is seen that model cannot solve such a large problem like this. No optimal schedule is generated. In order to observe the limits of model, it is seen that for 152 jobs, optimal schedule is generated however for 153 jobs, optimal schedule cannot be generated. Therefore, it is observed that for 4 stages and 60 time horizon, proposed model has 152 jobs limit.

Run-Result of a Real Scheduling Case of the Company:

After demonstrating that the proposed model has the ability of solving scheduling problems up to 152 jobs, for 4 stages and for 60 time horizon, model has been tried on a real scheduling problem based on real data of production orders and capacity limits that are given by the company.

In 15.02.2013, a snapshot of all jobs in production is taken from the company for testing our model. There were 124 jobs in this case and company wanted to obtain an optimal schedule for 60 time periods/4 work hours (30 days/1.5 Months). For process times and setup times of real-life example, please look at Appendix-7 Table 1- Process times and Setup times of Real-Life Example

Normal capacity level and max capacity level during periods was like following:

	Stage 1		Stage 2		Stage 3		Stage 4	
Time Period	Normal Limit	Max.	Normal Limit	Max.	Normal Limit	Max.	Normal Limit	Max.
t1	8	12	20	30	10	20	2	8
t2	8	12	20	30	10	20	2	8
t3	8	12	20	30	10	20	2	8
t4	8	12	20	30	10	20	2	8

t5	8	12	20	30	10	20	2	8
t6	8	12	20	30	10	20	2	8
t7	8	12	20	30	10	20	2	8
t8	8	12	20	30	10	20	2	8
t9	8	12	20	30	10	20	2	8
t10	8	12	20	30	10	20	2	8
t11	8	12	20	30	10	20	2	8
t12	8	12	20	30	10	20	2	8
t13	8	12	20	30	10	20	2	8
t14	8	12	20	30	10	20	2	8
t15	8	12	20	30	10	20	2	8
t16	8	12	20	30	10	20	2	8
t17	8	12	20	30	10	20	2	8
t18	8	12	20	30	10	20	2	8
t19	8	12	20	30	10	20	2	8
t20	8	12	20	30	10	20	2	8
t21	8	12	20	30	10	20	2	8
t22	8	12	20	30	10	20	2	8
t23	8	12	20	30	10	20	2	8
t24	8	12	20	30	10	20	2	8
t25	8	12	20	30	10	20	2	8
t26	8	12	20	30	10	20	2	8
t27	8	12	20	30	10	20	2	8
t28	8	12	20	30	10	20	2	8
t29	8	12	20	30	10	20	2	8
t30	8	12	20	30	10	20	2	8
t31	8	12	20	30	10	20	2	8
t32	8	12	20	30	10	20	2	8
t33	8	12	20	30	10	20	2	8
t34	8	12	20	30	10	20	2	8
t35	8	12	20	30	10	20	2	8
t36	8	12	20	30	10	20	2	8
t37	8	12	20	30	10	20	2	8
t38	8	12	20	30	10	20	2	8
t39	8	12	20	30	10	20	2	8
t40	8	12	20	30	10	20	2	8
t41	8	12	20	30	10	20	2	8
t42	8	12	20	30	10	20	2	8
t43	8	12	20	30	10	20	2	8
t44	8	12	20	30	10	20	2	8
t45	8	12	20	30	10	20	2	8
t46	8	12	20	30	10	20	2	8
t47	8	12	20	30	10	20	2	8
t48	8	12	20	30	10	20	2	8
t49	8	12	20	30	10	20	2	8
t50	8	12	20	30	10	20	2	8
t51	8	12	20	30	10	20	2	8
t52	8	12	20	30	10	20	2	8
t53	8	12	20	30	10	20	2	8

t54	8	12	20	30	10	20	2	8
t55	8	12	20	30	10	20	2	8
t56	8	12	20	30	10	20	2	8
t57	8	12	20	30	10	20	2	8
t58	8	12	20	30	10	20	2	8
t59	8	12	20	30	10	20	2	8
t60	8	12	20	30	10	20	2	8

Model has been run and execution statistics has been just like this:

BLOCKS OF EQUATIONS 369 SINGLE EQUATIONS 222,963

BLOCKS OF VARIABLES 6 SINGLE VARIABLES 60,009

NON ZERO ELEMENTS 4,258,716 DISCRETE VARIABLES 59,64

OBJECTIVE VALUE = - 116.800

Run Time = 237.73 Seconds

For optimal schedule output, please look at Appendix-7 Table 2- Optimal Schedule Output

For Completion times and due dates of each job, please look at Appendix-7 Table 3- Completion times and Due Dates Output

As it is seen, all due date constraints are met.

For capacity level for each stage at each time period, please look at Appendix-7 Table 4- Capacity Level for Each Stage Output

Discussion

As it is demonstrated in 9 numerical examples and a real scheduling case of ASELSAN Defense Systems Technologies Division, proposed model has ability of solving real life Hybrid Flow Shop Scheduling problems of the company up to 153 production orders.

For 9 numerical examples and real life case, following results has been gathered:

Problem Type				SOLUTION RESULTS				
	Stage #	Job #	Time Horizon	Discrete Var.	Equations	Nonzero Elements	Objective Value	Run Time (Sec.)
1	2	4	4	68	169	423	-9.100	0,05
2	3	6	8	290	1.033	3.579	-7.900	0,02
3	4	6	8	390	1.485	5.481	-8.700	0,01
4	4	15	20	2.415	9.116	64.795	-59.000	0,23
5	4	30	20	4.830	18.064	129.485	-48.400	0,48
6	4	60	60	28.860	108.316	2.073.541	-164.400	47,42
7	4	110	60	52.910	198.076	3.800.719	-129.200	169,28
8	4	152	60	73.110	273.554	5.249.831	-100.400	1.289,53
9	4	160	60	Unavalible	Unavalible	Unavalible	Unavalible	Unavalible
Real Case	4	124	60	59,64	222,963	4,258,716	- 116.800	237.73

For 152 jobs, 4 stages and 60 time horizons, it takes ~20 min. to solve the problem but it can find an optimal. According to real life experiences of ASELSAN Defense Systems Technologies Division Production Department, maximum load of production is average 140-150 production orders. Also, it is seen from the results of the model, there are no tardy jobs in the optimal schedules. There are early jobs because of not including “Cost for early jobs”. Model arranges all of the jobs due to tardy-job costs and capacity increment costs. Additionally, run-time of the model is short enough for fast re-scheduling and taking action immediately. It takes from 2 to 5 minutes for solving an average real-life case of ASELSAN Defense Systems Technologies Division. Therefore, proposed model in this research can be used as a decision support tool, for optimizing the schedules and deciding lot-splitting, capacity increment and due date strategies for each production order.

5. CONCLUSION AND FUTURE RESEARCH

In this research, for ASELSAN Defense Systems Technologies Division Production Scheduling Problem is examined and a Mixed Integer Program is proposed, demonstrated, and tested for numerical and real-life examples. As it is mentioned before, briefly ASELSAN Defense Systems Technologies Division Production Department Printed Wiring Board Production area has main 4 stages:

a. SMD Assembly

b. Through Hole Component Assembly and Rework

c. Functional Test

d. Conformal Coating and Gluing

Each stage has parallel labor and machine resources. All of labor and machine resources that are at the same stage are identical. Lot splitting is allowed in each stage. There are unlimited buffer between stages. Because of High Mix/low Volume, set-up times are inevitable and setup time of each job is independent from other jobs' setup times. (sequence – independent). And whenever lot of a production order is split to sub-lots, new setup time occurs for that stage.

Each production order has its own release date, due date, process and setup times for each stage. During manufacturing execution, capacity of each stage can be changed and lots of production orders can be divided to sub-lots due to scheduling strategies in line with the release date, due-date and capacity borders. ASELSAN Defense Systems Technologies Division Production Department mainly wants to minimize sum of total cost of tardy jobs and total cost of capacity increments. Therefore, briefly company has needed a decision support tool for its scheduling problem that gives optimal or near-optimal schedules corresponding to cost constraints.

The scheduling problem of ASELSAN Defense Systems Technologies Division is named as Hybrid Flow Shop Scheduling problem in literature. As it mentioned in (Gupta, 1988; VoX, 1993), it has m stage, each stage has parallel resources and each job follows the same routing. Corresponding to notation given in (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009), this specific scheduling problem of the company is denoted as:

$FHm\ (PM^{(k)})^{m}{}_{k=1}\ |\ r_j,\ split,\ S_{nsd}\ |\ U$ + Total Capacity

It is observed in (Rubén Ruiz, José Antonio Vázquez-Rodríguez, 2009) that this kind of problems can be solved by Exact Methods (such as Branch & Bound Algorithms, Integer Programming) and Heuristics/Meta-heuristics. In order to find exact optimal schedules for the company, Mixed Integer Programming method is chosen and a comprehensive Mixed Integer Program is built in GAMS Integrated Development Environment 23.7.3 version, solved by CPLEX solver and tested for 9 numerical and 1 real-life examples in this research. Summary of the results of examples can be seen at the table below:

Problem Type				**SOLUTION RESULTS**				
	Stage #	Job #	Time Horizon	Discrete Var.	Equations	Nonzero Elements	Objective Value	Run Time (Sec.)
1	2	4	4	68	169	423	-9.100	0,05
2	3	6	8	290	1.033	3.579	-7.900	0,02
3	4	6	8	390	1.485	5.481	-8.700	0,01
4	4	15	20	2.415	9.116	64.795	-59.000	0,23
5	4	30	20	4.830	18.064	129.485	-48.400	0,48
6	4	60	60	28.860	108.316	2.073.541	-164.400	47,42
7	4	110	60	52.910	198.076	3.800.719	-129.200	169,28
8	4	152	60	73.110	273.554	5.249.831	-100.400	1.289,53
9	4	160	60	Unavalible	Unavalible	Unavalible	Unavalible	Unavalible
Real Case	4	124	60	59,64	222,963	4,258,716	- 116.800	237.73

It's demonstrated that it gives optimal schedules up to 153 jobs, 4 stages and 60 Time-periods. It should be added that no due-date violations occur in optimal schedules for all of 9 numerical and 1 real-life examples.

According to the information that is taken from the ASELSAN Defense Systems Technologies Division Production Department, company has average 120-130 and maximum 140-150 production orders load. This means that proposed model can be used easily as a scheduling support tool for choosing optimal or near-optimal schedules. Additionally, run-time of the model for 130-140 production orders is average ~5 minutes long and it is small enough to take action immediately and re-schedule if it is needed.

For future research, some additional features can be added to the model just like:

1. Obligatory Wait times (Owen, Washing etc) can be added to each stage.
2. For each stage and each period, minimum capacity border can be determined in order to make optimal schedules more realistic. Because in real-life, in most cases, equalizing capacity level of a stage to 0, is impossible.
3. Early jobs and completion time objectives can be added.
4. Just In Time concept can be included at each stage by new constraints.
5. Advanced models can balance capacity level at each stage at each period by new constraints.

It is obvious that these features make the model more realistic, more accurate and more convenient to schedule real-life Hybrid Flow Shop Scheduling cases.

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APPENDIX-1

			Process Times				Setup Times			
Pr. Orders	Release Dates	Due Dates	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
j1	1	20	1	6	8	4	4	0	1	0
j2	0	13	1	3	2	1	2	0	1	0
j3	0	20	1	1	1	1	4	0	1	0
j4	0	20	0	1	0	1	0	0	0	0
j5	0	13	0	0	1	1	0	0	1	0
j6	0	20	1	3	2	1	2	0	1	0
j7	0	20	1	1	1	1	2	0	1	0
j8	1	17	0	1	0	1	0	0	0	0
j9	0	20	0	0	1	1	0	0	1	0
j10	0	22	1	2	1	0	2	0	1	0
j11	0	22	1	1	1	1	2	0	1	0
j12	0	13	0	1	0	1	0	0	0	0
j13	0	22	0	0	1	1	0	0	1	0
j14	0	13	1	3	2	1	4	0	1	0
j15	0	20	1	1	1	1	4	0	1	0

Table 1- Process times and Setup times of 4th Numerical Example

OPTIMAL SCHEDULE					
Job#	Time #	Stage 1	Stage 2	Stage 3	Stage 4
j1	t1	1	0	0	0
j1	t2	0	1	0	0
j1	t3	0	1	0	0
j1	t5	0	1	0	0
j1	t6	0	1	0	0
j1	t7	0	1	0	0
j1	t8	0	1	0	0
j1	t9	0	0	1	0
j1	t10	0	0	1	0
j1	t11	0	0	1	0
j1	t12	0	0	1	0
j1	t13	0	0	1	1
j1	t14	0	0	1	0
j1	t15	0	0	1	1
j1	t16	0	0	1	0
j1	t18	0	0	0	1
j1	t20	0	0	0	1
j2	t1	1	0	0	0
j2	t2	0	1	0	0

j2	**t9**	0	1	0	0
j2	**t10**	0	1	0	0
j2	**t11**	0	0	1	0
j2	**t12**	0	0	1	0
j2	**t13**	0	0	0	1
j3	**t2**	1	0	0	0
j3	**t15**	0	1	0	0
j3	**t17**	0	0	1	0
j3	**t18**	0	0	0	1
j4	**t1**	0	1	0	0
j4	**t3**	0	0	0	1
j5	**t3**	0	0	1	0
j5	**t11**	0	0	0	1
j6	**t1**	1	0	0	0
j6	**t2**	0	1	0	0
j6	**t12**	0	1	0	0
j6	**t13**	0	1	1	0
j6	**t14**	0	0	1	0
j6	**t15**	0	0	0	1
j7	**t13**	1	0	0	0
j7	**t14**	0	1	0	0
j7	**t18**	0	0	1	0
j7	**t20**	0	0	0	1
j8	**t1**	0	1	0	0
j8	**t2**	0	0	0	1
j9	**t5**	0	0	1	0
j9	**t6**	0	0	0	1
j10	**t11**	1	0	0	0
j10	**t13**	0	1	0	0
j10	**t14**	0	1	0	0
j10	**t19**	0	0	1	0
j11	**t3**	1	0	0	0
j11	**t16**	0	1	0	0
j11	**t17**	0	0	1	0
j11	**t20**	0	0	0	1
j12	**t1**	0	1	0	0
j12	**t3**	0	0	0	1
j13	**t6**	0	0	1	0
j13	**t15**	0	0	0	1
j14	**t2**	1	0	0	0
j14	**t3**	0	1	0	0
j14	**t8**	0	1	0	0
j14	**t9**	0	1	1	0
j14	**t10**	0	0	1	0
j14	**t13**	0	0	0	1

j15	**t16**	1	0	0	0
j15	**t18**	0	1	0	0
j15	**t19**	0	0	1	0
j15	**t20**	0	0	0	1

Table 2- Optimal Schedule Output

j1	20	20
j2	13	13
j3	18	20
j4	3	20
j5	11	13
j6	15	20
j7	20	20
j8	2	17
j9	6	20
j10	20	22
j11	20	22
j12	3	13
j13	15	22
j14	13	13
j15	20	20

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	11	3	0	0
t2	10	3	0	1
t3	3	2	2	2
t5	0	1	2	0
t6	0	1	2	1
t7	0	1	0	0
t8	0	2	0	0
t9	0	2	4	0
t10	0	1	2	0
t11	3	0	3	1
t12	0	1	2	0
t13	3	2	3	3
t14	0	2	2	0
t15	0	1	1	3
t16	5	1	1	0
t17	0	0	4	0
t18	0	1	2	2
t19	0	0	4	0
t20	0	0	0	4

Table 4- Capacity Level for Each Stage Output

APPENDIX-2

			Process Times				Setup Times			
Pr. Orders	Release Dates	Due Dates	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
j1	1	20	1	6	8	4	4	0	1	0
j2	0	13	1	3	2	1	2	0	1	0
j3	0	20	1	1	1	1	4	0	1	0
j4	0	20	0	1	0	1	0	0	0	0
j5	0	13	0	0	1	1	0	0	1	0
j6	0	20	1	3	2	1	2	0	1	0
j7	0	20	1	1	1	1	2	0	1	0
j8	1	17	0	1	0	1	0	0	0	0
j9	0	20	0	0	1	1	0	0	1	0
j10	0	22	1	2	1	0	2	0	1	0
j11	0	22	1	1	1	1	2	0	1	0
j12	0	13	0	1	0	1	0	0	0	0
j13	0	22	0	0	1	1	0	0	1	0
j14	0	13	1	3	2	1	4	0	1	0
j15	0	20	1	1	1	1	4	0	1	0
j16	0	20	0	1	0	1	0	0	0	0
j17	0	22	0	0	1	1	0	0	1	0
j18	2	22	1	3	2	1	2	1	1	0
j19	0	20	1	1	1	1	1	1	1	0
j20	0	13	0	1	0	1	0	0	0	0
j21	1	13	1	6	6	1	4	0	1	0
j22	0	13	1	1	1	1	1	1	1	0
j23	0	13	0	1	0	1	0	0	0	0
j24	0	20	0	0	1	1	0	0	1	0
j25	0	17	1	3	2	1	2	1	1	0
j26	0	13	1	1	1	1	1	1	1	0
j27	0	13	0	1	0	1	0	0	0	0
j28	1	22	0	0	1	1	0	0	1	0
j29	0	13	1	4	6	1	4	1	1	0
j30	0	20	1	1	1	1	1	1	1	0

Table 1- Process times and Setup times of 5^{th} Numerical Example

OPTIMAL SCHEDULE					
Job#	Time #	Stage 1	Stage 2	Stage 3	Stage 4
j1	t1	1	0	0	0
j1	t2	0	1	0	0
j1	t4	0	0	1	0
j1	t5	0	1	0	1
j1	t8	0	1	0	0
j1	t10	0	1	0	0

j1	t11	0	0	0	1
j1	t12	0	0	1	0
j1	t13	0	1	1	1
j1	t14	0	0	1	0
j1	t15	0	0	1	0
j1	t16	0	0	1	0
j1	t17	0	1	1	0
j1	t18	0	0	1	0
j1	t20	0	0	0	1
j2	t6	1	0	0	0
j2	t7	0	1	0	0
j2	t8	0	1	1	0
j2	t10	0	1	0	0
j2	t11	0	0	1	0
j2	t12	0	0	0	1
j3	t4	1	0	0	0
j3	t16	0	1	0	0
j3	t17	0	0	1	0
j3	t20	0	0	0	1
j4	t1	0	1	0	0
j4	t14	0	0	0	1
j5	t3	0	0	1	0
j5	t8	0	0	0	1
j6	t2	1	0	0	0
j6	t3	0	1	0	0
j6	t9	0	1	0	0
j6	t11	0	1	1	0
j6	t12	0	0	1	0
j6	t14	0	0	0	1
j7	t7	1	0	0	0
j7	t8	0	1	0	0
j7	t12	0	0	1	0
j7	t13	0	0	0	1
j8	t1	0	1	0	0
j8	t14	0	0	0	1
j9	t11	0	0	1	0
j9	t20	0	0	0	1
j10	t9	1	0	0	0
j10	t13	0	1	0	0
j10	t14	0	1	0	0
j10	t15	0	0	1	0
j11	t6	1	0	0	0
j11	t15	0	1	0	0
j11	t19	0	0	1	0
j11	t20	0	0	0	1

j12	**t1**	0	1	0	0
j12	**t5**	0	0	0	1
j13	**t19**	0	0	1	0
j13	**t20**	0	0	0	1
j14	**t5**	1	0	0	0
j14	**t6**	0	1	0	0
j14	**t7**	0	1	0	0
j14	**t10**	0	1	0	0
j14	**t11**	0	0	1	0
j14	**t12**	0	0	1	0
j14	**t13**	0	0	0	1
j15	**t9**	1	0	0	0
j15	**t12**	0	1	0	0
j15	**t13**	0	0	1	0
j15	**t17**	0	0	0	1
j16	**t1**	0	1	0	0
j16	**t11**	0	0	0	1
j17	**t3**	0	0	1	0
j17	**t11**	0	0	0	1
j18	**t2**	1	0	0	0
j18	**t3**	0	1	0	0
j18	**t4**	0	1	0	0
j18	**t5**	0	1	0	0
j18	**t18**	0	0	1	0
j18	**t19**	0	0	1	0
j18	**t20**	0	0	0	1
j19	**t6**	1	0	0	0
j19	**t9**	0	1	0	0
j19	**t12**	0	0	1	0
j19	**t13**	0	0	0	1
j20	**t1**	0	1	0	0
j20	**t5**	0	0	0	1
j21	**t4**	1	0	0	0
j21	**t5**	0	1	0	0
j21	**t6**	0	1	0	0
j21	**t7**	0	1	1	0
j21	**t8**	0	1	1	0
j21	**t9**	0	0	1	0
j21	**t10**	0	1	1	0
j21	**t11**	0	1	1	0
j21	**t12**	0	0	1	0
j21	**t13**	0	0	0	1
j22	**t6**	1	0	0	0
j22	**t7**	0	1	0	0
j22	**t8**	0	0	1	0

j22	t13	0	0	0	1
j23	t1	0	1	0	0
j23	t2	0	0	0	1
j24	t13	0	0	1	0
j24	t14	0	0	0	1
j25	t2	1	0	0	0
j25	t6	0	1	0	0
j25	t7	0	1	0	0
j25	t8	0	1	0	0
j25	t15	0	0	1	0
j25	t16	0	0	1	0
j25	t17	0	0	0	1
j26	t6	1	0	0	0
j26	t11	0	1	0	0
j26	t12	0	0	1	0
j26	t13	0	0	0	1
j27	t1	0	1	0	0
j27	t5	0	0	0	1
j28	t13	0	0	1	0
j28	t14	0	0	0	1
j29	t1	1	0	0	0
j29	t2	0	1	0	0
j29	t3	0	1	0	0
j29	t4	0	1	1	0
j29	t5	0	1	1	0
j29	t6	0	0	1	0
j29	t7	0	0	1	0
j29	t8	0	0	1	0
j29	t9	0	0	1	0
j29	t13	0	0	0	1
j30	t9	1	0	0	0
j30	t10	0	1	0	0
j30	t11	0	0	1	0
j30	t14	0	0	0	1

Table 2- Optimal Schedule Output

Job #	Completion Time	Due Dates
j1	20	20
j2	12	13
j3	20	20
j4	14	20
j5	8	13
j6	14	20
j7	13	20

j8	14	17
j9	20	20
j10	16	22
j11	20	22
j12	5	13
j13	20	22
j14	13	13
j15	17	20
j16	11	20
j17	11	22
j18	20	22
j19	13	20
j20	5	13
j21	13	13
j22	13	13
j23	2	13
j24	14	20
j25	17	17
j26	13	13
j27	5	13
j28	14	22
j29	13	13
j30	14	20

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	10	7	0	0
t2	9	3	0	1
t3	0	4	4	0
t4	10	2	4	0
t5	5	4	1	4
t6	12	4	1	0
t7	3	6	3	0
t8	0	5	6	1
t9	10	3	2	0
t10	0	6	1	0
t11	0	4	11	3
t12	0	1	11	1
t13	0	2	7	8
t14	0	1	1	6
t15	0	1	5	0
t16	0	1	2	0
t17	0	1	3	2
t18	0	0	3	0

t19	0	0	5	0
t20	0	0	0	6

Table 4- Capacity Level for Each Stage Output

APPENDIX-3

Pr. Orders	Release Dates	Due Dates	Process Times				Setup Times			
			Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
j1	0	60	1	6	8	4	4	0	1	0
j2	0	40	1	3	2	1	2	0	1	0
j3	0	60	1	1	1	1	4	0	1	0
j4	0	60	0	1	0	1	0	0	0	0
j5	0	40	0	0	1	1	0	0	1	0
j6	0	60	1	3	2	1	2	0	1	0
j7	0	60	1	1	1	1	2	0	1	0
j8	0	50	0	1	0	1	0	0	0	0
j9	0	60	0	0	1	1	0	0	1	0
j10	0	65	1	2	1	0	2	0	1	0
j11	0	65	1	1	1	1	2	0	1	0
j12	0	40	0	1	0	1	0	0	0	0
j13	0	65	0	0	1	1	0	0	1	0
j14	0	40	1	3	2	1	4	0	1	0
j15	0	60	1	1	1	1	4	0	1	0
j16	0	60	0	1	0	1	0	0	0	0
j17	0	65	0	0	1	1	0	0	1	0
j18	0	67	1	3	2	1	2	1	1	0
j19	0	60	1	1	1	1	1	1	1	0
j20	0	40	0	1	0	1	0	0	0	0
j21	0	40	1	6	6	1	4	0	1	0
j22	0	40	1	1	1	1	1	1	1	0
j23	0	40	0	1	0	1	0	0	0	0
j24	0	60	0	0	1	1	0	0	1	0
j25	0	50	1	3	2	1	2	1	1	0
j26	0	40	1	1	1	1	1	1	1	0
j27	0	40	0	1	0	1	0	0	0	0
j28	0	65	0	0	1	1	0	0	1	0
j29	0	40	1	4	6	1	4	1	1	0
j30	0	60	1	1	1	1	1	1	1	0
j31	0	40	0	0	1	1	0	0	1	0
j32	0	65	1	3	2	1	2	1	1	0
j33	0	69	1	1	1	1	1	1	1	0
j34	0	65	0	1	0	1	0	0	0	0
j35	0	65	0	0	1	1	0	0	1	0
j36	0	60	1	3	4	1	4	1	1	0
j37	0	69	1	1	1	1	1	1	1	0
j38	0	45	0	1	0	1	0	0	0	1
j39	0	65	0	0	1	1	0	0	1	0
j40	0	60	1	6	2	1	4	1	1	0
j41	0	60	1	6	6	1	4	0	1	1
j42	0	40	1	1	1	1	1	1	1	0
j43	0	40	0	1	0	1	0	0	0	0

j44	0	60	0	0	1	1	0	0	1	0
j45	0	60	1	3	2	1	2	1	1	0
j46	0	25	1	1	1	1	2	1	1	0
j47	0	29	0	1	0	1	0	0	0	0
j48	0	65	0	0	1	1	0	0	1	0
j49	0	65	1	4	6	1	4	1	1	0
j50	0	60	1	1	1	1	2	1	1	0
j51	0	50	0	0	1	1	0	0	1	1
j52	0	65	1	3	2	1	2	1	1	0
j53	0	69	1	1	1	1	2	1	1	0
j54	0	55	0	1	0	1	0	0	0	1
j55	0	65	0	0	1	1	0	0	1	0
j56	0	60	1	3	4	1	4	1	1	0
j57	0	69	1	1	1	1	1	1	1	0
j58	0	60	0	1	0	1	0	0	0	0
j59	0	65	0	0	1	1	0	0	1	0
j60	0	60	1	6	2	1	4	1	1	0

Table 1- Process times and Setup times of 6^{th} Numerical Example

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t4**	1	0	0	0
j1	**t5**	0	1	0	0
j1	**t41**	0	1	0	0
j1	**t42**	0	1	0	0
j1	**t44**	0	1	0	0
j1	**t45**	0	1	0	0
j1	**t48**	0	0	1	0
j1	**t49**	0	0	1	0
j1	**t50**	0	0	1	0
j1	**t51**	0	0	1	0
j1	**t52**	0	0	1	0
j1	**t54**	0	0	1	0
j1	**t55**	0	0	0	1
j1	**t56**	0	0	1	0
j1	**t58**	0	1	0	1
j1	**t59**	0	0	1	1
j1	**t60**	0	0	0	1
j2	**t16**	1	0	0	0
j2	**t21**	0	1	0	0
j2	**t25**	0	1	0	0
j2	**t29**	0	1	1	0
j2	**t30**	0	0	1	0
j2	**t31**	0	0	0	1
j3	**t34**	1	0	0	0

j3	**t38**	0	1	0	0
j3	**t52**	0	0	1	0
j3	**t59**	0	0	0	1
j4	**t1**	0	1	0	0
j4	**t55**	0	0	0	1
j5	**t25**	0	0	1	0
j5	**t39**	0	0	0	1
j6	**t2**	1	0	0	0
j6	**t5**	0	1	0	0
j6	**t6**	0	1	0	0
j6	**t14**	0	1	0	0
j6	**t18**	0	0	1	0
j6	**t37**	0	0	1	0
j6	**t60**	0	0	0	1
j7	**t36**	1	0	0	0
j7	**t40**	0	1	0	0
j7	**t48**	0	0	1	0
j7	**t51**	0	0	0	1
j8	**t32**	0	1	0	0
j8	**t49**	0	0	0	1
j9	**t27**	0	0	1	0
j9	**t49**	0	0	0	1
j10	**t3**	1	0	0	0
j10	**t18**	0	1	0	0
j10	**t19**	0	1	0	0
j10	**t52**	0	0	1	0
j11	**t30**	1	0	0	0
j11	**t32**	0	1	0	0
j11	**t37**	0	0	1	0
j11	**t39**	0	0	0	1
j12	**t1**	0	1	0	0
j12	**t26**	0	0	0	1
j13	**t7**	0	0	1	0
j13	**t48**	0	0	0	1
j14	**t5**	1	0	0	0
j14	**t6**	0	1	0	0
j14	**t10**	0	1	0	0
j14	**t14**	0	1	1	0
j14	**t15**	0	0	1	0
j14	**t33**	0	0	0	1
j15	**t19**	1	0	0	0
j15	**t32**	0	1	0	0
j15	**t36**	0	0	1	0
j15	**t49**	0	0	0	1
j16	**t19**	0	1	0	0

j16	**t29**	0	0	0	1
j17	**t24**	0	0	1	0
j17	**t26**	0	0	0	1
j18	**t9**	1	0	0	0
j18	**t11**	0	1	0	0
j18	**t12**	0	1	0	0
j18	**t14**	0	1	0	0
j18	**t18**	0	0	1	0
j18	**t44**	0	0	1	0
j18	**t55**	0	0	0	1
j19	**t43**	1	0	0	0
j19	**t45**	0	1	0	0
j19	**t46**	0	0	1	0
j19	**t48**	0	0	0	1
j20	**t14**	0	1	0	0
j20	**t26**	0	0	0	1
j21	**t7**	1	0	0	0
j21	**t8**	0	1	0	0
j21	**t9**	0	1	0	0
j21	**t10**	0	1	0	0
j21	**t14**	0	1	0	0
j21	**t17**	0	0	1	0
j21	**t18**	0	1	1	0
j21	**t19**	0	1	1	0
j21	**t20**	0	0	1	0
j21	**t21**	0	0	1	0
j21	**t22**	0	0	1	0
j21	**t40**	0	0	0	1
j22	**t3**	1	0	0	0
j22	**t25**	0	1	0	0
j22	**t36**	0	0	1	0
j22	**t39**	0	0	0	1
j23	**t1**	0	1	0	0
j23	**t29**	0	0	0	1
j24	**t55**	0	0	1	0
j24	**t56**	0	0	0	1
j25	**t11**	1	0	0	0
j25	**t23**	0	1	0	0
j25	**t24**	0	1	0	0
j25	**t25**	0	1	0	0
j25	**t44**	0	0	1	0
j25	**t48**	0	0	1	0
j25	**t50**	0	0	0	1
j26	**t4**	1	0	0	0
j26	**t19**	0	1	0	0

j26	t27	0	0	1	0
j26	t29	0	0	0	1
j27	t1	0	1	0	0
j27	t31	0	0	0	1
j28	t7	0	0	1	0
j28	t31	0	0	0	1
j29	t1	1	0	0	0
j29	t2	0	1	0	0
j29	t3	0	1	0	0
j29	t4	0	1	1	0
j29	t5	0	1	0	0
j29	t6	0	0	1	0
j29	t7	0	0	1	0
j29	t8	0	0	1	0
j29	t9	0	0	1	0
j29	t10	0	0	1	0
j29	t31	0	0	0	1
j30	t9	1	0	0	0
j30	t32	0	1	0	0
j30	t36	0	0	1	0
j30	t49	0	0	0	1
j31	t25	0	0	1	0
j31	t26	0	0	0	1
j32	t2	1	0	0	0
j32	t3	0	1	0	0
j32	t4	0	1	0	0
j32	t5	0	1	0	0
j32	t58	0	0	1	0
j32	t59	0	0	1	0
j32	t60	0	0	0	1
j33	t34	1	0	0	0
j33	t44	0	1	0	0
j33	t52	0	0	1	0
j33	t55	0	0	0	1
j34	t19	0	1	0	0
j34	t49	0	0	0	1
j35	t18	0	0	1	0
j35	t31	0	0	0	1
j36	t15	1	0	0	0
j36	t45	0	1	0	0
j36	t46	0	1	1	0
j36	t47	0	1	1	0
j36	t48	0	0	1	0
j36	t53	0	0	1	0
j36	t54	0	0	0	1

j37	**t1**	1	0	0	0
j37	**t2**	0	1	0	0
j37	**t38**	0	0	1	0
j37	**t60**	0	0	0	1
j38	**t1**	0	1	0	0
j38	**t4**	0	0	0	1
j39	**t2**	0	0	1	0
j39	**t26**	0	0	0	1
j40	**t12**	1	0	0	0
j40	**t34**	0	1	0	0
j40	**t40**	0	1	0	0
j40	**t42**	0	1	0	0
j40	**t45**	0	1	0	0
j40	**t49**	0	1	0	0
j40	**t57**	0	1	1	0
j40	**t58**	0	0	1	0
j40	**t59**	0	0	0	1
j41	**t1**	1	0	0	0
j41	**t2**	0	1	0	0
j41	**t3**	0	1	0	0
j41	**t4**	0	1	0	0
j41	**t21**	0	0	1	0
j41	**t22**	0	0	1	0
j41	**t26**	0	0	1	0
j41	**t27**	0	0	1	0
j41	**t48**	0	1	0	0
j41	**t49**	0	1	0	0
j41	**t50**	0	1	0	0
j41	**t51**	0	0	1	0
j41	**t52**	0	0	1	0
j41	**t59**	0	0	0	1
j42	**t35**	1	0	0	0
j42	**t36**	0	1	0	0
j42	**t39**	0	0	1	0
j42	**t40**	0	0	0	1
j43	**t19**	0	1	0	0
j43	**t37**	0	0	0	1
j44	**t20**	0	0	1	0
j44	**t49**	0	0	0	1
j45	**t3**	1	0	0	0
j45	**t4**	0	1	0	0
j45	**t6**	0	1	0	0
j45	**t7**	0	1	0	0
j45	**t30**	0	0	1	0
j45	**t31**	0	0	1	0

j45	**t60**	0	0	0	1
j46	**t3**	1	0	0	0
j46	**t17**	0	1	0	0
j46	**t23**	0	0	1	0
j46	**t25**	0	0	0	1
j47	**t25**	0	1	0	0
j47	**t26**	0	0	0	1
j48	**t2**	0	0	1	0
j48	**t29**	0	0	0	1
j49	**t2**	1	0	0	0
j49	**t3**	0	1	0	0
j49	**t4**	0	1	0	0
j49	**t5**	0	1	0	0
j49	**t6**	0	1	0	0
j49	**t8**	0	0	1	0
j49	**t9**	0	0	1	0
j49	**t10**	0	0	1	0
j49	**t11**	0	0	1	0
j49	**t12**	0	0	1	0
j49	**t13**	0	0	1	0
j49	**t59**	0	0	0	1
j50	**t34**	1	0	0	0
j50	**t36**	0	1	0	0
j50	**t47**	0	0	1	0
j50	**t60**	0	0	0	1
j51	**t47**	0	0	1	0
j51	**t49**	0	0	0	1
j52	**t4**	1	0	0	0
j52	**t6**	0	1	0	0
j52	**t7**	0	1	0	0
j52	**t8**	0	1	0	0
j52	**t18**	0	0	1	0
j52	**t19**	0	0	1	0
j52	**t21**	0	0	0	1
j53	**t52**	1	0	0	0
j53	**t54**	0	1	0	0
j53	**t59**	0	0	1	0
j53	**t60**	0	0	0	1
j54	**t1**	0	1	0	0
j54	**t8**	0	0	0	1
j55	**t2**	0	0	1	0
j55	**t26**	0	0	0	1
j56	**t16**	1	0	0	0
j56	**t27**	0	1	0	0
j56	**t28**	0	1	0	0

j56	**t29**	0	1	0	0
j56	**t52**	0	0	1	0
j56	**t53**	0	0	1	0
j56	**t54**	0	0	1	0
j56	**t55**	0	0	1	0
j56	**t59**	0	0	0	1
j57	**t12**	1	0	0	0
j57	**t17**	0	1	0	0
j57	**t31**	0	0	1	0
j57	**t48**	0	0	0	1
j58	**t1**	0	1	0	0
j58	**t8**	0	0	0	1
j59	**t44**	0	0	1	0
j59	**t60**	0	0	0	1
j60	**t20**	1	0	0	0
j60	**t49**	0	1	0	0
j60	**t50**	0	1	0	0
j60	**t51**	0	1	0	0
j60	**t54**	0	1	0	0
j60	**t55**	0	1	0	0
j60	**t56**	0	1	0	0
j60	**t57**	0	0	1	0
j60	**t58**	0	0	1	0
j60	**t59**	0	0	0	1

Table 2- Optimal Schedule Output

Job #	**Completion Time**	**Due Dates**
j1	60	60
j2	31	40
j3	59	60
j4	55	60
j5	39	40
j6	60	60
j7	51	60
j8	49	50
j9	49	60
j10	53	65
j11	39	65
j12	26	40
j13	48	65
j14	33	40
j15	49	60
j16	29	60
j17	26	65

j18	55	67
j19	48	60
j20	26	40
j21	40	40
j22	39	40
j23	29	40
j24	56	60
j25	50	50
j26	29	40
j27	31	40
j28	31	65
j29	31	40
j30	49	60
j31	26	40
j32	60	65
j33	55	69
j34	49	65
j35	31	65
j36	54	60
j37	60	69
j38	5	45
j39	26	65
j40	59	60
j41	60	60
j42	40	40
j43	37	40
j44	49	60
j45	60	60
j46	25	25
j47	26	29
j48	29	65
j49	59	65
j50	60	60
j51	50	50
j52	21	65
j53	60	69
j54	9	55
j55	26	65
j56	59	60
j57	48	69
j58	8	60
j59	60	65
j60	59	60

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	12	7	0	0
t2	11	5	6	0
t3	11	6	0	0
t4	10	6	2	2
t5	5	5	0	0
t6	0	7	2	0
t7	5	2	5	0
t8	0	2	3	3
t9	5	1	2	0
t10	0	2	2	0
t11	3	2	1	0
t12	7	1	1	0
t13	0	0	1	0
t14	0	6	2	0
t15	5	0	1	0
t16	8	0	0	0
t17	0	4	2	0
t18	0	2	9	0
t19	5	7	2	0
t20	5	0	3	0
t21	0	1	3	1
t22	0	0	2	0
t23	0	2	2	0
t24	0	1	2	0
t25	0	5	4	1
t26	0	0	2	7
t27	0	2	5	0
t28	0	1	0	0
t29	0	2	2	4
t30	3	0	3	0
t31	0	0	3	5
t32	0	5	0	0
t33	0	0	0	1
t34	10	2	0	0
t35	2	0	0	0
t36	3	4	6	0
t37	0	0	4	1
t38	0	1	2	0
t39	0	0	2	3
t40	0	3	0	2
t41	0	1	0	0
t42	0	3	0	0

t43	2	0	0	0
t44	0	3	6	0
t45	0	7	0	0
t46	0	1	4	0
t47	0	1	5	0
t48	0	1	7	3
t49	0	5	1	8
t50	0	2	1	1
t51	0	1	3	1
t52	3	0	10	0
t53	0	0	3	0
t54	0	4	3	1
t55	0	1	3	4
t56	0	1	2	1
t57	0	2	4	0
t58	0	1	4	1
t59	0	0	5	8
t60	0	0	0	8

Table 4- Capacity Level for Each Stage Output

APPENDIX-4

			Process Times				Setup Times			
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	0	60	1	6	8	4	4	0	1	0
j2	0	40	1	3	2	1	2	0	1	0
j3	0	60	1	1	1	1	4	0	1	0
j4	0	60	0	1	0	1	0	0	0	0
j5	0	40	0	0	1	1	0	0	1	0
j6	0	60	1	3	2	1	2	0	1	0
j7	0	60	1	1	1	1	2	0	1	0
j8	0	50	0	1	0	1	0	0	0	0
j9	0	60	0	0	1	1	0	0	1	0
j10	0	65	1	2	1	0	2	0	1	0
j11	0	65	1	1	1	1	2	0	1	0
j12	0	40	0	1	0	1	0	0	0	0
j13	0	65	0	0	1	1	0	0	1	0
j14	0	40	1	3	2	1	4	0	1	0
j15	0	60	1	1	1	1	4	0	1	0
j16	0	60	0	1	0	1	0	0	0	0
j17	0	65	0	0	1	1	0	0	1	0
j18	0	67	1	3	2	1	2	1	1	0
j19	0	60	1	1	1	1	1	1	1	0
j20	0	40	0	1	0	1	0	0	0	0
j21	0	40	1	6	6	1	4	0	1	0
j22	0	40	1	1	1	1	1	1	1	0
j23	0	40	0	1	0	1	0	0	0	0
j24	0	60	0	0	1	1	0	0	1	0
j25	0	50	1	3	2	1	2	1	1	0
j26	0	40	1	1	1	1	1	1	1	0
j27	0	40	0	1	0	1	0	0	0	0
j28	0	65	0	0	1	1	0	0	1	0
j29	0	40	1	4	6	1	4	1	1	0
j30	0	60	1	1	1	1	1	1	1	0
j31	0	40	0	0	1	1	0	0	1	0
j32	0	65	1	3	2	1	2	1	1	0
j33	0	69	1	1	1	1	1	1	1	0
j34	0	65	0	1	0	1	0	0	0	0
j35	0	65	0	0	1	1	0	0	1	0
j36	0	60	1	3	4	1	4	1	1	0
j37	0	69	1	1	1	1	1	1	1	0
j38	0	45	0	1	0	1	0	0	0	1
j39	0	65	0	0	1	1	0	0	1	0
j40	0	60	1	6	2	1	4	1	1	0
j41	0	60	1	6	6	1	4	0	1	1
j42	0	40	1	1	1	1	1	1	1	0
j43	0	40	0	1	0	1	0	0	0	0

j44	0	60	0	0	1	1	0	0	1	0
j45	0	60	1	3	2	1	2	1	1	0
j46	0	25	1	1	1	1	2	1	1	0
j47	0	29	0	1	0	1	0	0	0	0
j48	0	65	0	0	1	1	0	0	1	0
j49	0	65	1	4	6	1	4	1	1	0
j50	0	60	1	1	1	1	2	1	1	0
j51	0	50	0	0	1	1	0	0	1	1
j52	0	65	1	3	2	1	2	1	1	0
j53	0	69	1	1	1	1	2	1	1	0
j54	0	55	0	1	0	1	0	0	0	1
j55	0	65	0	0	1	1	0	0	1	0
j56	0	60	1	3	4	1	4	1	1	0
j57	0	69	1	1	1	1	1	1	1	0
j58	0	60	0	1	0	1	0	0	0	0
j59	0	65	0	0	1	1	0	0	1	0
j60	0	60	1	6	2	1	4	1	1	0
j61	5	65	1	1	1	1	1	0	1	0
j62	4	69	0	1	0	1	0	0	0	0
j63	0	50	0	0	1	1	0	0	1	0
j64	0	55	1	3	2	1	4	0	1	0
j65	0	50	1	1	1	1	4	0	1	0
j66	2	50	0	1	0	1	0	0	0	0
j67	1	55	0	0	1	1	0	0	1	0
j68	5	67	1	3	2	1	2	1	1	0
j69	6	50	1	1	1	1	1	1	1	0
j70	7	50	0	1	0	1	0	0	0	0
j71	8	60	1	6	6	1	4	0	1	0
j72	0	50	1	1	1	1	1	1	1	0
j73	1	60	0	1	0	1	0	0	0	0
j74	3	60	0	0	1	1	0	0	1	0
j75	8	50	1	3	2	1	2	1	1	0
j76	10	55	1	1	1	1	2	1	1	0
j77	4	59	0	1	0	1	0	0	0	0
j78	0	65	0	0	1	1	0	0	1	0
j79	5	55	1	4	6	1	4	1	1	0
j80	4	60	1	1	1	1	1	1	1	0
j81	0	60	0	0	1	1	0	0	1	0
j82	0	65	1	3	2	1	2	1	1	0
j83	0	69	1	1	1	1	1	1	1	0
j84	0	65	0	1	0	1	0	0	0	0
j85	1	65	0	0	1	1	0	0	1	0
j86	5	60	1	3	4	1	4	1	1	0
j87	6	69	1	1	1	1	2	1	1	0
j88	7	65	0	1	0	1	0	0	0	0
j89	8	65	0	0	1	1	0	0	1	0
j90	0	60	1	6	2	2	4	1	1	0
j91	1	60	1	6	6	2	4	0	1	0

j92	3	60	1	1	1	1	2	1	1	0
j93	8	60	0	1	0	1	0	0	0	0
j94	10	60	0	0	1	1	0	0	1	0
j95	4	50	1	3	2	1	2	1	1	0
j96	0	55	1	1	1	1	2	1	1	0
j97	5	59	0	1	0	1	0	0	0	0
j98	4	65	0	0	1	1	0	0	1	0
j99	0	65	1	4	6	2	4	1	1	0
j100	0	60	1	1	1	1	1	1	1	0
j101	0	60	0	0	1	1	0	0	1	0
j102	0	65	1	3	2	2	2	1	1	0
j103	1	69	1	1	1	1	2	1	1	0
j104	5	65	0	1	0	1	0	0	0	0
j105	6	65	0	0	1	1	0	0	1	0
j106	7	60	1	3	4	2	4	1	1	0
j107	8	69	1	1	1	1	2	1	1	0
j108	0	65	0	1	0	1	0	0	0	0
j109	1	65	0	0	1	1	0	0	1	0
j110	3	35	1	2	1	1	4	1	1	0

Table 1- Process times and Setup times of 7th Numerical Example

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t4**	1	0	0	0
j1	**t5**	0	1	0	0
j1	**t10**	0	1	0	0
j1	**t41**	0	1	0	0
j1	**t42**	0	0	1	0
j1	**t43**	0	0	1	0
j1	**t44**	0	1	1	0
j1	**t45**	0	1	1	1
j1	**t46**	0	1	1	1
j1	**t47**	0	0	1	0
j1	**t48**	0	0	1	0
j1	**t49**	0	0	1	1
j1	**t52**	0	0	0	1
j2	**t28**	1	0	0	0
j2	**t29**	0	1	0	0
j2	**t32**	0	1	0	0
j2	**t34**	0	1	0	0
j2	**t37**	0	0	1	0
j2	**t38**	0	0	1	0
j2	**t39**	0	0	0	1
j3	**t28**	1	0	0	0
j3	**t40**	0	1	0	0
j3	**t45**	0	0	1	0

j3	**t53**	0	0	0	1
j4	**t1**	0	1	0	0
j4	**t18**	0	0	0	1
j5	**t34**	0	0	1	0
j5	**t37**	0	0	0	1
j6	**t3**	1	0	0	0
j6	**t4**	0	1	0	0
j6	**t5**	0	1	0	0
j6	**t6**	0	1	0	0
j6	**t12**	0	0	1	0
j6	**t13**	0	0	1	0
j6	**t60**	0	0	0	1
j7	**t7**	1	0	0	0
j7	**t10**	0	1	0	0
j7	**t14**	0	0	1	0
j7	**t19**	0	0	0	1
j8	**t9**	0	1	0	0
j8	**t36**	0	0	0	1
j9	**t14**	0	0	1	0
j9	**t25**	0	0	0	1
j10	**t19**	1	0	0	0
j10	**t29**	0	1	0	0
j10	**t38**	0	1	0	0
j10	**t47**	0	0	1	0
j11	**t29**	1	0	0	0
j11	**t39**	0	1	0	0
j11	**t41**	0	0	1	0
j11	**t45**	0	0	0	1
j12	**t17**	0	1	0	0
j12	**t21**	0	0	0	1
j13	**t8**	0	0	1	0
j13	**t19**	0	0	0	1
j14	**t6**	1	0	0	0
j14	**t9**	0	1	0	0
j14	**t11**	0	1	0	0
j14	**t13**	0	1	0	0
j14	**t20**	0	0	1	0
j14	**t21**	0	0	1	0
j14	**t22**	0	0	0	1
j15	**t37**	1	0	0	0
j15	**t49**	0	1	0	0
j15	**t51**	0	0	1	0
j15	**t53**	0	0	0	1
j16	**t19**	0	1	0	0
j16	**t57**	0	0	0	1

j17	**t3**	0	0	1	0
j17	**t20**	0	0	0	1
j18	**t20**	1	0	0	0
j18	**t24**	0	1	0	0
j18	**t43**	0	1	0	0
j18	**t44**	0	1	0	0
j18	**t54**	0	0	1	0
j18	**t55**	0	0	1	0
j18	**t57**	0	0	0	1
j19	**t7**	1	0	0	0
j19	**t20**	0	1	0	0
j19	**t32**	0	0	1	0
j19	**t36**	0	0	0	1
j20	**t6**	0	1	0	0
j20	**t12**	0	0	0	1
j21	**t8**	1	0	0	0
j21	**t9**	0	1	0	0
j21	**t10**	0	1	0	0
j21	**t20**	0	1	0	0
j21	**t29**	0	1	0	0
j21	**t30**	0	1	1	0
j21	**t31**	0	0	1	0
j21	**t32**	0	0	1	0
j21	**t33**	0	0	1	0
j21	**t34**	0	1	1	0
j21	**t35**	0	0	1	0
j21	**t36**	0	0	0	1
j22	**t28**	1	0	0	0
j22	**t31**	0	1	0	0
j22	**t34**	0	0	1	0
j22	**t36**	0	0	0	1
j23	**t4**	0	1	0	0
j23	**t19**	0	0	0	1
j24	**t24**	0	0	1	0
j24	**t49**	0	0	0	1
j25	**t3**	1	0	0	0
j25	**t4**	0	1	0	0
j25	**t5**	0	1	0	0
j25	**t6**	0	1	0	0
j25	**t7**	0	0	1	0
j25	**t8**	0	0	1	0
j25	**t49**	0	0	0	1
j26	**t11**	1	0	0	0
j26	**t19**	0	1	0	0
j26	**t21**	0	0	1	0

j26	**t26**	0	0	0	1
j27	**t6**	0	1	0	0
j27	**t36**	0	0	0	1
j28	**t14**	0	0	1	0
j28	**t28**	0	0	0	1
j29	**t2**	1	0	0	0
j29	**t3**	0	1	0	0
j29	**t4**	0	1	0	0
j29	**t5**	0	1	0	0
j29	**t6**	0	1	0	0
j29	**t8**	0	0	1	0
j29	**t9**	0	0	1	0
j29	**t10**	0	0	1	0
j29	**t11**	0	0	1	0
j29	**t12**	0	0	1	0
j29	**t13**	0	0	1	0
j29	**t40**	0	0	0	1
j30	**t8**	1	0	0	0
j30	**t47**	0	1	0	0
j30	**t51**	0	0	1	0
j30	**t53**	0	0	0	1
j31	**t28**	0	0	1	0
j31	**t36**	0	0	0	1
j32	**t3**	1	0	0	0
j32	**t33**	0	1	0	0
j32	**t34**	0	1	0	0
j32	**t47**	0	1	0	0
j32	**t48**	0	0	1	0
j32	**t49**	0	0	1	0
j32	**t53**	0	0	0	1
j33	**t25**	1	0	0	0
j33	**t31**	0	1	0	0
j33	**t33**	0	0	1	0
j33	**t36**	0	0	0	1
j34	**t19**	0	1	0	0
j34	**t38**	0	0	0	1
j35	**t55**	0	0	1	0
j35	**t59**	0	0	0	1
j36	**t1**	1	0	0	0
j36	**t2**	0	1	0	0
j36	**t3**	0	1	0	0
j36	**t4**	0	1	0	0
j36	**t44**	0	0	1	0
j36	**t45**	0	0	1	0
j36	**t46**	0	0	1	0

j36	**t48**	0	0	1	0
j36	**t56**	0	0	0	1
j37	**t21**	1	0	0	0
j37	**t24**	0	1	0	0
j37	**t33**	0	0	1	0
j37	**t53**	0	0	0	1
j38	**t1**	0	1	0	0
j38	**t27**	0	0	0	1
j39	**t42**	0	0	1	0
j39	**t52**	0	0	0	1
j40	**t21**	1	0	0	0
j40	**t22**	0	1	0	0
j40	**t23**	0	1	0	0
j40	**t24**	0	1	0	0
j40	**t25**	0	1	0	0
j40	**t26**	0	1	0	0
j40	**t27**	0	1	0	0
j40	**t57**	0	0	1	0
j40	**t58**	0	0	1	0
j40	**t60**	0	0	0	1
j41	**t19**	1	0	0	0
j41	**t33**	0	1	0	0
j41	**t35**	0	1	0	0
j41	**t42**	0	1	0	0
j41	**t46**	0	1	0	0
j41	**t47**	0	1	0	0
j41	**t48**	0	0	1	0
j41	**t49**	0	1	1	0
j41	**t50**	0	0	1	0
j41	**t51**	0	0	1	0
j41	**t52**	0	0	1	0
j41	**t53**	0	0	1	0
j41	**t58**	0	0	0	1
j42	**t16**	1	0	0	0
j42	**t19**	0	1	0	0
j42	**t24**	0	0	1	0
j42	**t39**	0	0	0	1
j43	**t7**	0	1	0	0
j43	**t29**	0	0	0	1
j44	**t8**	0	0	1	0
j44	**t20**	0	0	0	1
j45	**t2**	1	0	0	0
j45	**t7**	0	1	0	0
j45	**t8**	0	1	0	0
j45	**t36**	0	1	0	0

j45	t40	0	0	1	0
j45	t41	0	0	1	0
j45	t60	0	0	0	1
j46	t6	1	0	0	0
j46	t10	0	1	0	0
j46	t21	0	0	1	0
j46	t25	0	0	0	1
j47	t1	0	1	0	0
j47	t21	0	0	0	1
j48	t14	0	0	1	0
j48	t25	0	0	0	1
j49	t1	1	0	0	0
j49	t3	0	1	0	0
j49	t4	0	1	1	0
j49	t5	0	1	1	0
j49	t6	0	1	1	0
j49	t15	0	0	1	0
j49	t16	0	0	1	0
j49	t17	0	0	1	0
j49	t53	0	0	0	1
j50	t13	1	0	0	0
j50	t29	0	1	0	0
j50	t34	0	0	1	0
j50	t37	0	0	0	1
j51	t29	0	0	1	0
j51	t37	0	0	0	1
j52	t9	1	0	0	0
j52	t12	0	1	0	0
j52	t13	0	1	0	0
j52	t14	0	1	0	0
j52	t16	0	0	1	0
j52	t17	0	0	1	0
j52	t60	0	0	0	1
j53	t30	1	0	0	0
j53	t31	0	1	0	0
j53	t33	0	0	1	0
j53	t37	0	0	0	1
j54	t7	0	1	0	0
j54	t49	0	0	0	1
j55	t2	0	0	1	0
j55	t52	0	0	0	1
j56	t21	1	0	0	0
j56	t22	0	1	0	0
j56	t23	0	0	1	0
j56	t27	0	1	1	0

j56	**t28**	0	1	1	0
j56	**t29**	0	0	1	0
j56	**t60**	0	0	0	1
j57	**t19**	1	0	0	0
j57	**t21**	0	1	0	0
j57	**t24**	0	0	1	0
j57	**t52**	0	0	0	1
j58	**t7**	0	1	0	0
j58	**t23**	0	0	0	1
j59	**t33**	0	0	1	0
j59	**t52**	0	0	0	1
j60	**t33**	1	0	0	0
j60	**t34**	0	1	0	0
j60	**t35**	0	1	0	0
j60	**t36**	0	1	0	0
j60	**t37**	0	1	0	0
j60	**t38**	0	1	0	0
j60	**t39**	0	1	0	0
j60	**t57**	0	0	1	0
j60	**t58**	0	0	1	0
j60	**t59**	0	0	0	1
j61	**t53**	1	0	0	0
j61	**t55**	0	1	0	0
j61	**t56**	0	0	1	0
j61	**t58**	0	0	0	1
j62	**t7**	0	1	0	0
j62	**t9**	0	0	0	1
j63	**t31**	0	0	1	0
j63	**t50**	0	0	0	1
j64	**t22**	1	0	0	0
j64	**t27**	0	1	0	0
j64	**t39**	0	1	0	0
j64	**t42**	0	1	0	0
j64	**t44**	0	0	1	0
j64	**t45**	0	0	1	0
j64	**t48**	0	0	0	1
j65	**t17**	1	0	0	0
j65	**t20**	0	1	0	0
j65	**t34**	0	0	1	0
j65	**t39**	0	0	0	1
j66	**t34**	0	1	0	0
j66	**t49**	0	0	0	1
j67	**t9**	0	0	1	0
j67	**t52**	0	0	0	1
j68	**t7**	1	0	0	0

j68	**t8**	0	1	0	0
j68	**t9**	0	1	0	0
j68	**t10**	0	1	0	0
j68	**t49**	0	0	1	0
j68	**t50**	0	0	1	0
j68	**t51**	0	0	0	1
j69	**t6**	1	0	0	0
j69	**t7**	0	1	0	0
j69	**t9**	0	0	1	0
j69	**t39**	0	0	0	1
j70	**t31**	0	1	0	0
j70	**t38**	0	0	0	1
j71	**t9**	1	0	0	0
j71	**t10**	0	1	0	0
j71	**t11**	0	0	1	0
j71	**t12**	0	0	1	0
j71	**t13**	0	0	1	0
j71	**t14**	0	0	1	0
j71	**t15**	0	0	1	0
j71	**t39**	0	1	0	0
j71	**t44**	0	1	0	0
j71	**t47**	0	1	0	0
j71	**t48**	0	1	0	0
j71	**t49**	0	1	0	0
j71	**t50**	0	0	1	0
j71	**t58**	0	0	0	1
j72	**t1**	1	0	0	0
j72	**t2**	0	1	0	0
j72	**t5**	0	0	1	0
j72	**t48**	0	0	0	1
j73	**t10**	0	1	0	0
j73	**t20**	0	0	0	1
j74	**t9**	0	0	1	0
j74	**t16**	0	0	0	1
j75	**t8**	1	0	0	0
j75	**t9**	0	1	0	0
j75	**t10**	0	1	0	0
j75	**t11**	0	1	0	0
j75	**t48**	0	0	1	0
j75	**t49**	0	0	1	0
j75	**t50**	0	0	0	1
j76	**t35**	1	0	0	0
j76	**t37**	0	1	0	0
j76	**t45**	0	0	1	0
j76	**t55**	0	0	0	1

j77	t29	0	1	0	0
j77	t56	0	0	0	1
j78	t6	0	0	1	0
j78	t19	0	0	0	1
j79	t5	1	0	0	0
j79	t6	0	1	0	0
j79	t7	0	1	0	0
j79	t8	0	1	0	0
j79	t9	0	1	1	0
j79	t10	0	0	1	0
j79	t11	0	0	1	0
j79	t12	0	0	1	0
j79	t13	0	0	1	0
j79	t14	0	0	1	0
j79	t53	0	0	0	1
j80	t24	1	0	0	0
j80	t35	0	1	0	0
j80	t56	0	0	1	0
j80	t59	0	0	0	1
j81	t5	0	0	1	0
j81	t30	0	0	0	1
j82	t17	1	0	0	0
j82	t30	0	1	0	0
j82	t37	0	0	1	0
j82	t44	0	1	0	0
j82	t45	0	1	0	0
j82	t58	0	0	1	0
j82	t59	0	0	0	1
j83	t10	1	0	0	0
j83	t14	0	1	0	0
j83	t23	0	0	1	0
j83	t54	0	0	0	1
j84	t6	0	1	0	0
j84	t9	0	0	0	1
j85	t5	0	0	1	0
j85	t9	0	0	0	1
j86	t5	1	0	0	0
j86	t6	0	1	0	0
j86	t7	0	1	0	0
j86	t8	0	1	1	0
j86	t9	0	0	1	0
j86	t10	0	0	1	0
j86	t11	0	0	1	0
j86	t60	0	0	0	1
j87	t9	1	0	0	0

j87	t14	0	1	0	0
j87	t15	0	0	1	0
j87	t45	0	0	0	1
j88	t7	0	1	0	0
j88	t8	0	0	0	1
j89	t16	0	0	1	0
j89	t18	0	0	0	1
j90	t43	1	0	0	0
j90	t44	0	1	0	0
j90	t45	0	1	0	0
j90	t46	0	1	0	0
j90	t47	0	1	0	0
j90	t48	0	1	0	0
j90	t49	0	1	0	0
j90	t57	0	0	1	0
j90	t58	0	0	1	1
j90	t59	0	0	0	1
j91	t4	1	0	0	0
j91	t5	0	1	0	0
j91	t8	0	0	1	0
j91	t9	0	0	0	1
j91	t12	0	1	0	0
j91	t13	0	1	0	0
j91	t33	0	1	0	0
j91	t34	0	1	0	0
j91	t36	0	1	0	0
j91	t50	0	0	1	0
j91	t51	0	0	1	0
j91	t52	0	0	1	0
j91	t53	0	0	1	0
j91	t54	0	0	1	0
j91	t58	0	0	0	1
j92	t57	1	0	0	0
j92	t58	0	1	0	0
j92	t59	0	0	1	0
j92	t60	0	0	0	1
j93	t19	0	1	0	0
j93	t49	0	0	0	1
j94	t24	0	0	1	0
j94	t25	0	0	0	1
j95	t45	1	0	0	0
j95	t46	0	1	0	0
j95	t47	0	1	0	0
j95	t48	0	1	1	0
j95	t49	0	0	1	0

j95	**t50**	0	0	0	1
j96	**t32**	1	0	0	0
j96	**t39**	0	1	0	0
j96	**t54**	0	0	1	0
j96	**t55**	0	0	0	1
j97	**t7**	0	1	0	0
j97	**t52**	0	0	0	1
j98	**t23**	0	0	1	0
j98	**t25**	0	0	0	1
j99	**t52**	1	0	0	0
j99	**t53**	0	1	0	0
j99	**t54**	0	1	1	0
j99	**t55**	0	1	1	0
j99	**t56**	0	1	1	1
j99	**t57**	0	0	1	0
j99	**t58**	0	0	1	0
j99	**t59**	0	0	1	0
j99	**t60**	0	0	0	1
j100	**t31**	1	0	0	0
j100	**t38**	0	1	0	0
j100	**t53**	0	0	1	0
j100	**t57**	0	0	0	1
j101	**t2**	0	0	1	0
j101	**t14**	0	0	0	1
j102	**t54**	1	0	0	0
j102	**t55**	0	1	0	0
j102	**t56**	0	1	0	0
j102	**t57**	0	1	1	0
j102	**t58**	0	0	1	1
j102	**t59**	0	0	0	1
j103	**t24**	1	0	0	0
j103	**t33**	0	1	0	0
j103	**t46**	0	0	1	0
j103	**t59**	0	0	0	1
j104	**t6**	0	1	0	0
j104	**t29**	0	0	0	1
j105	**t24**	0	0	1	0
j105	**t52**	0	0	0	1
j106	**t53**	1	0	0	0
j106	**t54**	0	1	0	0
j106	**t55**	0	1	1	0
j106	**t56**	0	1	1	0
j106	**t57**	0	0	1	0
j106	**t58**	0	0	1	1
j106	**t59**	0	0	0	1

j107	**t12**	1	0	0	0
j107	**t15**	0	1	0	0
j107	**t19**	0	0	1	0
j107	**t23**	0	0	0	1
j108	**t19**	0	1	0	0
j108	**t21**	0	0	0	1
j109	**t2**	0	0	1	0
j109	**t9**	0	0	0	1
j110	**t31**	1	0	0	0
j110	**t32**	0	1	0	0
j110	**t33**	0	1	0	0
j110	**t34**	0	0	1	0

Table 2- Optimal Schedule Output

Job #	**Completion Time**	**Due Dates**
j1	52	60
j2	39	40
j3	53	60
j4	18	60
j5	37	40
j6	60	60
j7	19	60
j8	36	50
j9	25	60
j10	48	65
j11	45	65
j12	21	40
j13	19	65
j14	22	40
j15	53	60
j16	57	60
j17	20	65
j18	57	67
j19	36	60
j20	12	40
j21	36	40
j22	36	40
j23	19	40
j24	49	60
j25	49	50
j26	26	40
j27	36	40
j28	28	65
j29	40	40

j30	53	60
j31	36	40
j32	53	65
j33	36	69
j34	38	65
j35	59	65
j36	56	60
j37	53	69
j38	28	45
j39	52	65
j40	60	60
j41	59	60
j42	39	40
j43	29	40
j44	20	60
j45	60	60
j46	25	25
j47	21	29
j48	25	65
j49	53	65
j50	37	60
j51	38	50
j52	60	65
j53	37	69
j54	50	55
j55	52	65
j56	60	60
j57	52	69
j58	23	60
j59	52	65
j60	59	60
j61	58	65
j62	9	69
j63	50	50
j64	48	55
j65	39	50
j66	49	50
j67	52	55
j68	51	67
j69	39	50
j70	38	50
j71	58	60
j72	48	50
j73	20	60
j74	16	60

j75	50	50
j76	55	55
j77	56	59
j78	19	65
j79	53	55
j80	59	60
j81	30	60
j82	59	65
j83	54	69
j84	9	65
j85	9	65
j86	60	60
j87	45	69
j88	8	65
j89	18	65
j90	59	60
j91	58	60
j92	60	60
j93	49	60
j94	25	60
j95	50	50
j96	55	55
j97	52	59
j98	25	65
j99	60	65
j100	57	60
j101	14	60
j102	59	65
j103	59	69
j104	29	65
j105	52	65
j106	59	60
j107	23	69
j108	21	65
j109	9	65
j110	35	35

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	12	3	0	0
t2	8	4	6	0
t3	9	5	2	0
t4	10	7	2	0

t5	10	6	7	0
t6	10	12	3	0
t7	8	12	2	0
t8	10	5	11	1
t9	11	7	10	5
t10	2	9	3	0
t11	2	2	5	0
t12	3	3	5	1
t13	3	3	4	0
t14	0	5	10	1
t15	0	2	5	0
t16	2	0	5	1
t17	8	1	2	0
t18	0	0	0	2
t19	10	8	2	4
t20	3	4	2	3
t21	12	2	5	3
t22	5	4	0	1
t23	0	1	6	2
t24	5	5	10	0
t25	2	1	0	5
t26	0	1	0	1
t27	0	4	2	2
t28	10	1	3	1
t29	3	6	3	2
t30	3	3	2	1
t31	7	7	3	0
t32	3	3	3	0
t33	5	7	9	0
t34	0	7	11	0
t35	3	4	1	1
t36	0	4	0	7
t37	5	3	4	5
t38	0	4	1	2
t39	0	6	0	4
t40	0	1	2	1
t41	0	1	3	0
t42	0	2	4	0
t43	5	2	1	0
t44	0	7	5	0
t45	3	3	7	3
t46	0	5	4	1
t47	0	8	3	0
t48	0	3	11	2
t49	0	4	7	7

t50	0	0	6	3
t51	0	0	6	1
t52	5	0	2	8
t53	7	2	4	7
t54	3	3	7	1
t55	0	5	6	2
t56	0	3	6	3
t57	3	1	10	3
t58	0	2	8	8
t59	0	0	3	8
t60	0	0	0	8

Table 4- Capacity Level for Each Stage Output

APPENDIX-5

			Process Times				Setup Times			
Pr. Orders	Release Dates	Due Dates	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
j1	0	60	1	6	8	4	4	0	1	0
j2	0	40	1	3	2	1	2	0	1	0
j3	0	60	1	1	1	1	4	0	1	0
j4	0	60	0	1	0	1	0	0	0	0
j5	0	40	0	0	1	1	0	0	1	0
j6	0	60	1	3	2	1	2	0	1	0
j7	0	60	1	1	1	1	2	0	1	0
j8	0	50	0	1	0	1	0	0	0	0
j9	0	60	0	0	1	1	0	0	1	0
j10	0	65	1	2	1	0	2	0	1	0
j11	0	65	1	1	1	1	2	0	1	0
j12	0	40	0	1	0	1	0	0	0	0
j13	0	65	0	0	1	1	0	0	1	0
j14	0	40	1	3	2	1	4	0	1	0
j15	0	60	1	1	1	1	4	0	1	0
j16	0	60	0	1	0	1	0	0	0	0
j17	0	65	0	0	1	1	0	0	1	0
j18	0	67	1	3	2	1	2	1	1	0
j19	0	60	1	1	1	1	1	1	1	0
j20	0	40	0	1	0	1	0	0	0	0
j21	0	40	1	6	6	1	4	0	1	0
j22	0	40	1	1	1	1	1	1	1	0
j23	0	40	0	1	0	1	0	0	0	0
j24	0	60	0	0	1	1	0	0	1	0
j25	0	50	1	3	2	1	2	1	1	0
j26	0	40	1	1	1	1	1	1	1	0
j27	0	40	0	1	0	1	0	0	0	0
j28	0	65	0	0	1	1	0	0	1	0
j29	0	40	1	4	6	1	4	1	1	0
j30	0	60	1	1	1	1	1	1	1	0
j31	0	40	0	0	1	1	0	0	1	0
j32	0	65	1	3	2	1	2	1	1	0
j33	0	69	1	1	1	1	1	1	1	0
j34	0	65	0	1	0	1	0	0	0	0
j35	0	65	0	0	1	1	0	0	1	0
j36	0	60	1	3	4	1	4	1	1	0
j37	0	69	1	1	1	1	1	1	1	0
j38	0	45	0	1	0	1	0	0	0	1
j39	0	65	0	0	1	1	0	0	1	0
j40	0	60	1	6	2	1	4	1	1	0
j41	0	60	1	6	6	1	4	0	1	1
j42	0	40	1	1	1	1	1	1	1	0

j43	0	40	0	1	0	1	0	0	0	0
j44	0	60	0	0	1	1	0	0	1	0
j45	0	60	1	3	2	1	2	1	1	0
j46	0	25	1	1	1	1	2	1	1	0
j47	0	29	0	1	0	1	0	0	0	0
j48	0	65	0	0	1	1	0	0	1	0
j49	0	65	1	4	6	1	4	1	1	0
j50	0	60	1	1	1	1	2	1	1	0
j51	0	50	0	0	1	1	0	0	1	1
j52	0	65	1	3	2	1	2	1	1	0
j53	0	69	1	1	1	1	2	1	1	0
j54	0	55	0	1	0	1	0	0	0	1
j55	0	65	0	0	1	1	0	0	1	0
j56	0	60	1	3	4	1	4	1	1	0
j57	0	69	1	1	1	1	1	1	1	0
j58	0	60	0	1	0	1	0	0	0	0
j59	0	65	0	0	1	1	0	0	1	0
j60	0	60	1	6	2	1	4	1	1	0
j61	5	65	1	1	1	1	1	0	1	0
j62	4	69	0	1	0	1	0	0	0	0
j63	0	50	0	0	1	1	0	0	1	0
j64	0	55	1	3	2	1	4	0	1	0
j65	0	50	1	1	1	1	4	0	1	0
j66	2	50	0	1	0	1	0	0	0	0
j67	1	55	0	0	1	1	0	0	1	0
j68	5	67	1	3	2	1	2	1	1	0
j69	6	50	1	1	1	1	1	1	1	0
j70	7	50	0	1	0	1	0	0	0	0
j71	8	60	1	6	6	1	4	0	1	0
j72	0	50	1	1	1	1	1	1	1	0
j73	1	60	0	1	0	1	0	0	0	0
j74	3	60	0	0	1	1	0	0	1	0
j75	8	50	1	3	2	1	2	1	1	0
j76	10	55	1	1	1	1	2	1	1	0
j77	4	59	0	1	0	1	0	0	0	0
j78	0	65	0	0	1	1	0	0	1	0
j79	5	55	1	4	6	1	4	1	1	0
j80	4	60	1	1	1	1	1	1	1	0
j81	0	60	0	0	1	1	0	0	1	0
j82	0	65	1	3	2	1	2	1	1	0
j83	0	69	1	1	1	1	1	1	1	0
j84	0	65	0	1	0	1	0	0	0	0
j85	1	65	0	0	1	1	0	0	1	0
j86	5	60	1	3	4	1	4	1	1	0
j87	6	69	1	1	1	1	2	1	1	0
j88	7	65	0	1	0	1	0	0	0	0
j89	8	65	0	0	1	1	0	0	1	0
j90	0	60	1	6	2	2	4	1	1	0

j91	1	60	1	6	6	2	4	0	1	0
j92	3	60	1	1	1	1	2	1	1	0
j93	8	60	0	1	0	1	0	0	0	0
j94	10	60	0	0	1	1	0	0	1	0
j95	4	50	1	3	2	1	2	1	1	0
j96	0	55	1	1	1	1	2	1	1	0
j97	5	59	0	1	0	1	0	0	0	0
j98	4	65	0	0	1	1	0	0	1	0
j99	0	65	1	4	6	2	4	1	1	0
j100	0	60	1	1	1	1	1	1	1	0
j101	0	60	0	0	1	1	0	0	1	0
j102	0	65	1	3	2	2	2	1	1	0
j103	1	69	1	1	1	1	2	1	1	0
j104	5	65	0	1	0	1	0	0	0	0
j105	6	65	0	0	1	1	0	0	1	0
j106	7	60	1	3	4	2	4	1	1	0
j107	8	69	1	1	1	1	2	1	1	0
j108	0	65	0	1	0	1	0	0	0	0
j109	1	65	0	0	1	1	0	0	1	0
j110	3	35	1	2	1	1	4	1	1	0
j111	0	50	1	6	6	1	0	0	0	0
j112	0	50	1	1	1	1	4	0	1	0
j113	0	60	0	1	0	1	0	1	0	0
j114	0	50	0	0	1	1	0	0	0	0
j115	0	60	1	3	2	1	0	0	1	0
j116	0	60	1	1	1	1	2	1	1	0
j117	0	50	0	1	0	1	0	1	0	0
j118	0	55	0	0	1	1	0	0	0	0
j119	0	59	1	4	6	1	0	0	1	0
j120	0	65	1	1	1	1	4	1	1	0
j121	0	55	0	0	1	1	0	0	1	0
j122	0	60	1	3	2	1	0	0	1	0
j123	0	60	1	1	1	1	2	1	1	0
j124	0	65	0	1	0	1	0	1	0	0
j125	0	69	0	0	1	1	0	0	0	0
j126	0	65	1	3	4	1	0	0	1	0
j127	0	65	1	1	1	1	4	1	1	0
j128	0	60	0	1	0	1	0	1	0	0
j129	0	69	0	0	1	1	0	0	0	1
j130	0	50	1	6	2	1	0	0	1	0
j131	0	50	1	6	6	1	0	0	1	0
j132	0	60	1	1	1	1	4	1	1	0
j133	0	50	0	1	0	1	0	1	0	0
j134	0	60	0	0	1	1	0	0	0	1
j135	0	60	1	3	2	1	0	0	1	0
j136	0	50	1	1	1	1	4	1	1	0
j137	0	55	0	1	0	1	4	0	1	1
j138	0	59	0	0	1	1	0	1	0	0

j139	0	65	1	4	6	1	0	0	0	0
j140	0	55	1	1	1	1	0	0	1	0
j141	0	60	0	0	1	1	2	1	1	0
j142	0	60	1	3	2	1	0	1	0	0
j143	0	65	1	1	1	1	0	0	0	0
j144	0	69	0	1	0	1	0	0	1	0
j145	0	65	0	0	1	1	4	1	1	0
j146	0	65	1	3	4	1	0	0	1	0
j147	5	60	1	1	1	1	0	0	1	1
j148	4	69	0	1	0	1	2	1	1	0
j149	0	60	0	0	1	1	0	1	0	0
j150	0	60	1	6	2	1	0	0	0	1
j151	0	55	1	1	1	1	0	0	1	0
j152	5	59	0	1	0	1	4	1	1	0

Table 1- Process times and Setup times of 8th Numerical Example

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t11**	1	0	0	0
j1	**t13**	0	1	0	0
j1	**t28**	0	0	1	0
j1	**t29**	0	0	1	0
j1	**t30**	0	0	1	0
j1	**t31**	0	0	1	0
j1	**t32**	0	1	1	1
j1	**t33**	0	0	1	0
j1	**t34**	0	0	1	1
j1	**t36**	0	0	0	1
j1	**t41**	0	1	0	0
j1	**t43**	0	1	0	0
j1	**t44**	0	1	0	0
j1	**t45**	0	1	0	0
j1	**t52**	0	0	1	0
j1	**t54**	0	0	0	1
j2	**t6**	1	0	0	0
j2	**t22**	0	1	0	0
j2	**t27**	0	1	0	0
j2	**t28**	0	1	0	0
j2	**t32**	0	0	1	0
j2	**t33**	0	0	1	0
j2	**t36**	0	0	0	1
j3	**t34**	1	0	0	0
j3	**t35**	0	1	0	0
j3	**t38**	0	0	1	0
j3	**t40**	0	0	0	1

j4	**t1**	0	1	0	0
j4	**t18**	0	0	0	1
j5	**t10**	0	0	1	0
j5	**t17**	0	0	0	1
j6	**t12**	1	0	0	0
j6	**t23**	0	1	0	0
j6	**t34**	0	0	1	0
j6	**t40**	0	1	0	0
j6	**t41**	0	1	0	0
j6	**t51**	0	0	1	0
j6	**t53**	0	0	0	1
j7	**t15**	1	0	0	0
j7	**t16**	0	1	0	0
j7	**t17**	0	0	1	0
j7	**t18**	0	0	0	1
j8	**t35**	0	1	0	0
j8	**t36**	0	0	0	1
j9	**t22**	0	0	1	0
j9	**t23**	0	0	0	1
j10	**t38**	1	0	0	0
j10	**t45**	0	1	0	0
j10	**t47**	0	1	0	0
j10	**t52**	0	0	1	0
j11	**t24**	1	0	0	0
j11	**t29**	0	1	0	0
j11	**t32**	0	0	1	0
j11	**t33**	0	0	0	1
j12	**t1**	0	1	0	0
j12	**t23**	0	0	0	1
j13	**t17**	0	0	1	0
j13	**t22**	0	0	0	1
j14	**t16**	1	0	0	0
j14	**t21**	0	1	0	0
j14	**t22**	0	1	0	0
j14	**t23**	0	1	0	0
j14	**t26**	0	0	1	0
j14	**t27**	0	0	1	0
j14	**t28**	0	0	0	1
j15	**t11**	1	0	0	0
j15	**t20**	0	1	0	0
j15	**t22**	0	0	1	0
j15	**t27**	0	0	0	1
j16	**t3**	0	1	0	0
j16	**t14**	0	0	0	1
j17	**t17**	0	0	1	0

j17	**t32**	0	0	0	1
j18	**t19**	1	0	0	0
j18	**t27**	0	1	0	0
j18	**t28**	0	1	0	0
j18	**t29**	0	1	0	0
j18	**t34**	0	0	1	0
j18	**t35**	0	0	1	0
j18	**t59**	0	0	0	1
j19	**t31**	1	0	0	0
j19	**t32**	0	1	0	0
j19	**t33**	0	0	1	0
j19	**t34**	0	0	0	1
j20	**t25**	0	1	0	0
j20	**t27**	0	0	0	1
j21	**t8**	1	0	0	0
j21	**t15**	0	1	0	0
j21	**t17**	0	1	0	0
j21	**t19**	0	1	0	0
j21	**t22**	0	1	0	0
j21	**t26**	0	0	1	0
j21	**t27**	0	1	1	0
j21	**t28**	0	0	1	0
j21	**t29**	0	0	1	0
j21	**t30**	0	1	1	0
j21	**t31**	0	0	1	0
j21	**t32**	0	0	0	1
j22	**t9**	1	0	0	0
j22	**t15**	0	1	0	0
j22	**t25**	0	0	1	0
j22	**t33**	0	0	0	1
j23	**t14**	0	1	0	0
j23	**t33**	0	0	0	1
j24	**t57**	0	0	1	0
j24	**t59**	0	0	0	1
j25	**t3**	1	0	0	0
j25	**t4**	0	1	0	0
j25	**t5**	0	1	1	0
j25	**t6**	0	1	0	0
j25	**t29**	0	0	1	0
j25	**t30**	0	0	0	1
j26	**t25**	1	0	0	0
j26	**t26**	0	1	0	0
j26	**t28**	0	0	1	0
j26	**t32**	0	0	0	1
j27	**t7**	0	1	0	0

j27	**t17**	0	0	0	1
j28	**t22**	0	0	1	0
j28	**t54**	0	0	0	1
j29	**t2**	1	0	0	0
j29	**t3**	0	1	0	0
j29	**t4**	0	1	0	0
j29	**t5**	0	1	0	0
j29	**t6**	0	1	0	0
j29	**t9**	0	0	1	0
j29	**t10**	0	0	1	0
j29	**t11**	0	0	1	0
j29	**t12**	0	0	1	0
j29	**t13**	0	0	1	0
j29	**t14**	0	0	1	0
j29	**t16**	0	0	0	1
j30	**t16**	1	0	0	0
j30	**t18**	0	1	0	0
j30	**t56**	0	0	1	0
j30	**t57**	0	0	0	1
j31	**t21**	0	0	1	0
j31	**t28**	0	0	0	1
j32	**t33**	1	0	0	0
j32	**t35**	0	1	0	0
j32	**t36**	0	1	0	0
j32	**t37**	0	1	0	0
j32	**t46**	0	0	1	0
j32	**t47**	0	0	1	0
j32	**t56**	0	0	0	1
j33	**t27**	1	0	0	0
j33	**t28**	0	1	0	0
j33	**t31**	0	0	1	0
j33	**t41**	0	0	0	1
j34	**t40**	0	1	0	0
j34	**t45**	0	0	0	1
j35	**t25**	0	0	1	0
j35	**t27**	0	0	0	1
j36	**t35**	1	0	0	0
j36	**t47**	0	1	0	0
j36	**t48**	0	1	0	0
j36	**t49**	0	1	0	0
j36	**t55**	0	0	1	0
j36	**t56**	0	0	1	0
j36	**t57**	0	0	1	0
j36	**t58**	0	0	1	0
j36	**t60**	0	0	0	1

j37	**t41**	1	0	0	0
j37	**t43**	0	1	0	0
j37	**t48**	0	0	1	0
j37	**t57**	0	0	0	1
j38	**t7**	0	1	0	0
j38	**t9**	0	0	0	1
j39	**t36**	0	0	1	0
j39	**t44**	0	0	0	1
j40	**t5**	1	0	0	0
j40	**t38**	0	1	0	0
j40	**t39**	0	1	0	0
j40	**t47**	0	1	0	0
j40	**t48**	0	1	1	0
j40	**t49**	0	1	0	0
j40	**t50**	0	1	0	0
j40	**t55**	0	0	1	0
j40	**t59**	0	0	0	1
j41	**t8**	1	0	0	0
j41	**t9**	0	1	0	0
j41	**t10**	0	1	1	0
j41	**t11**	0	1	1	0
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j152	**t53**	0	1	0	0
j152	**t57**	0	0	0	1

Table 2- Optimal Schedule Output

Job #	**Completion Time**	**Due Dates**
j1	54	60
j2	36	40
j3	40	60
j4	18	60
j5	17	40
j6	53	60
j7	18	60
j8	36	50
j9	23	60
j10	53	65
j11	33	65
j12	23	40
j13	22	65
j14	28	40
j15	27	60
j16	14	60
j17	32	65
j18	59	67
j19	34	60
j20	27	40
j21	32	40
j22	33	40
j23	33	40
j24	59	60
j25	30	50

j26	32	40
j27	17	40
j28	54	65
j29	16	40
j30	57	60
j31	28	40
j32	56	65
j33	41	69
j34	45	65
j35	27	65
j36	60	60
j37	57	69
j38	10	45
j39	44	65
j40	59	60
j41	19	60
j42	34	40
j43	23	40
j44	49	60
j45	60	60
j46	12	25
j47	17	29
j48	32	65
j49	48	65
j50	36	60
j51	18	50
j52	59	65
j53	34	69
j54	24	55
j55	12	65
j56	60	60
j57	28	69
j58	17	60
j59	38	65
j60	59	60
j61	42	65
j62	18	69
j63	44	50
j64	42	55
j65	44	50
j66	31	50
j67	30	55
j68	58	67
j69	33	50
j70	36	50

j71	25	60
j72	36	50
j73	53	60
j74	42	60
j75	33	50
j76	44	55
j77	25	59
j78	22	65
j79	49	55
j80	54	60
j81	32	60
j82	60	65
j83	36	69
j84	58	65
j85	33	65
j86	54	60
j87	54	69
j88	56	65
j89	53	65
j90	53	60
j91	43	60
j92	18	60
j93	17	60
j94	17	60
j95	50	50
j96	55	55
j97	42	59
j98	16	65
j99	32	65
j100	27	60
j101	54	60
j102	34	65
j103	60	69
j104	42	65
j105	55	65
j106	57	60
j107	57	69
j108	23	65
j109	60	65
j110	35	35
j111	48	50
j112	50	50
j113	60	60
j114	33	50

j115	51	60
j116	59	60
j117	34	50
j118	10	55
j119	12	59
j120	19	65
j121	30	55
j122	58	60
j123	50	60
j124	32	65
j125	21	69
j126	60	65
j127	50	65
j128	18	60
j129	43	69
j130	46	50
j131	45	50
j132	41	60
j133	33	50
j134	54	60
j135	58	60
j136	38	50
j137	23	55
j138	34	59
j139	59	65
j140	55	55
j141	58	60
j142	59	60
j143	39	65
j144	54	69
j145	13	65
j146	58	65
j147	60	60
j148	57	69
j149	42	60
j150	57	60
j151	31	55
j152	57	59

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	12	3	0	0
t2	11	2	0	0

t3	8	9	0	0
t4	9	11	2	0
t5	11	9	2	0
t6	9	7	2	0
t7	11	5	4	0
t8	10	3	5	0
t9	12	3	4	2
t10	12	12	11	1
t11	12	5	11	0
t12	6	9	8	5
t13	8	5	8	0
t14	3	7	7	1
t15	3	7	8	0
t16	8	5	6	2
t17	3	5	9	8
t18	3	6	2	8
t19	3	6	7	1
t20	0	10	6	0
t21	3	2	3	1
t22	0	5	10	2
t23	0	5	2	7
t24	12	0	2	1
t25	6	5	9	2
t26	10	4	4	0
t27	2	7	6	5
t28	0	11	11	3
t29	1	5	6	0
t30	3	4	6	3
t31	11	10	7	2
t32	0	4	11	8
t33	10	4	11	8
t34	5	4	7	7
t35	10	12	4	1
t36	0	5	11	7
t37	0	6	3	0
t38	8	9	10	2
t39	3	5	7	1
t40	0	8	1	3
t41	7	7	11	1
t42	0	1	6	8
t43	3	5	5	1
t44	5	3	2	4
t45	5	4	1	2
t46	3	0	2	1
t47	0	9	5	0

t48	0	3	4	2
t49	0	9	3	2
t50	0	7	7	4
t51	1	5	11	2
t52	0	2	11	0
t53	0	1	11	4
t54	1	0	4	8
t55	0	2	6	3
t56	8	2	6	3
t57	0	6	9	7
t58	0	0	10	8
t59	0	0	1	8
t60	0	0	0	8

Table 4- Capacity Level for Each Stage Output

APPENDIX-6

			Process Times				Setup Times			
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	0	60	1	6	8	4	4	0	1	0
j2	0	40	1	3	2	1	2	0	1	0
j3	0	60	1	1	1	1	4	0	1	0
j4	0	60	0	1	0	1	0	0	0	0
j5	0	40	0	0	1	1	0	0	1	0
j6	0	60	1	3	2	1	2	0	1	0
j7	0	60	1	1	1	1	2	0	1	0
j8	0	50	0	1	0	1	0	0	0	0
j9	0	60	0	0	1	1	0	0	1	0
j10	0	65	1	2	1	0	2	0	1	0
j11	0	65	1	1	1	1	2	0	1	0
j12	0	40	0	1	0	1	0	0	0	0
j13	0	65	0	0	1	1	0	0	1	0
j14	0	40	1	3	2	1	4	0	1	0
j15	0	60	1	1	1	1	4	0	1	0
j16	0	60	0	1	0	1	0	0	0	0
j17	0	65	0	0	1	1	0	0	1	0
j18	0	67	1	3	2	1	2	1	1	0
j19	0	60	1	1	1	1	1	1	1	0
j20	0	40	0	1	0	1	0	0	0	0
j21	0	40	1	6	6	1	4	0	1	0
j22	0	40	1	1	1	1	1	1	1	0
j23	0	40	0	1	0	1	0	0	0	0
j24	0	60	0	0	1	1	0	0	1	0
j25	0	50	1	3	2	1	2	1	1	0
j26	0	40	1	1	1	1	1	1	1	0
j27	0	40	0	1	0	1	0	0	0	0
j28	0	65	0	0	1	1	0	0	1	0
j29	0	40	1	4	6	1	4	1	1	0
j30	0	60	1	1	1	1	1	1	1	0
j31	0	40	0	0	1	1	0	0	1	0
j32	0	65	1	3	2	1	2	1	1	0
j33	0	69	1	1	1	1	1	1	1	0
j34	0	65	0	1	0	1	0	0	0	0
j35	0	65	0	0	1	1	0	0	1	0
j36	0	60	1	3	4	1	4	1	1	0
j37	0	69	1	1	1	1	1	1	1	0
j38	0	45	0	1	0	1	0	0	0	1
j39	0	65	0	0	1	1	0	0	1	0
j40	0	60	1	6	2	1	4	1	1	0
j41	0	60	1	6	6	1	4	0	1	1
j42	0	40	1	1	1	1	1	1	1	0

j43	0	40	0	1	0	1	0	0	0	0
j44	0	60	0	0	1	1	0	0	1	0
j45	0	60	1	3	2	1	2	1	1	0
j46	0	25	1	1	1	1	2	1	1	0
j47	0	29	0	1	0	1	0	0	0	0
j48	0	65	0	0	1	1	0	0	1	0
j49	0	65	1	4	6	1	4	1	1	0
j50	0	60	1	1	1	1	2	1	1	0
j51	0	50	0	0	1	1	0	0	1	1
j52	0	65	1	3	2	1	2	1	1	0
j53	0	69	1	1	1	1	2	1	1	0
j54	0	55	0	1	0	1	0	0	0	1
j55	0	65	0	0	1	1	0	0	1	0
j56	0	60	1	3	4	1	4	1	1	0
j57	0	69	1	1	1	1	1	1	1	0
j58	0	60	0	1	0	1	0	0	0	0
j59	0	65	0	0	1	1	0	0	1	0
j60	0	60	1	6	2	1	4	1	1	0
j61	5	65	1	1	1	1	1	0	1	0
j62	4	69	0	1	0	1	0	0	0	0
j63	0	50	0	0	1	1	0	0	1	0
j64	0	55	1	3	2	1	4	0	1	0
j65	0	50	1	1	1	1	4	0	1	0
j66	2	50	0	1	0	1	0	0	0	0
j67	1	55	0	0	1	1	0	0	1	0
j68	5	67	1	3	2	1	2	1	1	0
j69	6	50	1	1	1	1	1	1	1	0
j70	7	50	0	1	0	1	0	0	0	0
j71	8	60	1	6	6	1	4	0	1	0
j72	0	50	1	1	1	1	1	1	1	0
j73	1	60	0	1	0	1	0	0	0	0
j74	3	60	0	0	1	1	0	0	1	0
j75	8	50	1	3	2	1	2	1	1	0
j76	10	55	1	1	1	1	2	1	1	0
j77	4	59	0	1	0	1	0	0	0	0
j78	0	65	0	0	1	1	0	0	1	0
j79	5	55	1	4	6	1	4	1	1	0
j80	4	60	1	1	1	1	1	1	1	0
j81	0	60	0	0	1	1	0	0	1	0
j82	0	65	1	3	2	1	2	1	1	0
j83	0	69	1	1	1	1	1	1	1	0
j84	0	65	0	1	0	1	0	0	0	0
j85	1	65	0	0	1	1	0	0	1	0
j86	5	60	1	3	4	1	4	1	1	0
j87	6	69	1	1	1	1	2	1	1	0
j88	7	65	0	1	0	1	0	0	0	0
j89	8	65	0	0	1	1	0	0	1	0
j90	0	60	1	6	2	2	4	1	1	0

j91	1	60	1	6	6	2	4	0	1	0
j92	3	60	1	1	1	1	2	1	1	0
j93	8	60	0	1	0	1	0	0	0	0
j94	10	60	0	0	1	1	0	0	1	0
j95	4	50	1	3	2	1	2	1	1	0
j96	0	55	1	1	1	1	2	1	1	0
j97	5	59	0	1	0	1	0	0	0	0
j98	4	65	0	0	1	1	0	0	1	0
j99	0	65	1	4	6	2	4	1	1	0
j100	0	60	1	1	1	1	1	1	1	0
j101	0	60	0	0	1	1	0	0	1	0
j102	0	65	1	3	2	2	2	1	1	0
j103	1	69	1	1	1	1	2	1	1	0
j104	5	65	0	1	0	1	0	0	0	0
j105	6	65	0	0	1	1	0	0	1	0
j106	7	60	1	3	4	2	4	1	1	0
j107	8	69	1	1	1	1	2	1	1	0
j108	0	65	0	1	0	1	0	0	0	0
j109	1	65	0	0	1	1	0	0	1	0
j110	3	35	1	2	1	1	4	1	1	0
j111	0	50	1	6	6	1	0	0	0	0
j112	0	50	1	1	1	1	4	0	1	0
j113	0	60	0	1	0	1	0	1	0	0
j114	0	50	0	0	1	1	0	0	0	0
j115	0	60	1	3	2	1	0	0	1	0
j116	0	60	1	1	1	1	2	1	1	0
j117	0	50	0	1	0	1	0	1	0	0
j118	0	55	0	0	1	1	0	0	0	0
j119	0	59	1	4	6	1	0	0	1	0
j120	0	65	1	1	1	1	4	1	1	0
j121	0	55	0	0	1	1	0	0	1	0
j122	0	60	1	3	2	1	0	0	1	0
j123	0	60	1	1	1	1	2	1	1	0
j124	0	65	0	1	0	1	0	1	0	0
j125	0	69	0	0	1	1	0	0	0	0
j126	0	65	1	3	4	1	0	0	1	0
j127	0	65	1	1	1	1	4	1	1	0
j128	0	60	0	1	0	1	0	1	0	0
j129	0	69	0	0	1	1	0	0	0	1
j130	0	50	1	6	2	1	0	0	1	0
j131	0	50	1	6	6	1	4	1	1	0
j132	0	60	1	1	1	1	4	0	1	1
j133	0	50	0	1	0	1	0	1	0	0
j134	0	60	0	0	1	1	0	0	0	0
j135	0	60	1	3	2	1	0	0	1	0
j136	0	50	1	1	1	1	2	1	1	0
j137	0	55	0	1	0	1	0	1	0	0
j138	0	59	0	0	1	1	0	0	0	0

j139	0	65	1	4	6	1	0	0	1	0
j140	0	55	1	1	1	1	4	1	1	0
j141	0	60	0	0	1	1	0	0	1	0
j142	0	60	1	3	2	1	0	0	1	1
j143	0	65	1	1	1	1	2	1	1	0
j144	0	69	0	1	0	1	0	1	0	0
j145	0	65	0	0	1	1	0	0	0	1
j146	0	65	1	3	4	1	0	0	1	0
j147	5	60	1	1	1	1	4	1	1	0
j148	4	69	0	1	0	1	0	1	0	0
j149	0	60	0	0	1	1	0	0	0	0
j150	0	60	1	6	2	1	0	0	1	0
j151	0	55	1	1	1	1	2	1	1	0
j152	5	59	0	1	0	1	0	0	0	0
j153	4	65	0	0	1	1	0	0	1	0
j154	0	65	1	4	6	2	4	1	1	0
j155	0	60	1	1	1	1	1	1	1	0
j156	0	60	0	0	1	1	0	0	1	0
j157	0	65	1	3	2	2	2	1	1	0
j158	1	69	1	1	1	1	2	1	1	0
j159	5	65	0	1	0	1	0	0	0	0
j160	6	65	0	0	1	1	0	0	1	0

Table 1- Process times and Setup times of 9^{fh} Numerical Example

APPENDIX-7

			Process Times				Setup Times			
Pr. Orders	**Release Dates**	**Due Dates**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	0	62	0	9	2	0	0	0	1	0
j2	0	36	0	1	0	0	0	0	0	0
j3	0	24	0	0	0	6	0	0	0	0
j4	0	12	0	1	0	0	0	1	0	0
j5	0	26	0	1	4	0	0	0	0	0
j6	0	34	0	0	5	0	0	0	1	0
j7	0	28	0	0	5	0	0	0	1	0
j8	0	50	0	2	2	0	0	0	2	0
j9	0	52	0	1	1	0	0	0	0	0
j10	0	36	0	1	2	0	0	0	1	0
j11	0	62	0	5	2	1	0	0	2	0
j12	0	62	0	12	8	4	0	0	1	0
j13	0	66	0	3	21	1	0	1	0	0
j14	0	92	0	1	19	0	0	1	0	0
j15	0	26	0	0	1	0	0	0	0	0
j16	0	70	0	9	21	2	0	1	1	0
j17	0	56	0	2	5	0	0	0	0	0
j18	0	80	0	0	59	25	0	0	1	1
j19	0	14	0	0	0	2	0	0	0	0
j20	0	34	0	0	2	2	0	0	1	1
j21	0	64	0	10	6	3	0	0	2	0
j22	0	36	0	0	2	0	0	0	0	0
j23	0	62	0	3	2	1	0	0	1	0
j24	0	120	0	32	8	4	0	1	2	0
j25	0	64	0	0	1	2	0	0	0	1
j26	0	22	0	0	0	6	0	0	0	0
j27	0	84	0	21	20	8	0	5	2	1
j28	0	76	0	4	1	1	0	0	0	0
j29	0	94	0	0	0	2	0	0	0	0
j30	0	52	0	1	1	0	0	0	1	0
j31	0	54	0	10	9	0	0	1	0	0
j32	0	68	0	0	13	8	0	0	1	1
j33	0	50	0	0	8	2	0	0	1	0
j34	0	38	0	0	4	8	0	0	1	1
j35	0	42	0	0	1	1	0	0	1	0
j36	0	6	0	0	0	1	0	0	0	1
j37	0	50	0	3	1	2	0	0	1	0
j38	0	66	0	41	43	0	0	7	2	0
j39	0	76	0	0	1	0	0	0	4	0
j40	0	76	0	0	1	0	0	0	4	0
j41	0	76	0	0	1	0	0	0	4	0
j42	0	36	2	1	0	0	1	0	0	0

j43	0	42	1	3	0	0	1	0	0	0
j44	0	20	0	3	0	0	0	0	0	0
j45	0	20	0	2	0	0	0	0	0	0
j46	0	48	1	1	1	0	1	1	1	0
j47	10	56	0	1	1	1	0	1	1	0
j48	0	20	0	1	0	0	0	0	0	0
j49	0	22	0	1	1	0	0	0	1	0
j50	0	40	0	3	2	1	0	0	1	0
j51	0	38	0	1	2	1	0	1	2	2
j52	0	10	0	0	0	1	0	0	0	1
j53	0	26	0	7	4	0	0	1	1	0
j54	0	40	2	3	0	0	2	1	0	0
j55	0	40	2	3	0	0	2	1	0	0
j56	0	56	0	1	0	0	0	1	0	0
j57	0	34	0	1	1	0	0	1	0	0
j58	0	10	0	0	0	1	0	0	0	1
j59	0	10	0	0	0	1	0	0	0	0
j60	0	20	0	1	0	1	0	0	0	0
j61	0	46	0	7	5	2	0	1	1	1
j62	0	76	4	5	3	0	1	1	1	0
j63	0	20	0	4	3	0	0	1	1	0
j64	0	20	0	4	3	0	0	1	1	0
j65	0	26	0	1	1	0	0	1	1	0
j66	0	20	0	4	3	0	0	1	1	0
j67	0	26	0	7	0	0	0	0	0	0
j68	0	10	0	0	1	3	0	0	1	1
j69	0	10	0	0	0	1	0	0	0	0
j70	0	20	0	0	1	1	0	0	1	1
j71	0	30	0	7	0	0	0	1	0	0
j72	0	42	0	0	15	6	0	0	0	0
j73	0	26	0	5	6	6	0	1	1	0
j74	0	46	0	1	1	0	0	1	1	0
j75	0	26	0	3	1	0	0	1	1	0
j76	0	26	0	1	1	0	0	1	1	0
j77	0	46	0	0	0	1	0	1	1	1
j78	0	66	0	1	1	0	0	1	1	0
j79	0	66	1	1	1	0	1	1	1	0
j80	0	66	1	2	7	1	1	1	1	1
j81	0	28	0	3	2	0	0	0	1	0
j82	0	64	1	2	3	1	1	1	1	0
j83	10	64	1	1	0	0	1	0	0	0
j84	0	66	1	1	1	1	1	1	1	1
j85	0	30	1	1	1	0	1	1	1	0
j86	0	26	0	0	0	1	0	0	0	1
j87	0	56	1	1	1	0	1	1	1	0
j88	0	56	0	1	1	0	0	1	1	0
j89	0	90	1	1	1	1	1	1	1	1
j90	0	46	0	1	3	0	0	1	1	0

j91	0	26	4	2	17	0	1	1	1	0
j92	0	56	0	1	1	1	0	1	0	1
j93	10	66	0	4	0	0	0	1	0	0
j94	0	66	0	5	2	1	0	1	1	0
j95	0	64	0	0	0	2	0	0	0	0
j96	0	144	8	8	15	5	1	1	1	0
j97	0	36	0	1	1	1	0	1	1	0
j98	0	98	0	26	9	9	0	1	0	1
j99	0	86	0	1	1	1	0	1	0	0
j100	0	20	0	3	0	0	0	0	0	0
j101	0	66	2	1	1	0	2	1	0	0
j102	0	36	0	1	2	0	0	1	1	0
j103	10	46	0	2	1	1	0	1	0	1
j104	0	78	0	11	14	3	0	1	0	1
j105	0	10	0	0	2	0	0	0	1	0
j106	0	46	0	2	4	2	0	0	1	0
j107	0	66	2	2	1	1	1	0	1	0
j108	0	76	1	1	1	1	1	0	1	0
j109	0	76	1	2	1	1	1	1	1	0
j110	0	46	0	1	1	1	0	1	1	0
j111	0	46	0	2	1	1	0	1	0	1
j112	0	86	0	1	1	1	0	1	0	1
j113	0	86	0	1	1	1	0	1	0	1
j114	0	90	0	2	1	1	0	1	0	1
j115	0	28	0	1	1	1	0	2	0	0
j116	0	55	0	0	0	5	0	0	0	0
j117	0	60	0	0	1	0	0	0	1	0
j118	0	64	0	0	1	0	0	0	1	0
j119	0	136	0	0	1	0	0	0	1	0
j120	20	160	0	0	1	0	0	0	1	0
j121	30	70	0	2	2	0	0	1	1	0
j122	30	70	0	2	2	0	0	1	1	0
j123	30	70	0	2	2	0	0	1	1	0
j124	30	66	0	0	1	2	0	0	1	1

Table 1- Process times and Setup times of Real-Life Example

OPTIMAL SCHEDULE					
Job#	**Time #**	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
j1	**t4**	0	1	0	0
j1	**t13**	0	1	0	0
j1	**t14**	0	1	0	0
j1	**t16**	0	1	0	0
j1	**t18**	0	1	0	0
j1	**t25**	0	1	0	0
j1	**t27**	0	1	0	0
j1	**t32**	0	1	0	0
j1	**t45**	0	1	0	0

j1	**t47**	0	0	1	0
j1	**t48**	0	0	1	0
j2	**t32**	0	1	0	0
j3	**t10**	0	0	0	1
j3	**t14**	0	0	0	1
j3	**t15**	0	0	0	1
j3	**t19**	0	0	0	1
j3	**t20**	0	0	0	1
j3	**t23**	0	0	0	1
j4	**t10**	0	1	0	0
j5	**t9**	0	1	0	0
j5	**t12**	0	0	1	0
j5	**t14**	0	0	1	0
j5	**t15**	0	0	1	0
j5	**t23**	0	0	1	0
j6	**t22**	0	0	1	0
j6	**t23**	0	0	1	0
j6	**t24**	0	0	1	0
j6	**t25**	0	0	1	0
j6	**t26**	0	0	1	0
j7	**t5**	0	0	1	0
j7	**t6**	0	0	1	0
j7	**t7**	0	0	1	0
j7	**t8**	0	0	1	0
j7	**t9**	0	0	1	0
j8	**t1**	0	1	0	0
j8	**t37**	0	1	0	0
j8	**t43**	0	0	1	0
j8	**t44**	0	0	1	0
j9	**t34**	0	1	0	0
j9	**t39**	0	0	1	0
j10	**t1**	0	1	0	0
j10	**t27**	0	0	1	0
j10	**t28**	0	0	1	0
j11	**t1**	0	1	0	0
j11	**t2**	0	1	0	0
j11	**t54**	0	1	0	0
j11	**t55**	0	1	0	0
j11	**t56**	0	1	1	0
j11	**t57**	0	0	1	0
j11	**t59**	0	0	0	1
j12	**t1**	0	1	0	0
j12	**t2**	0	1	1	0
j12	**t3**	0	1	1	0
j12	**t4**	0	1	0	0

j12	**t5**	0	1	0	0
j12	**t6**	0	1	0	0
j12	**t7**	0	1	0	0
j12	**t8**	0	1	0	0
j12	**t29**	0	0	0	1
j12	**t43**	0	1	0	0
j12	**t48**	0	1	0	1
j12	**t50**	0	1	1	1
j12	**t51**	0	0	1	0
j12	**t52**	0	0	1	0
j12	**t53**	0	0	1	0
j12	**t54**	0	1	1	0
j12	**t55**	0	0	1	0
j12	**t56**	0	0	0	1
j13	**t1**	0	1	0	0
j13	**t2**	0	1	1	0
j13	**t3**	0	1	0	0
j13	**t5**	0	0	1	0
j13	**t12**	0	0	1	0
j13	**t13**	0	0	1	0
j13	**t14**	0	0	1	0
j13	**t17**	0	0	1	0
j13	**t19**	0	0	1	0
j13	**t20**	0	0	1	0
j13	**t22**	0	0	1	0
j13	**t23**	0	0	1	0
j13	**t25**	0	0	1	0
j13	**t29**	0	0	1	0
j13	**t33**	0	0	1	0
j13	**t36**	0	0	1	0
j13	**t38**	0	0	1	0
j13	**t39**	0	0	1	0
j13	**t46**	0	0	1	0
j13	**t49**	0	0	1	0
j13	**t53**	0	0	1	0
j13	**t54**	0	0	1	0
j13	**t57**	0	0	1	0
j13	**t59**	0	0	0	1
j14	**t8**	0	1	0	0
j14	**t9**	0	0	1	0
j14	**t18**	0	0	1	0
j14	**t19**	0	0	1	0
j14	**t21**	0	0	1	0
j14	**t22**	0	0	1	0
j14	**t28**	0	0	1	0

j14	**t33**	0	0	1	0
j14	**t35**	0	0	1	0
j14	**t36**	0	0	1	0
j14	**t38**	0	0	1	0
j14	**t40**	0	0	1	0
j14	**t42**	0	0	1	0
j14	**t44**	0	0	1	0
j14	**t47**	0	0	1	0
j14	**t48**	0	0	1	0
j14	**t50**	0	0	1	0
j14	**t52**	0	0	1	0
j14	**t53**	0	0	1	0
j14	**t59**	0	0	1	0
j15	**t19**	0	0	1	0
j16	**t1**	0	1	0	0
j16	**t2**	0	1	1	0
j16	**t3**	0	1	1	0
j16	**t4**	0	1	1	0
j16	**t5**	0	1	1	0
j16	**t6**	0	1	1	0
j16	**t7**	0	1	1	0
j16	**t8**	0	1	1	1
j16	**t9**	0	1	1	0
j16	**t10**	0	0	1	0
j16	**t11**	0	0	1	0
j16	**t12**	0	0	1	0
j16	**t13**	0	0	1	0
j16	**t14**	0	0	1	0
j16	**t15**	0	0	1	0
j16	**t16**	0	0	1	0
j16	**t17**	0	0	1	0
j16	**t18**	0	0	1	0
j16	**t19**	0	0	1	0
j16	**t20**	0	0	1	0
j16	**t21**	0	0	1	0
j16	**t22**	0	0	1	0
j16	**t51**	0	0	0	1
j17	**t1**	0	1	0	0
j17	**t2**	0	0	1	0
j17	**t12**	0	1	0	0
j17	**t20**	0	0	1	0
j17	**t35**	0	0	1	0
j17	**t51**	0	0	1	0
j17	**t55**	0	0	1	0
j18	**t1**	0	0	1	0

j18	**t2**	0	0	1	0
j18	**t3**	0	0	1	0
j18	**t4**	0	0	1	0
j18	**t5**	0	0	1	0
j18	**t6**	0	0	1	0
j18	**t7**	0	0	1	0
j18	**t8**	0	0	1	0
j18	**t9**	0	0	1	0
j18	**t10**	0	0	1	0
j18	**t11**	0	0	1	0
j18	**t12**	0	0	1	0
j18	**t13**	0	0	1	0
j18	**t14**	0	0	1	0
j18	**t15**	0	0	1	0
j18	**t16**	0	0	1	0
j18	**t17**	0	0	1	0
j18	**t18**	0	0	1	0
j18	**t19**	0	0	1	0
j18	**t20**	0	0	1	0
j18	**t21**	0	0	1	0
j18	**t22**	0	0	1	0
j18	**t23**	0	0	1	0
j18	**t24**	0	0	1	0
j18	**t25**	0	0	1	0
j18	**t26**	0	0	1	0
j18	**t27**	0	0	1	0
j18	**t28**	0	0	1	0
j18	**t29**	0	0	1	0
j18	**t30**	0	0	1	0
j18	**t31**	0	0	1	0
j18	**t32**	0	0	1	0
j18	**t33**	0	0	1	0
j18	**t34**	0	0	1	0
j18	**t35**	0	0	1	0
j18	**t36**	0	0	1	1
j18	**t37**	0	0	1	1
j18	**t38**	0	0	1	1
j18	**t39**	0	0	1	1
j18	**t40**	0	0	1	1
j18	**t41**	0	0	1	1
j18	**t42**	0	0	1	1
j18	**t43**	0	0	1	1
j18	**t44**	0	0	1	1
j18	**t45**	0	0	1	1
j18	**t46**	0	0	1	1

j18	**t47**	0	0	1	1
j18	**t48**	0	0	1	1
j18	**t49**	0	0	1	1
j18	**t50**	0	0	1	1
j18	**t51**	0	0	1	1
j18	**t52**	0	0	1	1
j18	**t53**	0	0	1	1
j18	**t54**	0	0	1	1
j18	**t55**	0	0	1	1
j18	**t56**	0	0	1	1
j18	**t57**	0	0	1	1
j18	**t58**	0	0	1	1
j18	**t59**	0	0	1	1
j18	**t60**	0	0	0	1
j19	**t1**	0	0	0	1
j19	**t11**	0	0	0	1
j20	**t1**	0	0	1	0
j20	**t2**	0	0	1	0
j20	**t28**	0	0	0	1
j20	**t29**	0	0	0	1
j21	**t1**	0	1	0	0
j21	**t8**	0	1	0	0
j21	**t18**	0	1	0	0
j21	**t21**	0	1	0	0
j21	**t25**	0	1	0	0
j21	**t26**	0	1	0	0
j21	**t29**	0	1	0	0
j21	**t40**	0	1	0	0
j21	**t45**	0	1	0	0
j21	**t52**	0	0	1	0
j21	**t53**	0	0	1	0
j21	**t54**	0	1	1	0
j21	**t55**	0	0	1	0
j21	**t56**	0	0	1	1
j21	**t57**	0	0	1	0
j21	**t58**	0	0	0	1
j21	**t60**	0	0	0	1
j22	**t1**	0	0	1	0
j22	**t34**	0	0	1	0
j23	**t1**	0	1	0	0
j23	**t2**	0	1	0	0
j23	**t13**	0	1	0	0
j23	**t19**	0	0	1	0
j23	**t20**	0	0	1	0
j23	**t26**	0	0	0	1

j24	**t17**	0	1	0	0
j24	**t18**	0	1	0	0
j24	**t19**	0	1	0	0
j24	**t20**	0	1	0	0
j24	**t21**	0	1	0	0
j24	**t22**	0	1	0	0
j24	**t23**	0	1	0	0
j24	**t24**	0	1	0	0
j24	**t25**	0	1	0	0
j24	**t26**	0	1	0	0
j24	**t27**	0	1	0	0
j24	**t28**	0	1	0	0
j24	**t29**	0	1	0	0
j24	**t30**	0	1	0	0
j24	**t31**	0	1	0	0
j24	**t32**	0	1	0	0
j24	**t33**	0	1	0	0
j24	**t34**	0	1	0	0
j24	**t35**	0	1	0	0
j24	**t36**	0	1	0	0
j24	**t37**	0	1	0	0
j24	**t38**	0	1	0	0
j24	**t39**	0	1	0	0
j24	**t40**	0	1	0	0
j24	**t41**	0	1	0	0
j24	**t42**	0	1	0	0
j24	**t43**	0	1	0	0
j24	**t44**	0	1	0	0
j24	**t45**	0	1	0	0
j24	**t46**	0	1	0	0
j24	**t47**	0	1	0	0
j24	**t48**	0	1	1	0
j24	**t49**	0	0	1	0
j24	**t50**	0	0	1	0
j24	**t51**	0	0	1	0
j24	**t52**	0	0	1	1
j24	**t53**	0	0	1	0
j24	**t54**	0	0	1	1
j24	**t55**	0	0	1	0
j24	**t56**	0	0	0	1
j24	**t58**	0	0	0	1
j25	**t1**	0	0	1	0
j25	**t41**	0	0	0	1
j25	**t42**	0	0	0	1
j26	**t5**	0	0	0	1

j26	t9	0	0	0	1
j26	t13	0	0	0	1
j26	t14	0	0	0	1
j26	t19	0	0	0	1
j26	t22	0	0	0	1
j27	t32	0	1	0	0
j27	t33	0	1	0	0
j27	t34	0	1	0	0
j27	t35	0	1	0	0
j27	t36	0	1	0	0
j27	t37	0	1	0	0
j27	t38	0	1	1	0
j27	t39	0	1	1	0
j27	t40	0	1	1	0
j27	t41	0	1	1	0
j27	t42	0	1	1	0
j27	t43	0	1	1	0
j27	t44	0	1	1	0
j27	t45	0	1	1	0
j27	t46	0	1	1	0
j27	t47	0	1	1	0
j27	t48	0	1	1	0
j27	t49	0	1	1	0
j27	t50	0	1	1	0
j27	t51	0	1	1	0
j27	t52	0	1	1	0
j27	t53	0	0	1	1
j27	t54	0	0	1	1
j27	t55	0	0	1	1
j27	t56	0	0	1	1
j27	t57	0	0	1	1
j27	t58	0	0	0	1
j27	t59	0	0	0	1
j27	t60	0	0	0	1
j28	t17	0	1	0	0
j28	t30	0	1	0	0
j28	t34	0	1	0	0
j28	t37	0	1	0	0
j28	t40	0	0	1	0
j28	t48	0	0	0	1
j29	t20	0	0	0	1
j29	t51	0	0	0	1
j30	t10	0	1	0	0
j30	t37	0	0	1	0
j31	t1	0	1	0	0

j31	**t2**	0	1	1	0
j31	**t3**	0	1	0	0
j31	**t4**	0	1	0	0
j31	**t5**	0	1	0	0
j31	**t6**	0	1	0	0
j31	**t7**	0	1	0	0
j31	**t8**	0	1	0	0
j31	**t9**	0	1	0	0
j31	**t10**	0	1	0	0
j31	**t11**	0	0	1	0
j31	**t24**	0	0	1	0
j31	**t28**	0	0	1	0
j31	**t30**	0	0	1	0
j31	**t31**	0	0	1	0
j31	**t40**	0	0	1	0
j31	**t45**	0	0	1	0
j31	**t47**	0	0	1	0
j32	**t2**	0	0	1	0
j32	**t3**	0	0	1	0
j32	**t4**	0	0	1	0
j32	**t5**	0	0	1	0
j32	**t6**	0	0	1	0
j32	**t7**	0	0	1	0
j32	**t8**	0	0	1	0
j32	**t9**	0	0	1	0
j32	**t10**	0	0	1	0
j32	**t11**	0	0	1	0
j32	**t12**	0	0	1	0
j32	**t13**	0	0	1	0
j32	**t14**	0	0	1	0
j32	**t30**	0	0	0	1
j32	**t31**	0	0	0	1
j32	**t32**	0	0	0	1
j32	**t33**	0	0	0	1
j32	**t34**	0	0	0	1
j32	**t35**	0	0	0	1
j32	**t36**	0	0	0	1
j32	**t37**	0	0	0	1
j33	**t22**	0	0	1	0
j33	**t23**	0	0	1	0
j33	**t24**	0	0	1	0
j33	**t25**	0	0	1	0
j33	**t26**	0	0	1	0
j33	**t27**	0	0	1	0
j33	**t28**	0	0	1	0

j33	t29	0	0	1	0
j33	t35	0	0	0	1
j33	t40	0	0	0	1
j34	t1	0	0	1	0
j34	t2	0	0	1	0
j34	t3	0	0	1	0
j34	t4	0	0	1	0
j34	t6	0	0	0	1
j34	t7	0	0	0	1
j34	t8	0	0	0	1
j34	t9	0	0	0	1
j34	t10	0	0	0	1
j34	t11	0	0	0	1
j34	t12	0	0	0	1
j34	t13	0	0	0	1
j35	t1	0	0	1	0
j35	t40	0	0	0	1
j36	t1	0	0	0	1
j37	t1	0	1	0	0
j37	t15	0	1	0	0
j37	t26	0	1	0	0
j37	t27	0	0	1	0
j37	t29	0	0	0	1
j37	t48	0	0	0	1
j38	t1	0	1	0	0
j38	t2	0	1	0	0
j38	t3	0	1	0	0
j38	t4	0	1	1	0
j38	t5	0	1	1	0
j38	t6	0	1	1	0
j38	t7	0	1	1	0
j38	t8	0	1	1	0
j38	t9	0	1	1	0
j38	t10	0	1	1	0
j38	t11	0	1	1	0
j38	t12	0	1	1	0
j38	t13	0	1	1	0
j38	t14	0	1	1	0
j38	t15	0	1	1	0
j38	t16	0	1	1	0
j38	t17	0	1	1	0
j38	t18	0	1	1	0
j38	t19	0	1	1	0
j38	t20	0	1	1	0
j38	t21	0	1	1	0

j38	t22	0	1	1	0
j38	t23	0	1	1	0
j38	t24	0	1	1	0
j38	t25	0	1	1	0
j38	t26	0	1	1	0
j38	t27	0	1	1	0
j38	t28	0	1	1	0
j38	t29	0	1	1	0
j38	t30	0	1	1	0
j38	t31	0	1	1	0
j38	t32	0	1	1	0
j38	t33	0	1	1	0
j38	t34	0	1	1	0
j38	t35	0	1	1	0
j38	t36	0	1	1	0
j38	t37	0	1	1	0
j38	t38	0	1	1	0
j38	t39	0	1	1	0
j38	t40	0	1	1	0
j38	t41	0	1	1	0
j38	t42	0	0	1	0
j38	t43	0	0	1	0
j38	t44	0	0	1	0
j38	t45	0	0	1	0
j38	t46	0	0	1	0
j39	t5	0	0	1	0
j40	t1	0	0	1	0
j41	t39	0	0	1	0
j42	t1	1	0	0	0
j42	t2	1	0	0	0
j42	t18	0	1	0	0
j43	t11	1	0	0	0
j43	t23	0	1	0	0
j43	t26	0	1	0	0
j43	t39	0	1	0	0
j44	t4	0	1	0	0
j44	t9	0	1	0	0
j44	t13	0	1	0	0
j45	t7	0	1	0	0
j45	t13	0	1	0	0
j46	t1	1	0	0	0
j46	t6	0	1	0	0
j46	t34	0	0	1	0
j47	t39	0	1	0	0
j47	t41	0	0	1	0

j47	**t49**	0	0	0	1
j48	**t10**	0	1	0	0
j49	**t12**	0	1	0	0
j49	**t17**	0	0	1	0
j50	**t1**	0	1	0	0
j50	**t9**	0	1	0	0
j50	**t15**	0	1	0	0
j50	**t26**	0	0	1	0
j50	**t27**	0	0	1	0
j50	**t39**	0	0	0	1
j51	**t8**	0	1	0	0
j51	**t9**	0	0	1	0
j51	**t10**	0	0	1	0
j51	**t24**	0	0	0	1
j52	**t1**	0	0	0	1
j53	**t17**	0	1	0	0
j53	**t18**	0	1	0	0
j53	**t19**	0	1	0	0
j53	**t20**	0	1	0	0
j53	**t21**	0	1	0	0
j53	**t22**	0	1	0	0
j53	**t23**	0	1	1	0
j53	**t24**	0	0	1	0
j53	**t25**	0	0	1	0
j53	**t26**	0	0	1	0
j54	**t33**	1	0	0	0
j54	**t39**	0	1	0	0
j54	**t40**	0	1	0	0
j55	**t2**	1	0	0	0
j55	**t3**	1	0	0	0
j55	**t14**	0	1	0	0
j55	**t15**	0	1	0	0
j55	**t16**	0	1	0	0
j56	**t12**	0	1	0	0
j57	**t3**	0	1	0	0
j57	**t21**	0	0	1	0
j58	**t1**	0	0	0	1
j59	**t8**	0	0	0	1
j60	**t18**	0	1	0	0
j60	**t20**	0	0	0	1
j61	**t7**	0	1	0	0
j61	**t8**	0	1	0	0
j61	**t12**	0	0	1	0
j61	**t13**	0	0	1	0
j61	**t14**	0	0	1	0

j61	t15	0	0	1	0
j61	t24	0	0	0	1
j61	t38	0	1	0	0
j61	t39	0	1	0	0
j61	t40	0	1	0	0
j61	t41	0	1	0	0
j61	t42	0	1	0	0
j61	t43	0	0	1	0
j61	t44	0	0	0	1
j62	t51	1	0	0	0
j62	t52	0	1	0	0
j62	t53	0	1	0	0
j62	t55	1	0	0	0
j62	t56	1	1	0	0
j62	t57	1	1	0	0
j62	t58	0	1	1	0
j62	t59	0	0	1	0
j62	t60	0	0	1	0
j63	t2	0	1	0	0
j63	t3	0	1	0	0
j63	t4	0	1	0	0
j63	t5	0	1	0	0
j63	t7	0	0	1	0
j63	t8	0	0	1	0
j63	t9	0	0	1	0
j64	t14	0	1	0	0
j64	t15	0	1	0	0
j64	t16	0	1	1	0
j64	t17	0	1	1	0
j64	t18	0	0	1	0
j65	t5	0	1	0	0
j65	t12	0	0	1	0
j66	t2	0	1	0	0
j66	t3	0	1	0	0
j66	t4	0	1	0	0
j66	t5	0	1	0	0
j66	t6	0	0	1	0
j66	t7	0	0	1	0
j66	t8	0	0	1	0
j67	t1	0	1	0	0
j67	t2	0	1	0	0
j67	t9	0	1	0	0
j67	t14	0	1	0	0
j67	t17	0	1	0	0
j67	t21	0	1	0	0

j67	**t23**	0	1	0	0
j68	**t3**	0	0	1	0
j68	**t6**	0	0	0	1
j68	**t7**	0	0	0	1
j68	**t8**	0	0	0	1
j69	**t9**	0	0	0	1
j70	**t6**	0	0	1	0
j70	**t8**	0	0	0	1
j71	**t7**	0	1	0	0
j71	**t8**	0	1	0	0
j71	**t9**	0	1	0	0
j71	**t10**	0	1	0	0
j71	**t11**	0	1	0	0
j71	**t12**	0	1	0	0
j71	**t13**	0	1	0	0
j72	**t3**	0	0	1	0
j72	**t5**	0	0	1	0
j72	**t7**	0	0	1	0
j72	**t8**	0	0	0	1
j72	**t9**	0	0	1	0
j72	**t10**	0	0	1	1
j72	**t11**	0	0	1	0
j72	**t12**	0	0	1	0
j72	**t15**	0	0	1	0
j72	**t18**	0	0	0	1
j72	**t23**	0	0	0	1
j72	**t25**	0	0	1	0
j72	**t26**	0	0	1	0
j72	**t28**	0	0	1	0
j72	**t29**	0	0	1	0
j72	**t35**	0	0	1	1
j72	**t37**	0	0	1	0
j72	**t38**	0	0	1	0
j72	**t39**	0	0	0	1
j73	**t15**	0	1	0	0
j73	**t16**	0	1	1	0
j73	**t17**	0	1	1	1
j73	**t18**	0	1	1	0
j73	**t19**	0	1	1	0
j73	**t20**	0	0	1	1
j73	**t21**	0	0	1	0
j73	**t22**	0	0	0	1
j73	**t24**	0	0	0	1
j73	**t25**	0	0	0	1
j73	**t26**	0	0	0	1

j74	t18	0	1	0	0
j74	t24	0	0	1	0
j75	t9	0	1	0	0
j75	t10	0	1	0	0
j75	t11	0	1	0	0
j75	t13	0	0	1	0
j76	t18	0	1	0	0
j76	t20	0	0	1	0
j77	t34	0	0	0	1
j78	t44	0	1	0	0
j78	t46	0	0	1	0
j79	t47	1	0	0	0
j79	t56	0	1	0	0
j79	t57	0	0	1	0
j80	t7	1	0	0	0
j80	t13	0	1	0	0
j80	t14	0	1	0	0
j80	t49	0	0	1	0
j80	t50	0	0	1	0
j80	t51	0	0	1	0
j80	t52	0	0	1	0
j80	t53	0	0	1	0
j80	t54	0	0	1	0
j80	t55	0	0	1	0
j80	t58	0	0	0	1
j81	t1	0	1	0	0
j81	t2	0	1	0	0
j81	t4	0	1	1	0
j81	t5	0	0	1	0
j82	t1	1	0	0	0
j82	t4	0	1	0	0
j82	t5	0	1	1	0
j82	t6	0	0	1	0
j82	t7	0	0	1	0
j82	t20	0	0	0	1
j83	t36	1	0	0	0
j83	t38	0	1	0	0
j84	t27	1	0	0	0
j84	t28	0	1	0	0
j84	t33	0	0	1	0
j84	t44	0	0	0	1
j85	t15	1	0	0	0
j85	t19	0	1	0	0
j85	t23	0	0	1	0
j86	t23	0	0	0	1

j87	**t20**	1	0	0	0
j87	**t21**	0	1	0	0
j87	**t52**	0	0	1	0
j88	**t17**	0	1	0	0
j88	**t26**	0	0	1	0
j89	**t10**	1	0	0	0
j89	**t11**	0	1	0	0
j89	**t19**	0	0	1	0
j89	**t23**	0	0	0	1
j90	**t3**	0	1	0	0
j90	**t36**	0	0	1	0
j90	**t37**	0	0	1	0
j90	**t38**	0	0	1	0
j91	**t4**	1	0	0	0
j91	**t5**	1	0	0	0
j91	**t6**	1	0	0	0
j91	**t7**	1	1	0	0
j91	**t9**	0	1	1	0
j91	**t11**	0	0	1	0
j91	**t12**	0	0	1	0
j91	**t13**	0	0	1	0
j91	**t14**	0	0	1	0
j91	**t15**	0	0	1	0
j91	**t16**	0	0	1	0
j91	**t17**	0	0	1	0
j91	**t18**	0	0	1	0
j91	**t19**	0	0	1	0
j91	**t20**	0	0	1	0
j91	**t21**	0	0	1	0
j91	**t22**	0	0	1	0
j91	**t23**	0	0	1	0
j91	**t24**	0	0	1	0
j91	**t25**	0	0	1	0
j91	**t26**	0	0	1	0
j92	**t31**	0	1	0	0
j92	**t33**	0	0	1	0
j92	**t40**	0	0	0	1
j93	**t6**	0	1	0	0
j93	**t7**	0	1	0	0
j93	**t8**	0	1	0	0
j93	**t9**	0	1	0	0
j94	**t2**	0	1	0	0
j94	**t3**	0	1	1	0
j94	**t4**	0	1	0	0
j94	**t5**	0	1	0	0

j94	**t6**	0	1	0	0
j94	**t13**	0	0	1	0
j94	**t60**	0	0	0	1
j95	**t23**	0	0	0	1
j95	**t40**	0	0	0	1
j96	**t16**	1	0	0	0
j96	**t17**	1	1	0	0
j96	**t18**	1	1	0	0
j96	**t19**	1	1	0	0
j96	**t20**	1	1	0	0
j96	**t21**	1	1	0	0
j96	**t22**	1	1	0	0
j96	**t23**	1	1	0	0
j96	**t24**	0	1	0	0
j96	**t36**	0	0	1	0
j96	**t37**	0	0	1	0
j96	**t38**	0	0	1	0
j96	**t39**	0	0	1	0
j96	**t40**	0	0	1	0
j96	**t41**	0	0	1	0
j96	**t42**	0	0	1	0
j96	**t43**	0	0	1	1
j96	**t44**	0	0	1	0
j96	**t45**	0	0	1	0
j96	**t46**	0	0	1	0
j96	**t47**	0	0	1	0
j96	**t48**	0	0	1	0
j96	**t49**	0	0	1	0
j96	**t50**	0	0	1	0
j96	**t56**	0	0	0	1
j96	**t57**	0	0	0	1
j96	**t59**	0	0	0	1
j96	**t60**	0	0	0	1
j97	**t8**	0	1	0	0
j97	**t17**	0	0	1	0
j97	**t29**	0	0	0	1
j98	**t9**	0	1	0	0
j98	**t10**	0	1	1	0
j98	**t11**	0	1	1	0
j98	**t12**	0	1	1	0
j98	**t13**	0	1	0	0
j98	**t14**	0	1	0	0
j98	**t15**	0	1	0	0
j98	**t16**	0	1	0	0
j98	**t17**	0	1	0	0

j98	t18	0	1	1	0
j98	t19	0	1	1	0
j98	t20	0	1	0	0
j98	t21	0	1	1	0
j98	t22	0	1	1	0
j98	t23	0	1	0	0
j98	t24	0	1	1	0
j98	t25	0	1	0	0
j98	t26	0	1	0	0
j98	t27	0	1	0	0
j98	t28	0	1	0	0
j98	t29	0	1	0	0
j98	t30	0	1	0	0
j98	t31	0	1	0	0
j98	t32	0	1	0	0
j98	t33	0	1	0	0
j98	t34	0	1	0	0
j98	t36	0	0	0	1
j98	t37	0	0	0	1
j98	t38	0	0	0	1
j98	t39	0	0	0	1
j98	t40	0	0	0	1
j98	t41	0	0	0	1
j98	t42	0	0	0	1
j98	t43	0	0	1	1
j98	t44	0	0	0	1
j99	t21	0	1	0	0
j99	t25	0	0	1	0
j99	t48	0	0	0	1
j100	t4	0	1	0	0
j100	t5	0	1	0	0
j100	t19	0	1	0	0
j101	t1	1	0	0	0
j101	t2	1	0	0	0
j101	t3	0	1	0	0
j101	t5	0	0	1	0
j102	t13	0	1	0	0
j102	t23	0	0	1	0
j102	t24	0	0	1	0
j103	t26	0	1	0	0
j103	t27	0	1	0	0
j103	t40	0	0	1	0
j103	t42	0	0	0	1
j104	t1	0	1	0	0
j104	t2	0	1	0	0

j104	**t3**	0	1	0	0
j104	**t4**	0	1	0	0
j104	**t5**	0	1	1	0
j104	**t6**	0	1	1	0
j104	**t7**	0	1	0	0
j104	**t8**	0	1	0	0
j104	**t9**	0	1	0	0
j104	**t10**	0	1	0	0
j104	**t11**	0	1	0	0
j104	**t16**	0	0	1	0
j104	**t19**	0	0	1	0
j104	**t20**	0	0	1	0
j104	**t24**	0	0	1	0
j104	**t25**	0	0	1	0
j104	**t28**	0	0	1	0
j104	**t31**	0	0	1	0
j104	**t40**	0	0	1	0
j104	**t46**	0	0	1	0
j104	**t47**	0	0	1	0
j104	**t50**	0	0	1	0
j104	**t58**	0	0	0	1
j104	**t59**	0	0	1	1
j104	**t60**	0	0	0	1
j105	**t1**	0	0	1	0
j105	**t2**	0	0	1	0
j106	**t3**	0	1	0	0
j106	**t19**	0	1	0	0
j106	**t22**	0	0	1	0
j106	**t23**	0	0	1	1
j106	**t24**	0	0	1	0
j106	**t25**	0	0	1	0
j106	**t41**	0	0	0	1
j107	**t8**	1	0	0	0
j107	**t9**	1	0	0	0
j107	**t27**	0	1	0	0
j107	**t28**	0	1	0	0
j107	**t29**	0	0	1	0
j107	**t60**	0	0	0	1
j108	**t17**	1	0	0	0
j108	**t18**	0	1	0	0
j108	**t30**	0	0	1	0
j108	**t34**	0	0	0	1
j109	**t2**	1	0	0	0
j109	**t22**	0	1	0	0
j109	**t23**	0	1	0	0

j109	**t33**	0	0	1	0
j109	**t60**	0	0	0	1
j110	**t40**	0	1	0	0
j110	**t45**	0	0	1	0
j110	**t46**	0	0	0	1
j111	**t17**	0	1	0	0
j111	**t18**	0	1	0	0
j111	**t44**	0	0	1	0
j111	**t45**	0	0	0	1
j112	**t34**	0	1	0	0
j112	**t41**	0	0	1	0
j112	**t49**	0	0	0	1
j113	**t27**	0	1	0	0
j113	**t30**	0	0	1	0
j113	**t31**	0	0	0	1
j114	**t48**	0	1	0	0
j114	**t54**	0	1	0	0
j114	**t55**	0	0	1	0
j114	**t57**	0	0	0	1
j115	**t10**	0	1	0	0
j115	**t20**	0	0	1	0
j115	**t22**	0	0	0	1
j116	**t26**	0	0	0	1
j116	**t33**	0	0	0	1
j116	**t35**	0	0	0	1
j116	**t46**	0	0	0	1
j116	**t49**	0	0	0	1
j117	**t40**	0	0	1	0
j118	**t40**	0	0	1	0
j119	**t39**	0	0	1	0
j120	**t60**	0	0	1	0
j121	**t41**	0	1	0	0
j121	**t42**	0	1	0	0
j121	**t51**	0	0	1	0
j121	**t52**	0	0	1	0
j122	**t41**	0	1	0	0
j122	**t42**	0	1	0	0
j122	**t44**	0	0	1	0
j122	**t45**	0	0	1	0
j123	**t41**	0	1	0	0
j123	**t42**	0	1	0	0
j123	**t47**	0	0	1	0
j123	**t48**	0	0	1	0
j124	**t40**	0	0	1	0
j124	**t53**	0	0	0	1

j124	**t54**	0	0	0	1

Table 2- Optimal Schedule Output

Job #	Completion Time	Due Dates
j1	48	62
j2	32	36
j3	23	24
j4	11	12
j5	23	26
j6	26	34
j7	9	28
j8	45	50
j9	39	52
j10	28	36
j11	59	62
j12	56	62
j13	59	66
j14	59	92
j15	19	26
j16	51	70
j17	55	56
j18	60	80
j19	11	14
j20	29	34
j21	60	64
j22	34	36
j23	26	62
j24	58	120
j25	42	64
j26	22	22
j27	60	84
j28	48	76
j29	51	94
j30	38	52
j31	47	54
j32	37	68
j33	40	50
j34	13	38
j35	40	42
j36	2	6
j37	48	50
j38	46	66
j39	9	76
j40	5	76

j41	43	76
j42	18	36
j43	39	42
j44	13	20
j45	13	20
j46	35	48
j47	49	56
j48	10	20
j49	18	22
j50	39	40
j51	26	38
j52	2	10
j53	26	26
j54	40	40
j55	16	40
j56	13	56
j57	21	34
j58	2	10
j59	8	10
j60	20	20
j61	45	46
j62	60	76
j63	9	20
j64	18	20
j65	13	26
j66	8	20
j67	23	26
j68	8	10
j69	9	10
j70	9	20
j71	13	30
j72	39	42
j73	26	26
j74	25	46
j75	14	26
j76	21	26
j77	35	46
j78	47	66
j79	58	66
j80	59	66
j81	5	28
j82	20	64
j83	38	64
j84	45	66

j85	24	30
j86	24	26
j87	53	56
j88	27	56
j89	24	90
j90	38	46
j91	26	26
j92	41	56
j93	9	66
j94	60	66
j95	40	64
j96	60	144
j97	29	36
j98	44	98
j99	48	86
j100	19	20
j101	5	66
j102	24	36
j103	43	46
j104	60	78
j105	2	10
j106	41	46
j107	60	66
j108	34	76
j109	60	76
j110	46	46
j111	46	46
j112	50	86
j113	32	86
j114	58	90
j115	22	28
j116	49	55
j117	41	60
j118	41	64
j119	40	136
j120	61	160
j121	52	70
j122	45	70
j123	48	70
j124	54	66

Table 3- Completion times and Due Dates Output

CAPACITY LEVEL AT EACH TIME PERIOD				
Time #	**Stage 1**	**Stage 2**	**Stage 3**	**Stage 4**
t1	9	27	17	7
t2	7	16	13	0
t3	1	16	10	0
t4	2	14	9	0
t5	1	12	18	1
t6	1	10	11	4
t7	3	13	10	2
t8	2	15	7	7
t9	1	16	13	3
t10	2	13	7	3
t11	2	7	9	2
t12	0	7	13	1
t13	0	11	11	2
t14	0	9	8	2
t15	2	8	7	1
t16	2	6	9	0
t17	3	16	11	1
t18	1	16	8	1
t19	1	10	14	2
t20	3	5	12	5
t21	1	11	8	0
t22	1	7	13	3
t23	1	8	14	8
t24	0	4	13	6
t25	0	5	11	1
t26	0	8	11	3
t27	2	8	8	0
t28	0	6	8	2
t29	0	4	7	4
t30	0	4	6	2
t31	0	5	4	3
t32	0	11	2	1
t33	3	4	9	2
t34	1	8	5	4
t35	0	3	5	4
t36	2	3	8	5
t37	0	5	7	3
t38	0	8	10	2
t39	0	8	13	4
t40	0	8	15	7
t41	0	10	7	5
t42	0	6	5	5

t43	0	3	10	3
t44	0	4	9	6
t45	0	4	8	3
t46	0	2	8	3
t47	2	2	10	1
t48	0	5	9	5
t49	0	1	7	5
t50	0	2	9	2
t51	2	1	8	3
t52	0	3	12	2
t53	0	1	8	5
t54	1	5	7	4
t55	2	1	8	2
t56	1	5	6	6
t57	1	1	7	5
t58	0	1	3	8
t59	0	0	4	6
t60	0	0	3	8

Table 4- Capacity Level for Each Stage Output

CURRICULUM VITAE:

Emre Özgenç Ekici

Current Address
Yıldızevler Mah. Duyu Sok. 31/28
Çankaya/ANKARA

E-Mail : emrekare@gmail.com
Cellular Phone: + (90) 505 282 72 92

EDUCATION

1999-2004 Bilkent University
Industrial Engineering (Undergraduate), Ankara
Full Scholarship Awarded
CGPA: **3.17** / 4.0

2010 Hacettepe University
Business Administration Faculty
Production Management (Graduate)
(Still continued)
CGPA: **3,69** / 4,0

WORK EXPERIENCE

(Compulsory Military Service has been accomplished.)

August 2005 – ,**ASELSAN A.ş. Ankara / Workshop Planning Senior Engineer and Lean Team Leader**

- Providing production flow dynamically and interfering production problems as soon as possible, scheduling jobs for each workshop, capacity planning and balancing job allocations for different workshops.
- **Additionally, leading Lean applications, preparing VSM and Kaizen Team Leader**

November 2003 – May 2004, **MAN Turkey A.ş., Ankara (Senior Project)**

- **Designing and Programming using C#** a Forklift Scheduling Program in order to improve material flow between assembly line and warehouse

August – September 2002, Kale Holding KaleData A.Ş., İstanbul (summer training)

- Marketing Research Project of Company

SKILLS AND ABILITIES

Computer Programming Languages:
Visual Basic (Very Good), C# (good), Java (good), ASP.NET (good), SQL (good), Html (medium),

Application Programs:
Microsoft Office (Excel, Access, Word, MS Project, MS Visio)(Advanced), Excel Macro (Good), ARENA Simulation Software (Advanced), GAMS Integer Programming Software (Advanced)

Language:
Advanced English, Intermediate German

CERTIFICATES

- **Lean 5S ve Visual Plant Applications, 2011**
- **Lean Hoshin Kanri and VSM Applications, 2011**
- Microsoft Office Project , 2009
- **Ranked Turkey 46th in the University Entrance Exam, 1999**
- **Ranked Turkey 200th in the Fen Liseleri Entrance Exam, 1996**
- Tübitak Secondary School Math Olympiad **Turkey 3rd**, 1996

SOCIAL ACTIVITIES

- **Founder and Organizer of ASELSAN Basketball Tournament, 2009-2012**
- Coordinator and founder of **IYEM (International Young Entrepreneurs Meeting) Organization- FIRST in Turkey-, 2002**
- **Young Entrepreneurs Club President, 2002-2003**
- Student Union Engineering Faculty Representative, 2000-2001 - General Secretary, 2001-2002

Personal Traits

- Intelligent
- Creative
- Responsible

Interests

- **Lego Robotics designing**
- Playing Basketball
- **Playing guitar**, listening music