

PRODUCTION PLANNING FOR FOUNDRY WORKSHOP



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# PRODUCTION PLANNING FOR FOUNDRY WORKSHOP

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Approval of theGraduate School of Natural andAppliedSciences

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## ABSTRACT

## PRODUCTION PLANNING FOR FOUNDRY WORKSHOP

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Foundries have a wide range of applications depending on the size and type of products produced with selected technologies. Foundries must work with efficiency because they support a fast-paced (serial) production.

In this thesis, a new mathematical modelling is proposed for the foundries planning and scheduling. The scheduling model will increase the efficiency and effectiveness, will decrease the total backlog, total setup cost, total mold maintenance cost and total inventory cost without any order delay through the usage of production constraints from necessary materials and parameters.

**Keywords:** Foundry Planning and Scheduling, Optimization, Mathematical Model, Backlog, Setup, Maintenance, Inventory and Minimization

## DÖKÜM ATÖLYESİ İÇİN PLANLAMA

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Dökümhaneler, seçili teknolojiler ile kullanarak seri üretimle boyutu ve türüne göre geniş bir yelpazede ürünler üretir. Dökümhaneler seri üretimi destekledikleri için, verimli çalışmak zorundadırlar.

Bu projede, dökümhane planlama ve çizelgeleme için yeni bir matematiksel model önerilmiştir. Bu modelle birlikte gelen siparişlerde gecikme yaşamadan gerekli malzemelerin üretim kısıtları ve parametrelerle oluşturulacak çizelgeleme ile mevcut durumdaki etkinliği ve verimliliği artırmakla birlikte, toplam gecikme, toplam kurulum, toplam envanter, toplam kalıp bakım ve toplam maliyeti en aza indirgenmiştir.

**Anahtar Kelimeler:** Dökümhane Çizelgelemesi, Optimizasyon, Matematiksel Model, Gecikme, Kurulum, Envanter ve Kalıp Bakım Minimizasyonu

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# TERMS AND ABBREVIATIONS

LP	: Linear Programming
IP	: Integer Programming
MIP	: Mix Integer Programming
DP	: Dynamic Programming
Non-LP	: Non-Linear Programming
ILP	: Integer Linear Programming

#### **CHAPTER 1: INTRODUCTION**

Foundries melt ferrous and non-ferrous metals and alloys; these plants reshape alloys that are finished or close to finished by means of foundry metals or alloys into a mold or through hardening. Foundry industry is a differentiated and diverse industry. Foundries consist of various sizes of plants ranging from small facilities to large-scale installations that have a combination of various sizes and types of products in a given facility with suitable technology and unit operations to suit each input. Organization within the industry is based on the type of metal input together with the main distinction of ferrous and non-ferrous foundries.

European foundry industry is the world's third-largest industry in ferrous foundry and the second largest industry for non-ferrous foundry. Germany, France and Italy are the three biggest producing countries in Europe each of which has a total annual production of over two million tonnes of foundries. Spain, in recent years, has moved to the fourth place taking the place of UK with a production over one million tons. In addition, these top five countries produce more than 80% of the total European production. Despite some fluctuations for individual countries, the total tonnage of ferrous foundry production in Europe has shown stability for the last five years (European Commission, 2005). For instance, while the trend is towards growth in Spain, figures for England suggest the existence of a general downward trend in manufacturing output. A steady growth has occurred in the non-ferrous foundry industry since 1998. The total figure for 2001 was unclear due to lack of data for UK. This applies to not only major producing countries but also countries with lower levels of production.

Outside metal types (ferrous/non-ferrous), size of foundries depends largely on dimensions of foundry products and series. A small series foundry is called 'subcontractor foundry', and a large series foundry is called 'series foundry'. Foundries can also be classified according to the type of ferrous produced, namely, the type of non-ferrous and ferrous foundry.

Foundry Process: A general flow chart of foundry process is provided below in Figure 1.1.

A typical foundry process can be divided into following main activities:

- Melting and metal processing: melting area
- Preparation of molds and cores: molding area
- Pouring molten metal into the mold, cooling for solidification, extraction of foundry from the mold: foundry space
- Crude foundry coating: coating area

Foundries produce coated foundry starting with foundry scrap (scraps selected according to a specific chemical composition) or ingots. Typically, these are compounds that require further treatment or assembly for final product yield.

Chambers, cores and lost templates are produced as a part of the foundry process. Diagram of General Foundry Process (European Commission, 2005) is presented in Figure 1.



Figure 1 Diagram of general foundry process (European Commission, 2005)

## 1.1. Scope of the Master Thesis

In this thesis, we consider production planning and scheduling problem in a foundry. First, a literature review on this topic is provided, and a new mathematical model is presented for planning and scheduling problem in a typical foundry.

In this problem, a factory supporting mass production is envisioned. Therefore, cost of maintenance, setup cost, backlog cost, inventory cost in modeling is also considered. In order to identify these; such as machine-mold compatibility, product-period compatibility, alloy-period compatibility, molditem compatibility is provided. At this time, molds are unable periodically. Difficulties due to the problems that emerge for use and maintenance of the mold have been ignored. While satisfying demand, emerging problems were studied due to the ignoring of mold and maintenance. Mold usage was minimized and cost of maintenance were minimized with this solution technique. A new mathematical (an improved model is) proposed and it was solved with CPLEX considering specific constraints and parameters.

The objective of the problem is minimizing total cost. Total cost is composed of backlog cost, inventory cost, maintenance cost and setup cost of furnace during planning horizon.

## CHAPTER 2 : LITERATURE REVIEW

Landmann *et al.* (2013) studied production scheduling optimization problem in the foundry industry. There were two important production stage, which were melting and molding. There was different capacity in molding lines. More melting center was made for best use of melting line. Using the foundry capacity in the best possible way, efficiency of the foundry operator is increased, and consumption of energy decreased. Possible combinations were created in order to produce product in optimal time. They presented a genetic algorithm. They also compared other by (fuzzy logic) solution.

Sortrakul *et al.* (2005) studied genetic algorithms for integrated preventive maintenance planning and production scheduling for a single machine. In this paper an integrated production planning and optimization models for planning preventative maintenance is studied. They have developed a solution based on genetic algorithms. Their main algorithm was implemented which they have shown to be efficient for optimizing.

Yulan *et al.* (2007) studied multi-objective integrated optimization research on preventive maintenance planning and production scheduling for a single machine. The article aimed at maintenance costs, completion time, total weighted completion time jobs, while minimizing total weighted delays, and maximize machine availability. Solution methods were proposed genetic algorithms (MOGA) by visual basic, and they were made maintenance plan with production planning.

Ugarte *et al.* (2009) studied development and integration of a reactive realtime decision support system in the industry. This paper aimed to provide real-time decision support in production environments. They showed (ERP) enterprise resource planning delay in the process in a controlled environment. They were in search of genetic algorithm and real-time solution with discrete event simulation model and they showed availability. Nonas *et al.* (2000) studied scheduling problem arising in a foundry industry. The aim of the problem was to find an efficient production plan that minimizes the total number of days orders are late. Constraints were measured by a capacity matrix. They solved MIP and proposed heuristic strategies. They obtained optimal solution by mathematical model. Strategy performance was shown via numerical solution.

CherngWu *et al.* (2005) studied an operator staffing and assignment model for foundry industry. The aim of the problem was to minimize operator staffing costs because, there are frequent changes of product mix and keeping high-quality was paramount. They developed LP (linear programming) model. Their proposed LP model aims to minimize the operator staffing cost. They solve staffing problem with 90% confidence that the computed solution differs by no more than one operator from best solution.

Arouje *et al.* (2012) explained a lot sizing and scheduling problem in small foundries. There were decision variables which were metal alloy production for furnace and molding machine planning. They presented a MIP model and solved it via the RF (relax-and-fix) approach. The methods helped small foundries to reduce delays considerably. Schedules were generated in a small fraction of the time of those created manually in the foundry.

Aghezzaf *et al.* (2007) studied an integrated production and preventive maintenance planning model. The aim of the problem; it is to find integrated system that meets the demands and preventive maintenance strategy for all items. Production and maintenance costs are minimized. Example model was created for the solution method with mixed integer programming. An example of the model is consistent with and optimal production and shows preventive maintenance schedule is consistent. In addition to maintenance

the problems with the integration of operations planning models will also be searched.

Stawawy *et al.* (2007) studied XML model of planning system in foundry. The disadvantage of solution was differently production planning and scheduling problem. They presented XML model of manufacturing and planning system for a sample foundry. The model was formed of customer's order model, resources model and scheduling model. The XML model use to access the data stored in an XML document.

Maticevic *et al.* (2006) studied production scheduling model in Aluminum foundry. The aim was satisfying just in time customer demand with quality products. They developed new mathematical model. The mathematical model was successfully applied and tested in the foundry in Mostar.

Stawawy *et al.* (2012) studied model and algorithm for planning and scheduling in foundry. They developed model and algorithm for foundry planning. They accepted shop floor scheduling or lot sizing as scheduling with batching. Also, scheduling model and optimization techniques were solved for computing capacity.

Cassady *et al.* (2005) studied integrating preventive maintenance planning and production scheduling for a single machine. The aim of the problem is expected to minimize the total weighted completion time. They have developed a mathematical model that includes a production planning and scheduling preventive maintenance on a single machine. They are a simple example, showed the PM decided to define an optimal schedule. Their future work is to develop this model with more intuitive solution methods.

Cassady *et al.* (2003) studied minimizing job tardiness using integrated preventive maintenance planning and production scheduling. The aim was to minimize the total weighted tardiness production planning and work. Thus, determining the preventive methods was a model of integrated care planning

decisions. This model an integrated solution for production planning and scheduling preventive maintenance and independent problem solving compared with the performance obtained in the solution. The resulting numerical model results indicated 30% average reduction on expected total weighted tardiness. Their future work includes multiple machines or workshops constraints to be included and aims to further improve the operational maintenance capacity.

Austgen *et al.* (2015) studied scheduling foundry production without an inventory of sand molds. They assumed given weekly demand and sequence products per hour. They solved MIP model and implemented a genetic algorithm due to solving problems with MIP model. The molds must be used in the order mold sequence are split among two pouring lines without need to store molds.

Camargo *et al.* (2012) studied a knapsack problem as a tool solve the production planning problem in small foundries. The purpose of this study was to prepare plans for minimum production costs very sizing problem for small foundries. In this study, an important problem was furnace setup capacity. They prepared the solution with genetic algorithms and mathematical methods. The recommended method was better than the results in the literature. Furthermore, the proposed method is suitable for small foundries.

Landmann *et al.* (2007) studied production scheduling optimization in the foundry industry using genetic algorithm. In this report, they have submitted applications with the results of genetic algorithms techniques to use in the foundry industry and production planning. They have minimized energy consumption and smelting capacity in the foundry. Their solution techniques were genetic algorithms and mathematical methods. The results of mathematical models (MIP) and the method by intuition (meta-heuristic algorithm) compared the results were enough to solve this problem.

Ballestion *et al.* (2012) studied production scheduling in a market-driven foundry a mathematical programming approach versus a project scheduling mateheuristic algorithm. The aim of this paper is different processes required for the manufacture of parts (molding, baking, cutting, molding, etc.) was to find an efficient production plan. They made solution with integer linear programming. They developed metaheuristic algorithm based on this model. They reached the conclusion that compare both approaches with real examples.

Duda *et al.* (2013) studied lot-sizing problem in an automated foundry. They worked on a make-to-order foundry of medium size. They assumed the furnace as bottleneck and solved a mix integer programming (MIP) problem. They improved planning with using MIP model to find the needed alloy in addition to products that will be produced.

Fernandes *et al.* (2010) studied binary integer programming formulations for scheduling in market-driven foundries. This article described the development of market-oriented foundry and binary integer formulations for production scheduling problems in foundry. However, there were few studies on the subject. They supplied solution with mathematical methods. This model demonstrated the feasibility of computational tests the robustness of the model and proposed a similar situation to the industrial sector as production planning was analyzed.

In this thesis the mathematical model was developed to minimize total backlog cost, total setup cost, total maintenance cost and total inventory cost. Significant constraints considered. These are; machine-mold compatibility, mold-product compatibility, minimize and maximize product run, mold maintenance compatibility. In these literatures; setup cost, inventory cost, backlog and mold maintenance cost were never evaluated together. If the mold maintenance ignores, problems may occur during the planning.

Especially, the usage of mold and maintenance cost has been minimized with this solution technique.



 Table 1
 Literature survey

References	Торіс	Aim	Mathematical	Genetic
			Model	Algorithm
Landmann et	Production scheduling optimization	Minimize the efficiency of the		
al.	problem in the foundry industry.	operator.		
(2013)				
Sortrakul <i>et al.</i>	Genetic algorithms for integrated	Minimize the integrated optimization		
(2005)	preventive maintenance planning	model for production scheduling and		
	and production scheduling for a	preventive maintenance planning.		
	single machine.			
Yulan <i>et al.</i>	Multi-objective integrated	Minimize the maintenance cost,		
(2007)	optimization research	makespan, total weighted completion		
	on preventive maintenance	time of jobs,		
	planning and production	total weighted tardiness, and		
	scheduling for a single machine.	maximizing machine availability.		

Table 1	(Continued)	). Additional	literature	survey
---------	-------------	---------------	------------	--------

References	Торіс	Aim	Mathematical	Genetic
			Model	Algorithm
Ugarte <i>et al.</i>	Development and integration of a	The aims at providing real-time		
(2009)	reactive real-time decision support	decision support.		
	system in the industry .			
Nonas <i>et al.</i>	Scheduling problem arising in a	Minimize the total number of		
(2000)	foundry industry .	days orders		
CherngWu et al.	An Operator Staffing and	Minimize the operator cost		
(2005)	Assignment Model.			
Arouje <i>et al.</i>	Lot sizing and scheduling problem in	Minimize the total inventory and		
(2012)	small foundries.	total delay cost		
Aghezzaf <i>et al.</i>	An integrated production and	Minimize the maintenance cost		
(2007)	preventive maintenance planning			
	model.			

Table 1 (C	ontinued).	Additional	literature survey
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References	Торіс	Aim	Mathematical	Genetic
			Model	Algorithm
Stawawy <i>et al.</i>	Model and algorithm for planning	Minimize the cost and delivery		
(2012)	and scheduling in foundry.	time		
Maticevic <i>et al.</i>	Production scheduling model in	Minimize the delivery time		
(2006)	Aluminum foundry.			
Cassady et al.	Integrating preventive maintenance	Minimize the total expected		
(2005)	planning and	weighted completion time of		
	production scheduling for a single	jobs.		
	machine.			

Table 1	(Continued).	Additional	literature survey	/
---------	--------------	------------	-------------------	---

References	Торіс	Aim	Mathematical	Genetic
			Model	Algorithm
Cassady <i>et al.</i>	Minimizing job tardiness using	Minimize the total weighted		
(2003)	integrated preventive maintenance	tardiness of jobs.		
	planning and production scheduling.			
Duda <i>et al.</i>	Lot-sizing problem in an automated	Minimize the bottleneck and		
(2013)	foundry.	delivery time		
Austgen <i>et al.</i>	Scheduling foundry production	Minimize the weekly demand		
(2015)	without mold inventory.			
Landmann <i>et al.</i>	Production scheduling optimization	Minimize the efficiency of the		
(2007)	in the casting industry using genetic	foundry operation and to reduce		
	algorithm.	energy consumption		

References	Торіс	Aim	Mathematical	Genetic
			Model	Algorithm
Landmann <i>et al.</i>	Production scheduling optimization	Minimize the efficiency of the		
(2007)	in the casting industry using genetic	foundry operation and to reduce		
	algorithm.	energy consumption		
Ballestion <i>et al.</i>	Production scheduling in a market-	The aim is to make efficient		
(2012)	driven foundry a mathematical	production plan.		
	programming approach versus a			
	project scheduling mateheuristic			
	algorithm.			
Duda <i>et al.</i>	Lot-sizing problem in an automated	Minimize the bottleneck and		
(2013)	foundry.	delivery time		

 Table 1 (Continued). Additional literature survey

## **CHAPTER 3 : PROBLEM DEFINITION**

## **3.1. INTRODUCTION**

Manufacturing plants should implement necessary plans or tools to come up with plans to meet incoming demand for their products. In this context, determination of production quantities and workflows in the production environment is critical for production planning. There are many factors that make it difficult to implement plans in production environments. Machine capacity, orders and work orders, routes, setups, product trees, raw materials, semi-finished goods, labor, molds and production elements, deadlines, delay penalties, quality problems and etc. can be considered as the limiting factor in production in this context. The presence of a large number of limiting factors makes it difficult to plan production effectively in the organization.

The first important goal for all businesses is to optimize cost and maximize profit, and to minimize operating cost with the incoming demand.

In this foundry plant, foundry planning and scheduling are provided over Excel file with a program used in the company. The following problems are encountered while analyzing the system.

- Mold and labor costs are not taken into consideration while it is aimed to decrease stock cost based on mold-part compatibility.
- Since mold usage and maintenance limitations are not considered, delay costs emerge.
- Machine is working as automatically. One person is assigned to each machine, and thus unnecessary labor costs emerge.

These criteria are set out as pioneering ones.

Under the light of decision variables and performance criteria described above, a mathematical model will be developed to analyze the current situation. The model will represent all the factors affecting the problem (gross weight, demand, delay, cost, inventory cost) in a realistic way.

Purpose of this model is to minimize delay costs, inventory costs and furnace installation costs and mold maintenance cost.

## **3.2. MATHEMATICAL MODELS: OBJECTIVES & FORMULATION**

With the mathematical model, it will be possible to ensure timely delivery of orders with less inventory levels by considering other constraints such as usage of mold and maintenance, parts to produce, machine of production and date of production. The model will represent all factors affecting the problem such as Foundry and smelting machine park (availability, maintenance compatibility), setup times (sometimes sequence dependent), BOM structure, raw materials (availability, compatibility and preparing), mold (maintenance, availability, compatibility) in a realistic way. These constraints are given by considering all possible combinations.

In this model, two models were developed by considering machine-mold, mold-part compatibilities, minimum and maximum production quantities, mold usage/maintenance costs.

The mathematical model-1 was developed to minimize the total backlog cost, the total cost and setup cost. The mathematical model-2 was developed to minimize the total backlog cost, the total cost, setup cost and mold maintenance costs.

# 3.2.1. MATHEMATICAL FORMULATION (MODEL-1)

The mathematical model-1 was developed to minimize the total backlog cost, the total inventory cost and total setup cost.

## **SETS & INDICES**

A = Set of alloy

- a =Index of set of alloy,  $a \in A$
- I = Set of items
- i = Index of set of items, production,  $i \in I$

T = set of periods

t = Index of set of periods (hours, days,weeks,months etc.),  $t \in T$ 

*M* = Set of machines

- m =Index of set of machines
- K = Set of molds

k =Index of set of molds

B = A big number

M = A big number

#### PARAMETERS

*Cap;* capacity (kg) of a single furnace loading. Same for all, different type of furnaces

 $r_i$  gross weight (kg) of item *i* 

 $\mathbb{Z}_{it}$  demand of item *i* ordered in period *t* 

 $\mathbb{Z}_{\mathbb{Z}}$  set of item *i* that use alloy *a*.

 $h_{it}$  penalty for delaying a unit of item *i* in period *t* 

 $h_{it}^+$  Penalty for holding an unit of item i in period t

 $\square_{(m)}$  setup penalty for alloy *a* (money)

 $\boxed{22}$  setup loss of capacity (kg) due to a setup for alloy a $\boxed{22}$   $\underbrace{222}$  
antml:image>
5LondnmvS7SW20nQbFpspHDBHGmTngKAKANoSZOMfN3Gafu5xWTpl9b3i3E9tMJIWmIJHZto4/l+dXZ7iG1hLySCNfU0ATtKq5z0HWqr6paRStHJMiMBkgtVG28QabeXhsoJ1aVgdo9cAn+leY3dpZ3HjDWrnUknnWG3RkjSUr3oA9ZGs2ZXImj64++KfBqlrctIIZFcx9cGvHb2HS7C0TUJPDGoC3ZgPMN2cD3rsNEs9Pt9Hvr3SlkSO8tIZTuct3lHFAHXHWbEIW8+PI4xuFK+sWSAkzR4AzncK8a0iw0xNIhkubC7vrq4uJFwk5XoauW1vokPiK30e/0K+smuSoR5LondnmgD1x9StkgSZpFEb4wxPrTP7XsvM2ieM8ZzuFed+OLRBoegWQZ1t18hCAxBIAA61ny6XpUk1zFaeHr+5FuTudbojOBmgD1SPV7OSZIllUyODgA5p76paRyNHJMisvUFq868Dx6LqV3DfWdlPa3dpK0bRyTF9uYn4NY91aWU3inXLrUop7gQxoUjjlK96APWl1mzZQ3nR4Jx98U6LU7aeF5Y5FZEJDHPAxXjt/HpWlQwXtz4a1CK2kbHnG7OF464rrbmxtbDwNqK6aHjhmbzRucsfmiTvQB2R1mx2qRPGc/7QpJNasYgxaePAOPvDmvItO0zSl03Tof7KvL66ng3sUuCOalsLXQ7rVLvRLnR7yyuUikZRJdFt21c5oA9em1C2gZRLIqBuhJxmov7YsiWAmjO0Z+8Oa8/wDHVpHe+L9JgujIbfe25EYrnj2rFms9Maznu7fwzqE0VvnLLdkZwcUAetLrNi06widN7dBu61oA5Ga8NuYdIubDQ9X0y3uInN/5UimYnGB0r2mwULZxkAjcM8mgC1RRRQAUUUUAU9V/5A97/wBe8n/oJrmfhR/yS7w9/wBe3/sxqj448UNcrJ4Q8OlbzxBqCNEwjbK2UZ4eSUj7uAeB1zj2z12haTBoOhWOlW+TFZwJCrHq20Yyfc9fxoA0qKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigApsmfLbHXFOpko3RMPagDzvw4Fl+IWuRzqrL9nTgj3pfFNvc+JdVh8PQxGO2TEzuBwQOo4rO0fxJpOifELWl1XULe2zAm0yHGeam0XxFpNpr9zfXHiCxkgcNtKk8CgDp206LSNPurK1BEUVpEoBOcDMlZvgDyj4PWd40eRJ5SCVHHzVZOt6bri6tNpd7HcJFbQhmRsgZMtcp4d8WaIvgKbT21qztb9pZAFc8g7qANTRdGk8U+KH8R6hE8ccDeXBHnBDISM8etdTqElva+E98+DH9lGCfXZxXPeG/FmgaTpC297rlmZDIzAqxGc1k/FHV5Lb4W2txZNkTRw4l6rtZR/SgCT4Kz+Z4N1WeYvtOqysu4548uKsu4vtQ8eeO59MWRotOsZDG23jd0PUVo/ChY2+FMkdtMkkrNIXC9d+0f0xXNfDPXdN8N63r8euXC2129wNgmbBPy0AepLo2naVqulrCGE4Mgjy2ST5bZ+vGawvDgWX4ha5HOqsv2dOCPes6XxFc6t8TfDFuBi233JVwMBv9HkpdH8SaTonxC1pdV1C3tswJtMhxnmgDR8U29z4l1WHw9DEY7ZMTO4HBA6jitxtOi0jT7qytQRFFaRKATnAzJXMaL4i0m01+5vrjxBYyQOG2lSeBW8db03XF1abS72O4SK2hDMjZAyZaAK3gDyj4PWd40eRJ5SCVHHzVR0XRpPFPih/EeoRPHHA3lwR5wQyEjPHrWX4d8WaIvgKbT21qztb9pZAFc8g7q3PDfizQNJ0hbe91yzMhkZgVYjOaAK3jMslroA42+bAOfTit/xVftpOlOLK2DyXLCH5AM/Nxn9a5XxpqNta6V4cvpLiMWrtbv5jdNpAOfyqbxH4k0bVtVs5rHxDYGCLG9Mk5Oc0AbfhbwonhqwttxLXc0paZs8M3lv2rP8MKk3jjX0nVWAjTgj3rai8VaHq2pWdlY6nBPdGRjsRsniJya5TRPEukaL4416PVdRt7VjGm0yHGaALviCxn8X+IYdEMRjsbIiaRhwHDDGBitbxDbCw8LalbwA+XFwM84xGlYXh3xHpGnalfXd74gsZIpR8rKSMDOa0tb1ay1XwprF9p91HPbrKVLqcjIiTP8AOgC74emjtPAun3qwq8yWuQQoz34rF8PeH21CS/8AFd+rpPdRO8KZx5alcEH8qoReK9EvPAOm2Fvr1jBeLGu9WJyMdRW1a+MPD1n4XFlPrVobhbZlAVsZODQAzxCzH4haEr42tK2cj2q34zmnNnHoen2+06iTCXVRhO+T+VZPi3VLTR/H2hzahcxQ2/mNl5Og4pt34j0e78XwajB4hsHs4yp2AnIwOaAItf8AD1r4c0XQbVCVxeb3yerEc16XZSIbCJww2hOSe1eY+NvE+h6xc6DDYanBO63wLBWz2r0+yw1ogwCMdhxQBysnxW8DRbt3iSzO087dzflgc1Rn+NXgWMhINWlu5m4WK3tJWZj7ZUD9a6FvA3hF2LN4W0QknJJ0+LJP/fNU7v4Z+CL3/W+GNNX/AK4wiL/0DFAGX/wsDXdRXGheAdbnz0k1EpZJ9fmJJFMfQPHniVQmu67baJYt9+00ZSZmX0MzfdP+6MVJ/wAKl0Wz+bQtS1vRGHIFhfuFz7q+7I9qjeP4jeF/3qXNn4rsE+9E8YtbsL/skfI2Pfk0AdR4e8LaN4Ws/s2kWMVurffkAzJIfVnPLH61t1znhrxnpHipJY7OSSC9h4ubG6Ty54D6Mh/mMiujoAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAprrvQrnGadRQBlXHh3SbuYzXOmWksp4Z3iBJFRf8IrorLtbS7QAHICxCtqigDNtdGsLISC0s4IFkADLGgAYDOM/mfzqu3hXRCWI0iy3HnPkjrW1RQBinwtohbedLtC2MYMQwKsz6TaXFitjLawyWoUAROoKgAYGB7Vo0UAeXeMru68GGxs9EsUisZJUkmcJ8oJbB/QCtWaTwVclr6c2E12wLMMAkmuzu7K1vofKuraG4jznZNGHH5GqI8LeHlbcug6WG9RZx5/lQB534TsLrxB47XXPszW2nWYf7OrLjJKshx+dejXHh3SbuYzXOmWksp4Z3iBJFX7e3gtYhFbwxwxjokahQPwFTUAYv/CK6Ky7W0u0AByAsQqxa6NYWQkFpZwQLIAGWNAAwGcZ/M/nWlRQBit4V0QliNIstx5z5I60HwtohbedLtC2MYMQwK2qKAM2bRrCe2jtp7OCWCMAJG6AhcdABUC+F9FVvl0qzUEc4iFbNFAGTbeHtKs5UltrC3ilTOJEQBuhHX6Gifw5pF1MZrnTLSWVvvO8QJNa1FAGL/wiuisoD6XaYBzgRDBqxDo9jBbvbw2kKQOctEqAKeAM4+gFaVFAGJ/wiuiL9zSLIEHj9yOlOPhXRNzN/ZdqS3rEOK2aKAM670awv8fbLOC5K/dMqBsVWHhXRcMo0u0VSP4YgK2qKAMZfC+ipJG6aZaqYzuUiIA5rXVQowoAA7CnUUAFFFFABRRRQBw/j/wnHqenSa7pgNp4i02Mz2l5EMOxQZ8tv7ykZGD6/UHofDGsr4i8MaZq6oF+126Sso6KxHzD8DkVb1X/AJA97/17yf8AoJrmfhR/yS7w9/17f+zGgDsqKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAp6r/yB73/AK95P/QTXM/Cj/kl3h7/AK9v/ZjXTar/AMge9/695P8A0E1zPwo/5Jd4e/69v/ZjQB2VFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAU9V/5A97/ANe8n/oJrmfhR/yS7w9/17f+zGum1X/kD3v/AF7yf+gmuZ+FH/JLvD3/AF7f+zGgDsqKKKACiiigAorz7WvjB4b0fVptNji1HUriDIn/ALPtxKsRHXcSw6e2a6Xwx4r0jxdpf2/SLnzowdrow2vG3ow7GgDcooooAKKKydb8Q6V4eghl1O7S3E8qwwgglpHPQADk0Aa1Fc14t8Z6f4Nt7KbUILqVby4FvGIFViGPc7mHFdLQAUUUU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xrIGXDKD0yOPwr6Ar538a+N/wDhNPFHhKTTbG7j0a31OMLdXEewTyll4UegA/WvoigDhvi9qn9lfDHWZA2HnjFuv1cgH9M15XpPiI+JrPw/8NdD1D7BYtbBb+/AO6dgNzxx/jkZ7/Tr2PxuJ1M+F/DKEk6lqS71H90YH/s/6VF8VvDUXh7w1ouv+H7VLd/DtwjKkYx+6JGc+vzYz9TQB6X4f8P6b4Y0iLS9Kt1gtox2+857sx7k+tcd8dP+SV6h/wBdYf8A0MV3GkapBrOjWep2pzBdRLKn0IziuH+On/JK9Q/66w/+higDk/i2JT8OPBSwSbJjNbBHU4Kt5XBFdFrfwi8I2/gm9jXTwb6K1eUXrSMZWlCk7ic85I6dKwfip/yIPgT/AK+bX/0WK9c8Rf8AIs6r/wBec3/oBoA5L4Najc6l8MNLkupGkkiMkIZjk7VYgfkOPwrrfEf/ACLOrf8AXnN/6Aa4n4E/8krsf+u03/oZrtvEf/Is6t/15zf+gGgDx/4PfDzRdX8GwaxrtouoyTF47eO4JZIIgxGFXpktuOaveGrYeA/jXN4X0+R/7G1W1NzFbsxIhcAnjP8AusPoR6Vg/C74l23hDwRb2XiCxvo7PzJGsruGHekg3Hch9GDZ/Oul8GWuo+MviTceO7rT57HTIbf7NpyXC7XkB43Y9MFvbnvigDhW8V+FNd+IGtaj48luLi3tpjb6dZqjtEiAkEkL9B9STUepeK/B2jeK9H1rwA09pN54ivrQRvHFNESOx4/D6HtXVWd7dfB7xprQ1TT7qbw5q032iG8t494ibJOG/PBHXgEZrZi+JWr+MPEWn2PgfT5Tp6vuv7+8tyI1T0XnrjPuT2oAyfihpMev/GHwjpkrutvdW7JNsYqWj3MWXI9QCPxq78VfCWg+GPhdq7aNpsNkZ5LcSmPPzbX46n3NTeM/+S++Cf8ArhJ/7PWr8dP+SV6h/wBdYf8A0MUAc149v7690XwJ4Ps7h7aPWY4VuZEOCYwqDb9OSfwFdNffBjwbPoL6fb6WtvcBMRXiu3mq+OGJzzz26VieNPD2q3fhnwd4l0O3a5v9EihmNuoy0ibEJwO5G3oPWprn446XcaY0Gl6Tqs2uyJsjsDbnKyHjkjsD6c+woAw9F+IGrWnwO1qea4d9U02Y2EVwxy3zEBWz3IBPPsK6Hwh8JfCs/gyzl1fTxfahfQLPcXMrtv3ON3ynPGM/41S0L4Y37fBzU9Ev9ser6m5vCrHiOTgopP8AwHn0zTPDvxctfDeg22heJdK1S31yxjFuIEg3eftGFKnPcAe3pmgCP4N6U+ieO/GulyTyTm2kjjEshyzKC20k+uMV7VXivwbu73UPHfjW91K1a2u53ikkhfrHksQp9wMV7VQB4T418JaJr/x20fTPsRb7TA11qZ85/wB6ADgfe+XhQPlx1r2bSNJstD0u30zTYPIs7ddsUe4ttGc9SSTyT1NeN2niiw0v9obWpdYSdJZUjsLELEW5OwZ9gfX3r0zXPHOmaB4p0jw9dQXb3eqMFheJFMa5bb8xLAjn0BoA6iiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigDgvhJ/yKt//wBhe8/9GGu9rgvhJ/yKt/8A9he8/wDRhrvaACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACs7XIZLjQNSghQvLJayoijqxKkAVo0UAcH8INI1DQ/h3Z2Gp2kltdJLKWikGCAWJFd5RRQAUUUUAFFFFABRRRQAUUUUAFFFFAFeSztpbhJ5LaJ5k+5IyAsv0PUVjaz4el1rXNHupboJZadMbryBH80kwGEJbPCjJOMda6GigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooppIVSSQAOST2oA4T4Sf8irf/APYXvP8A0Ya72uA+ETCXwdcTod0U+p3ckbjo6mU4I9uK7+gAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiikOccdaAForO1HWbPSoxJdzxxp3LHGKNM1uw1eIyWVxHMo/uNmgDRoqFpdsbucALyS3pWNaeLtIvbyS1hu4jKhwRuHNAG/RRRQAUUUUAFFFFABRRRQAUUUUAFc/4o8Ry+GrKC5i0PU9WMkvlmLT4fNdBgncR1xxXQUUAePa18c5dLZU/4QzV7YsQN+pg2yqff5WqzpsetfE23I1HxTpcGkMP32naFNvlkX+7LIeV9CAOQa9WIDKVYAg8EHvXG698N/D+rMby0t/7J1VMtFqGnDyZEf1O3Ab3z+YoA6nT9PtdKsILGyhSG1gQJFGo4VRVuuS+HeuXmv8AhCCfUdv2+3lktLll6SPGxUsPrgH65rraACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKaxIUkY/GnU1wChBGaAPOPi3HbzeHvsskKmW5yiMBk5rlfgcGsLu604sCyguQTyBmug8bvLqXjXw5pUTfu47rMv+6VNc3oNxb+Gfifq8rAeXHZbsHjPNAHbfEzxBcWOjPp+muTfy8kL2j/iNed/BnQIL/W9RvLgvILeQKpZeGyK25ppX0vVPFl7n94jw2yt2R1NSeFrq5g+HnhOxwxju45C23gj52PWgD2aivI5r6Ozg/fWl9HbIx3SvJwfWu8l1qy0nw3DdzXKIotFaPcevyjFAHQUVxXhXxxY+INPSWedEZwCOcV2tABRXP60fFou0/sBdENts+f7e0ofdntsGMYxWbu+JP9zwp/33cf4UAdlRWRoR1/7PJ/b400Tbv3f2AyFduO+/nOa16ACiiigAooooAKKKKAOC+En/ACKt/wD9he8/9GGu9rgvhJ/yKt//ANhe8/8ARhrvaACiiigDgfiz4pvPDXhJRpjFNS1CdbS3cdULdWHvjp9a5qf4I2sGhtfW2saoPE8cXmi++0H5pQM4x1xnjrmpPjbxqXglm/1Q1UbvTqn/ANevXWxtOemOaAOL+Fniqfxd4Jt7y8P+nQO1tcnGNzr/ABfiCD9c121eQ/AIH+wdfI+4dUfb/wB8ivSvEV8+leG9T1CIZktrWSVPqqkigDK134h+EvDV19l1bW4ILgdYlVpHX6hASPxrS0TxLoviWza60fUYLyFeHMZ5Q/7SnkfiK86+C/hjTbnweviLULaG91PUppJJbi4QSMAGIwM9OhJ9c1S1jT7fwV8cvDs+ixLa2+tI0N3bRDajHOM7RwOqn6igCrB8WNJHxgu57nxBN/wjqWnk26+TLsEx25+QLnOQ3JH41dl1Ky0z9orUL6+uora1j0dWeWVtqgYX1qXTbWA/tJaxGYIvLGlqQpQYziPnFZ+paDYeIP2knt9SgSe3gsFn8pxlXZVAGR3GTnHtQB6Ho/xL8HeINQWw0zXYZbpjhI2R4y59F3qAT9K6a7vLbT7WW6vLiO3t4l3SSysFVR6kmvH/AI5aNp2maBpOrWNnb219b6hGiSwRhDtwTjj3AqD42apNNrHhbQ2tbu9sp2+03NnaAmS5wQAoA69/zoA7q1+LPgW8vhZw+IrbzmbaN6OiE/77KF/Wul1XVrDRdKm1TULgRWcC75JQpfA6ZwoJPXsK8d1fW9P1Tw/LpB+EOvxQtEUiMel7TEccMpC5BFFsdZX9m7V7XXbW8trm1RoUW6iaNzGGUrwwBxzj8KAPQW+KHg1Ly3s212I3FwivHGsUjEhhlQcLwSCODg+1bXh/xHpXijTv7Q0e7F1a7zHv8tkww6jDAH9K5T4W+GdHtfh7ok4061e4miW5eZ4VLlzznJGeOg+lc74EvI/BXiPx5oU52W9kzanAD/zzIycfhtoA9G0zxdoWta3faNp+oLNqFiSLiERuuzBweSADz6E1DrniPQILqTw7qF+0V3d2kknlRxOzCLa25shSBgA9fSvEfh7FdeHvHHhfXbtm2+KI7gSljxuLkr+fyH8a6rTl/wCEj8deP/EjfNb6fZSabbN2yEO7H5H/AL6oA7X4eJ4b0vwLCfD2py3OjRNI4ubr5SOSWzlVwAc9qi/4W94CF59l/wCEjt/MzjPlSbP++9u38c1wPhTQ9R8Rfs3yaZpbf6XLJIUTO3zAJclc+4FU7Txr4X03QY/DHjPwNcaR+5EDyraKQxxgyAkBge+Ru5oA97t7iG6t47i3lSWGRQySRsGVgehBHUVyeofFTwRpl+1ndeIbcTq21hGjyKD6FlUgfnXG+JL/AE3w18BJR4R1Oa7sZWFvDcvJl1Dt8w6DB6jGBjNZPhfW7DRPDNrp6fCfXbsNCpmmbTPM+0MRyxJU5B7e1AHuGn6hZ6pZR3lhdRXNtIMpLE4ZW/EVbrxn4QJqdh4q8Q2w0DVtI0G5xcWsF9bugifIBUEjHQ/kBXs1ABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFQXUy29s8ruEVRksegqemOquhVlDKeoIoA8h0HU7HXPi7qkguUbyoo/s/PBfJBxVrxT8OLnXviHbasjFLREQShQQHx1HFekRaVZQ3Anis7eOTP30jAP51bMfy4BPXNAHjnxi1HT7Hw7a6LBMkLefH8nfaG5rXs0t4tG8Kx28geNkYIy9MZNehXGk2F5Ir3VnBMwGMyRhv51zPiawu0vNOOnacZEtycCMAAUAR6zYzavqMGjBEFmgDynPJDDnisL4sRw2vhKwtExvMsNuijrt4FaUF14hj1+e7bQZ2UxKo5HasT4j6PrOrPo+o2VnJI0TRNLAP4WyCQfpQB0nhTwVYaZo9qkkQ8xU/u13VcvpWpazfXQ+06VLaRjqWIOa6igDn9a8H6P4iu0udQS6aRE2KYb2aEYznojAHr1rO/4Vf4W/54aj/wCDW6/+OV2NFAGRovh3TvDsEsGnJOscrb2865kmOcY4LsSPwrXoooAKKKKACiiigAooooA4L4Sf8irf/wDYXvP/AEYa72uC+En/ACKt/wD9he8/9GGu9oAKKKKAOG+KXhK48W+EzDp+P7Ss5lurUE43MvVc9sg/niuWn+Kut3OhtpUHg3XF8TSR+SVNsRCrkYL7uuO/THv3r2KigDj/AIaeE5PB3gu2065Km9kZp7kqcjzG7Z74AA/CunvbWK/sbiznGYp42iceqsMH+dWaKAPE/Dt14u+FkU+gT+GL7XdIWVnsrvT0LsATnDKAcfjjBz1rR0HRPEfjL4h2/jHxFph0mx0+MpYWUrZlJOfmYdupPIHbjvXrdFAHjPiNde8KfGOfxRaeGr/WLG8slg/0OMuUIABztBx93v61pWWnag/7QFxq50+8TT5NKVBctCwj3YX5d2MZ9q9UooA8x+N2m3+reDrODTtPur2ZdQjcx20LSMFAbJIUHj3qX4k+D9U1qDRtd0DH9taO4kijc481eCV575Hf3r0migDyO6+IvjW/017HT/h/q9tq8ieWJplIgjY8bgxAB9Rk/jWhr2i+Il+Cmo6dqc8+r63Lb5fyo97FiwOxQoycD29a9MooA5rwDbT2ngHQra6gkgnis41kilQqyEDoQeQa8z+M3hrXpfENrqXh6xurk6jZtp959mhaTau4EFto4GD1PpXuNFAHlHxN8K3sPgDQzoNtNNqOgzQNbpbxl3IACnCjk8gH8KveBvDl5o3wjuLe5tphqd7BcXE8TIRIZHU4Ur1zjAx616TRQB494N0LxVB8D1sNLa50jXUlkkjS4h8tj85O0hxxkdD9Kc3j7xRNop0rVPhrq13qBTypCYd1tI2Mbi20jHfv9a9fooA8g8PfCu8/4VFqHhzVJFgv76U3SqDuW3fjavH+7zj1pmieNPGnhbSIdD1jwJq2o3VmghiurEF45VHC5YAgcY5/QV7FRQBwngGDxlO9/q3iucwfa3za6aNpFunuRznoMZ+td3RRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFNaMMwJ6inUUAR7XGMFfemvCsigMB1zx61NRQAx49w4OKfRRQAUUUUAFFFFABRRRQAUUUUAFFFFAHBfCT/kVb/wD7C95/6MNd7XBfCT/kVb//ALC95/6MNd7QAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQAUUUUAFFFFABRRRQB5vJpPiTwPqt7feG7VdZ0K9na5n0wyBJ7eVjlmiY8Mp67T+HrV22+LXhcyfZ9Ulu9FvMfNbapbPCw/HBX9a7uoLi1t7uPy7mCKZP7siBh+RoAyLHxp4X1OeOCx8Q6XPPIdqRJdoXY+gXOSa3qx4/C/h+K7ju49C0xLmJsxzLaRh0PqGxkGtigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigAooooAKKKKACiiigD//2Q==

## **DECISION VARIABLES**

 $\mathbb{Z}_{i\mathbb{Z}t}$  = Quantity of item *i* to be produced on mold *k* in period *t* 

 $I_{t}$  = Quantity of item *i* delayed at the end of period *t* 

 $I_t^+$  = Quantity of item *i* inventory at the end of period *t* 

Binary variable ,

1 if item *i* can be produced with mold *k* in period *t*,

G<sub>illt</sub> = 0 otherwise

222221t binary variable,

 $\boxed{2222}_{122t} = \begin{cases} 1 \text{ if machine } m \text{ has mold } k \text{ in period } t, \\ 0 \text{ otherwise} \end{cases}$ 

 $\boxed{2222}_{\boxed{22}} - \boxed{2222}_{\boxed{22}(t-1)} \text{ binary variable,}$ 

 $\boxed{2222}_{22}t - \boxed{2222}_{22}(t-1) - \boxed{0}$ 1 means setup for machine *m* in period *t*0 means no mold setup on machine to *m* in period *t* 

 $\square$  binary variable,

1 indicates that the furnace is set up for producing alloy a in period t

0 otherwise

 $\mathbb{I}_{L}^{\mathbb{Z}}$  binary variable,

 $\mathbb{E}_{t}^{[7]} = \left\{ \begin{array}{c} 1 \text{ if there is setup alloy } a \text{ in period } t \\ 0 \text{ in period } t \\ 0 \text{ if there is setup alloy } a \text{ in period } t \\ 0 \text{ in period } t \\ 0$ 

Thus  $\mathbb{Z}_{t}^{\mathbb{N}} = 0$  if  $\mathbb{Z}_{t-1}^{\mathbb{N}} = 1$   $\mathbb{Z}_{t}^{\mathbb{N}}$  and  $\mathbb{Z}_{t-1}^{\mathbb{N}} < \mathbb{Z}_{t}^{\mathbb{N}}$ .  $\mathbb{Z}_{t}$  binary variable,

 $\mathbb{Z}_{\mathbb{Z}t} = -\begin{cases} 1 \text{ if mold } k \text{ is used in period } t \\ 0 \text{ otherwise} \end{cases}$ 

MIP model:

The objective function (1) minimizes total cost. Total cost includes order, delay cost for each period. This part is setup cost alloy changeovers in each period. Thus, the objective function seeks balance between conflicting goals: inventory, backlog and setup.

Subject to:

 $K \square$   $I_{tt-1}^{+} - I_{tt-1}^{-} + \square$   $I_{tt}^{+} \square I_{tt-1}^{+} - I_{tt}^{+} + I_{tt}^{-} \square I_{tt}^{+} + I_{tt}^{-} \square I_{tt}^{+} + I_{tt}^{-} \square I_{tt}^{+} + I_{tt}^{-} \square I_{tt}^{+} + I_{tt}^{-} \square I_{tt}^{-} \square I_{tt}^{-} + I_{tt}^{-} \square$ 

Constraint set (2) assures inventory balance. In constraint is (3) limits furnace usage by furnace capacity manages. Each alloy can use one furnace. Therefore constraint 4 allows number of furnace different alloys being used during each period. Constraint (5) makes sure that only 1 item can be scheduled to be produced on a machine in a period.

$$[ 2222 (2222_{22t} - 2222_{22t-1}) ] \times 222 + [ i22 - 22F_{222t-1}] \times$$

2 (22 Fait

 $\mathbb{Z}F_{i} + \begin{bmatrix} i & \mathbb{Z}h \times \mathbb{Z}_{i\mathbb{Z}t} \end{bmatrix} P(6)$ 

Constraint (6) t molds m which can be used in machines in the period, and if the previous period (t-1) production to continue and period t in the setup mold needs to be done to mold change t can be produced in the short mold in period *i* items and if in the previous period (t-1) in the period t continue production *i* items should be included in the setup and period length must be less than or equal.

$M  imes$ ZZZ $\mathbb{Z}_{\mathbb{Z}\mathbb{Z}t}  imes M_{\mathbb{Z}t}$		ľ	7	2	2 (7)
$\mathbb{Z}_{l\mathbb{Z}t}$	i				
$M \times \mathbb{Z}\mathbb{Z}F_{\mathbb{Z}it} \times M_{\mathbb{Z}t}$		?	i	2	(8)
□ <sup>i</sup> □t i					

Constraint (7): The mold used in the machine of mold in t period eligibility must be greater than or equal to the t period i items in manufacturability. Constraint (8): The product manufacturability mold used in molding the period must be greater than or equal to the period of production of each product.

2222001 2
**F**<sub>2it</sub> 1 2, 2 (10) i



Constraint (9): Production can be done only in a mold consistent for each machine in the period. Constraint (10): Each mold compliant product manufacturability of the period is less than or equal to 1.

$$\mathbb{Z}_{\mathbb{I}\mathbb{Z}t} \quad M \times \mathbb{Z}_{\mathbb{Z}t} \quad \mathbb{Z} \quad \mathbb{Z} \quad (11)$$

 $\mathbb{E}_{\mathbb{Z}t} \quad 1 \text{ m} = 1, ..., \text{M t} = 1, ..., \text{T} \quad (12)$   $\mathbb{E} \{ K \mathbb{E} \mathbb{E}_{t} \mathbb{E}$ 

Constraint (11): Mold that is available must be equal to or smaller than the reproducibility for t period and k mold. Constraint (12): Production of mold in period t must be smaller or equal to 1.

$$\vec{c}_{t}\vec{c}_{t} \quad \vec{c}_{t} \times \vec{c}_{t}\vec{c}_{t} \quad \vec{c}_{t} \quad (13)$$

$$\vec{c}_{t}^{[2]} \quad \vec{c}_{t}^{[2]} - \vec{c}_{t-1}^{[2]} \quad \vec{c} = 1, \dots, \vec{c} \quad \vec{c} = 1, \dots, \vec{c} \quad (14)$$

Constraint (13) produce only if properly ensures production on a machine occurs only when properly setup. Constraint (14): If there is a setup carryover to alloy *a* or to equal 0.

```
A = P_{t} = 1 \ P = 1, ..., T (15)
B_{t} = 1 \ P = 1, ..., T (15)
B_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t} = 1, ..., P_{t}
```

Constraint (15) and (16) furnace is setup only for 1 alloy at a period. Along with constraint (17) and (18) there is a changeover to alloy a just 0 or 1 values, even if the variables are not integer optimal.

 $I_{it}^+ \mathbb{Z}\mathbb{Z}\mathbb{Z} I_t^- = 0, i = 1, ..., I, \mathbb{Z} = 0, ..., \mathbb{Z}$  (19)

Constraint is (19) inventory and delay as non-negative variables, due to their positive parameters in the objective function.

### 3.2.2. MATHEMATICAL FORMULATION (MODEL-2)

In the field literature, the cost of installation, inventory costs, delays cost and maintenance costs are not reviewed and analyzed together. At this time, molds are unable periodically. Difficulties due to the problems that emerge for use and maintenance of the mold have been ignored. While satisfying demand, emerging problems were studied due to the ignoring of mold and maintenance. Mold usage was minimized and cost of maintenance were minimized with this solution technique. Problems that may occur due mold usage and ignoring maintenance while planning and estimating the demand were analyzed, and a mathematical model was developed.

The mathematical model-2 was developed to minimize the total backlog cost, the total cost, setup cost and total mold maintenance costs.

### **SETS & INDICES**

A = Set of alloy

- a =Index of set of alloy,  $a \in A$
- I = Set of items
- i = Index of set of items, production,  $i \in I$
- T = set of periods
- t = Index of set of periods (hours, days, weeks, months),  $t \in T$
- M = Set of machines

m =Index of set of machines

*K* = Set of molds

k =Index of set of molds

B = A big number

M = A big number

### PARAMETERS

capacity (kg) of a single furnace loading. Same for all, different type of

furnaces

ri gross weight (kg) of item i

 $\mathbb{Z}_{it}$  demand of item *i* ordered in period *t* 

 $\mathbb{Z}_{\mathbb{Z}}$  set of item *i* that use alloy *a*.

 $h_t$  penalty for delaying a unit of item *i* in period *t* 

 $h_t^+$  Penalty cost for holding an unit of item *i* in period *t* 

2 (money) setup penalty for alloy *a* 

 $\boxed{\mathbb{Z}}$  setup loss of capacity (kg) due to a setup for alloy

а



## 0 otherwise



 $M_{\square}$  = 0 otherwise

 $i\mathbb{Z}p\mathbb{Z}\mathbb{Z}\mathbb{Z}_{i}$  = Initial stock for item *i* 

 $12222222_i =$ Initial backlog for item *i* 

 $\mathbb{Z}_{i}$  = Cycle time of mold *k* 

 $\mathbb{Z}_i = \text{Cycle time of item } i$ 

P = Period length (1 hour)

 $\boxed{2}\boxed{2}\boxed{2}$  = Setup time of mold *k* 

 $\mathbb{Z}P =$  Setup time of item *i* on mold

 $M_{\mathbb{Z}t} = \begin{cases} 1 \text{ if available mold } k \text{ in period } t, \\ 0 \text{ otherwise} \end{cases}$ 

222 = cost of regular maintenance

 $\boxed{\mathbb{Z}}$  = ( $\boxed{\mathbb{Z}}$   $\boxed{\mathbb{Z}}$  cr<sub>k</sub>) cost of carry out irregular maintenance

**r**= duration of planning period

 $r_i$  = processing time for unit of product *i* 

### **DECISION VARIABLES**

 $\mathbb{Z}_{i\mathbb{Z}t}$  = Quantity of item *i* to be produced on mold *k* in period *t* 

 $I_{it}$  = Quantity of item *i* delayed at the end of period *t* 

 $I_{it}^+$  = Quantity of item *i* inventory at the end of period *t* 

Preventive maintenance cycle

 $\boxed{\mathbb{Z}}$  = Total production of units for mold

Dint binary variable,

 $\Box_{i\square t} = \begin{cases} 1 \text{ if item } i \text{ can be produced with mold } k \text{ in period } t, \\ 0 \text{ otherwise} \end{cases}$ 

2222 binary variable,

$$\boxed{2222} \xrightarrow{1}_{1} = 1 \text{ if machine } m \text{ has mold } k \text{ in period } t,$$
  
0 otherwise

 $\mathbb{Z}\mathbb{Z}\mathbb{Z}\mathbb{Z}_{\mathbb{Z}\mathbb{Z}t}^{t} - \mathbb{Z}\mathbb{Z}\mathbb{Z}\mathbb{Z}_{\mathbb{Z}\mathbb{Z}(t-1)}^{t}$  binary variable,

 $\boxed{2222}_{22t} - \boxed{2222}_{22t}(t-1) = \begin{bmatrix} 1 \text{ means setup for machine } m \text{ in period } t \\ 0 \text{ means no mold setup on machine to } m \text{ in period } t \end{bmatrix}$ 

 $\square_{L}^{\square}$  binary variable,

1 indicates that the furnace is set up for producing alloy *a* in period *t*  $\overline{a}_{t}^{[2]} = \langle$ 

0 otherwise

 $\mathbb{G}_{L}^{\mathbb{Z}}$  binary variable,

 $\mathbb{E}_{t}^{\mathbb{P}} = \begin{cases} 1 \text{ if there is setup alloy } a \text{ in period } t \\ 0 \text{ otherwise} \end{cases}$ Thus  $\mathbb{E}_{t}^{\mathbb{P}} = 0 \text{ if } \mathbb{E}_{t-1}^{\mathbb{P}} = 1$   $\mathbb{E}_{t}^{\mathbb{P}} \text{ and } \mathbb{E}_{t-1}^{\mathbb{P}} < \mathbb{E}_{t}^{\mathbb{P}}.$ 

**P**<sub>t</sub> binary variable,

$$\mathbb{Z}_{\mathbb{Z}t} = -\begin{cases} 1 \text{ if mold } k \text{ is used in period } t \\ 0 \text{ otherwise} \end{cases}$$

MIP model:

$$M_{12} = I_{12} + h_{it} + h_{it} + h_{it} + I_{it} + h_{it} e objective function (1) minimizes total cost. Total cost includes order, backlog cost for each period. These part is maintenance cost in each period. Thus, the objective function seeks balance between conflicting goals: inventory, backlog, setup and maintenance.

Subject to:

$$t = 1, ..., T(2)$$

(3)

<u>G</u><sub>iEt</sub> = 1 k = 1,...,K t = 1,...,T *i* {⊠ ⊡⊡⊡⊡⊡∑y}1

Constraint set (2) is inventory balance. Constraint (3) makes sure that only 1 item can be scheduled to be produced on a machine in a period.

$$\begin{bmatrix} 2222 (2222_{22t} - 2222_{22}(t-1))] \times 222 + \begin{bmatrix} i22 & -22F_{222}(t-1) \end{bmatrix} \times \\ \begin{bmatrix} 222F_{2it} \end{bmatrix} \begin{bmatrix} 22F_{2it} \end{bmatrix} \begin{bmatrix} 22F_{2it} \end{bmatrix}$$

$$\mathbb{Z}F_i + \begin{bmatrix} i & \mathbb{Z}h[\mathbb{Z}_{i\mathbb{Z}t}] \end{bmatrix} P(4)$$

Constraint (4) t molds m which can be used in machines in the period, and if

the previous period (t-1) production to continue and period t in the setup mold

31

needs to be done to mold change t can be produced in the short mold in period *i* items and if in the previous period (t-1) in the period *t* continue production *i* items should be included in the setup and period length must be less than or equal.

 $M \times \mathbb{Z}\mathbb{Z}\mathbb{Z}\mathbb{Z}_{\mathbb{Z}\mathbb{Z}t} \times M_{\mathbb{Z}t} \qquad \mathbb{Z}, \ \mathbb{Z}, \ \mathbb{Z} \ (5)$   $\mathbb{Z}_{i\mathbb{Z}t} \qquad i$   $M \times \mathbb{Z}\mathbb{Z}F_{\mathbb{Z}it} \times M_{\mathbb{Z}t} \qquad \mathbb{Z}, \ i, \ \mathbb{Z} \ (6)$   $\mathbb{Z}_{i\mathbb{Z}t}$ 

i

Constraint (5): The mold used in the machine of mold in t period eligibility, must be greater than or equal to the t period i items in manufacturability. Constraint (6): The product manufacturability mold used in molding the period must be greater than or equal to the period of production of each product.

Constraint (7): Production can be done only in a mold consistent for each machine in the period. Constraint (8) each mold compliant product manufacturability of the period is less than or equal to 1.

```
□<sub>1□2t</sub> M×□<sub>□t</sub> □ □ (9)
iI
```

```
\mathbb{Z}_{\mathbb{Z}t} \quad 1 \text{ m} = 1, ..., \text{M} \text{ t} = 1, ..., \text{T} \quad (10)
\mathbb{Z} \{ K \mathbb{Z} \cong \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} : \mathbb{Z} :
```

 $\mathbb{C}_{i\mathbb{C}t} \quad \mathbb{C} \times \mathbb{G}_{i\mathbb{C}t} \quad i\mathbb{C}t \quad (11)$ 

Constraint (9): Mold that is available must be equal to or smaller than the

reproducibility for *t* period and *k* mold. Constraint (10): Production of mold in 33



period t must be smaller or equal to 1. Constraint (11) produce only if properly ensures production on a machine occurs only when properly setup.

$$\mathcal{F}_{i} \times \mathbb{Z}_{i\mathbb{Z}t} \quad \mathbb{Z}(\mathbb{Z}) \quad \mathbb{Z} \quad (12)$$

Constraint (12): The production system has a known nominal capacity denoted by  $C_{max}$  and that each maintenance action consumes a certain percentage of this capacity.

$$\mathbb{Z}_{i\mathbb{Z}\ell}$$
 o  $\mathbb{Z}\mathbb{Z}$   $\mathbb{Z}\mathbb{Z}\mathbb{Z}g\mathbb{Z}$  ,  $i = 1, ..., I$  ,  $\mathbb{Z} = 1, ... \mathbb{Z}$ 

(13)

$$I_{it}^+ \mathbb{Z}\mathbb{Z}\mathbb{Z} I_t^- = 0, i = 1, ..., I, \mathbb{Z} = 0, ..., \mathbb{Z}$$
 (14)

Constraint (13): There is a changeover to mold k just 0 or 1 values, even if the variables are not integer optimal. Constraint is (14) inventory and delay as non-negative variables, due to their positive parameters in the objective function.

$$\mathbb{E}_{t} \mathbb{E}_{t} \mathbb{E}_{t} \mathbb{E}_{t} \mathbb{E}_{t}$$

$$\mathbb{E}_{t} \mathbb{E}_{t} $

Constraint set (15) is inventory balance. In constraint is (16) limits furnace usage by furnace capacity manages. Each alloy can use one furnace. Therefore constraint 4 allows number of furnace different alloys being used during each period. Constraint (17): If there is a setup carryover to alloy *a* or to equal 0.

```
A = 1 = 1 = 1, ..., A (18)
a = 1 = 1, ..., A (18)
a = 1 = 0, = 1, ..., 2, = 2, ..., 2 (19)
a = 1, ..., 2, 2 = 1, ..., 2 (20)
```

Constraint (18) and (19) furnace is setup only for 1 alloy at a period. Along with constraint (20): There is a changeover to alloy *a* just 0 or 1 values, even if the variables are not integer optimal.



### CHAPTER 4: VOLT ELECTRIC CASE STUDY

There is a planning and scheduling problem at the foundry workshop at Volt Electric Motor (a Saya Group company). Volt Engine has become one of the leading electric motor producers in Turkey with its technology, product quality, product range and a capacity of 45,000 m2 production space.

3 shifts per day and 6 days a week operations are conducted in this plant. Production consists of 5 sections including lamination, foundry, machining, winding and assembly.

Production process first starts in the lamination section. In laminating section, two types of package production are carried out ranging from 63 type body to 315 type body. Rotor packages are poured in the foundry section respectively and sent to the machining section for shaft connection. Shaft is installed in machining production and it is left to be mounted to the body after balancing process. Stator packages is processed in the winding section to coil up. After coiling, cable connections are made and they are varnished. After varnishing process is completed, the part will be mounted on the body and sent to assembly department. Other ready spare parts are also mounted, packed and sent to the storehouse. General business flow chart of the plant is below in Figure 2.



Figure 2 Production foundry study

In this thesis, foundry section was discussed that is one of the production departments. Foundry operates with an integrated system in itself. Drawings created by the R&D department are designed. Emerging designs are modelled in CNC processing machines in machining production model. Horizontal injection molding machines have automated foundry line. All processes ranging from mold preparation to removing of part from the mold are carried out on computer controlled automated foundry line.

Depending on requested production quantities coming from production planning, purchasing department provides necessary resources. Foundry department prepares monthly or weekly production plan and distributes over current machines. There are seven horizontal and four vertical injection molding machines. Existing machine park is shown in the table below in Table 2.



	Horizontal Injection Machine
	Horizontal Inj. Rbt. 560 tons
	Horizontal Inj. Rbt. 730 tons
	Horizontal Inj. Rbt. 400 tons
	Horizontal Inj. Rbt. 730 tons
/	Horizontal Inj. Rbt. 730 tons
	Horizontal Inj. Rbt. 430 tons
	Horizontal Inj. Rbt. 430 tons

Horizontal injection machine mechanism is shown in the below Figure 3.



Figure 3 Horizontal injection machine mechanism

According to the given plan, machine assignment is done based on mold tonnages. By considering mold tonnages, suitable mold is attached to the machine. In the meantime, main melting machines are loaded with aluminum and it is melted.

There are two units of main melting machines, Etial-7 Aluminum and Etial-160 Aluminum are melted in these machines. Etial-160 is used in Feet, Cover, Body foundry. Etial-7 is used for rotor foundries. Aluminum found in the main melting is fed from furnaces located next to each foundry machine, feeding operation is carried out by the operating using a forklift. Each furnace is maintained at a constant temperature using natural gas, this temperature ranges from 700 to 750 degrees.

Horizontal injection molding machines work fully automatically. Robot arm of the injection machine takes the aluminum with predetermined grams into the furnace. The arm drops aluminum into injection chamber of the machine that is also called shell. This process is repeated after the completion of a product cycle. The first process modelling with regard to the subject is as follows:



Figure 4 Flow chart of the foundry production process

Process flow of the overall foundry production in the model was established on an analytical order. This flow illustrates a conventional linear flow of production. Classical linear process flow is similar for almost all factories for foundry large parts throughout the world. After pouring the product into the injection machine, again product that is poured with the robot arm is taken and left to the stacking area. Vertical injection machines are operated semi-automatically. In these machines, operator carries out the work of robotic arm in horizontal injection. During injection, operator takes aluminum in predetermined gram and its monitoring is provided over Excel with a program used in injection chamber planning and scheduling. With the developed model, analysis of current situation will be made. With the developed model, it will be possible to ensure timely delivery of orders with less inventory levels by considering other constraints such as usage of mold and maintenance, parts to produce, machine of production and date of production. Consideration shall be given to the following matters while analyzing the system;

- A single product is mass-produced in a certain period of time.
- Production occurs at a fixed cycle.
- Processes are assigned to workstations based on priority relationships.
- There are series production lines consisting of **N** units of workstations.
- In workstations, equal number of labor and machine equipment is provided as much as possible.
- Production stop is not allowed.
- It is not possible to carry out a work in more than one station.
- Due to technological priorities, it is not possible to carry out processes in an arbitrary order.
- Output weight of the alloy is equal to the gross weight of products used. Processed alloys cannot be processed in the furnace.
- Only one alloy is processed on the furnace in a given period.

These criteria are set out as pioneering ones. Under the light of decision variables and performance criteria described above, a mathematical model

will be developed to analyze the current situation. The model will represent all the factors affecting the problem (gross weight, demand, delay, cost, inventory cost) in a realistic way. Answers to be sought on the model:

- Based on priority order, when, under what conditions and with what results constraints and crisis emerge in the production plan for production plan,
- Results of alternative machines grouping policies,
- For defined different situation, to minimize mold maintenance and mold change positions,
- To minimize delay cost and total cost
- To minimize stock cost by producing at minimum stock level
- To prevent cluttering in current capacities

Success of an optimization study is determined at which level the prepared mathematical model reflects the real system. Therefore, while preparing the mathematical model, order related to processes must be followed. This process starts with the purpose of preparation of the model and correct identification of existing problems in current situation. Required data is collected and analyzed to achieve the specified objective, and a mathematical model indicating the current status is prepared. It must be investigated whether the prepared model represents the real system and, if necessary, corrections should be made. Then the model is run, and obtained results are recorded. In accordance with the determined objective, alternative models are prepared, run and their results are compared with the results of the current situation.

### 4.1.DATA COLLECTION

There are two hundred product groups, seven machines, two hundred molds, two alloy types. Data were collected from foundry workshop of Volt Electric. Product code, product description, product group, product weight, alloy type for ten products data tables are shown below Table 3. There are two hundred product group, seven machine, two hundred mold, two alloy type. The table below shows only 10 items as an example, because listing all items and molds would take too much space.

Product Code	Product	Product Weight	Alloy Type
	Description	(kg)	
AYAK60000000	80 GÖVDE	0,100	Etial-160
	AYAĞI		
GOV100710001	Y.M. 71'LİK A.SZ	0,607	Etial-160
	ALÜM.GÖVDE		
KP215T136205	6205 Y.M. 90	0,537	Etial-160
	ST.SĞKAPAK		
GOV1132S000	Y.M 132S'LİK	3,546	Etial-160
	A.SZ		
	ALÜM.DÖK.		
KLKT01022000	ÜÇ FAZLI 132	0,480	Etial-160
	ALÜMİNYUM		
	K.KUTUSU		
GOV190L00000	Y.M. 90L'LİK	1,658	Etial-160
	ALÜM. GÖVDE		
KP204T016204	6204 Y.M. 80	0,317	Etial-160
	KAPAK		
KP215T036205	6205 Y.M. 90	0,766	Etial-160
	B14 FLANŞ		
	KAPAK		
KP216T036206	6206 Y.M.100	0,880	Etial-160
	B14 FLANŞ		
	KAPAK		
GOV190S0000	Y.M. 90S'LİK	1,250	Etial-160
	ALÜM. GÖVDE		

 Table 3 Product group for item

Products transition between change mold need a preparation time necessary in the machine. Normally there are two hundred items. Therefore, you need a matrix setup in size 200 x 200.Instead, the preparation time between product groups in this case is simplified and shown in the following table.

- AY: Foot product group
- BO: The extension part of the product group
- GO: Body product groups
- KL: Terminal box product line
- PE: Propeller product line

Table 4 Product groups between setup times (h)

	AY	BO	GO	KL	KP	PE
AY	2.5	2.5	3.0	2.5	2.5	2.5
BO	2.5	2.5	3.0	2.5	2.5	2.5
GO	3.0	3.0	3.0	3.0	3.0	3.0
KL	2.5	2.5	3.0	2.5	2.5	2.5
KP	2.5	2.5	3.0	2.5	2.5	2.5
PE	2.5	2.5	3.0	2.5	2.5	2.5

The distribution of production for 20 periods is given below in Table 5. I have shown ten item table as an example because of much more production number.

demand(d)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
AYAK60000000	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900	900
GOV100710001	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225
KP215T136205	568	568	568	568	568	568	568	433	0	568	568	568	568	568	568	0	0	568	568	568
GOV1132S0000	144	144	144	144	144	144	144	144	23	0	0	0	0	0	0	0	0	0	0	0
KLKT01022000	251	251	251	251	251	251	251	251	251	43	0	0	0	0	0	0	0	0	0	0
GOV190L00000	177	177	177	177	177	177	177	177	177	177	97	0	0	0	0	0	0	0	0	0
KP204T016204	900	900	900	900	900	900	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KP215T036205	568	568	568	568	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
KP216T036206	150	580	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
GOV190S00000	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207	207

Table 5 Demand and item ordered for period

Cycle time of item ten and setup time of ten mold is as follows for ten item below Table 6. I have shown ten item table as an example because of much more production number.

Product Code	Product Description	Cycle time of item <i>i</i>	Setup time of mold <i>k</i>
		(dk)	(dk)
AYAK60000000	80 GOVDE AYAGI	1,20	150
GOV100710001	Y.M. 71'LİK A.SZ ALÜM.GÖVDE	1,50	180
KP215T136205	6205 Y.M. 90 ST.SĞKAPAK	1,15	150
GOV1132S0000	Y.M 132S'LİK A.SZ ALÜM.DÖK.	1,50	180
KLKT01022000	ÜÇ FAZLI 132 ALÜMİNYUM K.KUTUSU	1,45	150
GOV190L00000	Y.M. 90L'LİK ALÜM. GÖVDE	1,45	180
KP204T016204	6204 Y.M. 80 KAPAK	1,20	150
KP215T036205	6205 Y.M. 90 B14 FLANŞ KAPAK	1,30	150
KP216T036206	6206 Y.M.100 B14 FLANŞ KAPAK	1,00	150
GOV190S00000	Y.M. 90S'LİK ALÜM. GÖVDE	1,00	180

Table 6 Cycle time of item and setup time of mold

There are 7 horizontal injection machines. Product-machine compatibility eligible matrix is shown in below Table 7 .I have shown ten item table as an example because of much more production number.

eligible	HORIZONTAL INJ.RBT_1 (430 TONS)	HORIZONTAL INJ.RBT_2 (430 TONS)	HORIZONTAL INJ.RBT_3 (730 TONS)	HORIZONTAL INJ.RBT_4 (730 TONS)	HORIZONTAL INJ.RBT_6 (400 TONS)	HORIZONTAL INJ.RBT_7 (730 TONS)	HORIZONTAL INJ.RBT_8 (560 TONS)
KP215T036205	0	0	1	0	0	0	0
KP216T036206	0	0	1	0	0	0	0
AYAK60000000	1	0	0	0	0	0	0
GOV100710001	0	1	0	0	0	0	0
GOV1132S0000	0	0	0	1	0	0	0
KLKT01022000	0	0	0	0	1	0	0
GOV190L00000	0	0	0	0	0	1	0
KP204T016204	0	0	0	0	0	0	1
GOV190S00000	0	0	0	0	0	0	1
KP215T136205	0	1	1	0	0	0	0

**Table 7** Production-machine compatibility eligible matrix

Product-mold compatibility is as follows for ten item. I have shown ten item table as an example because of much more production number.

Mold	AYAK6000 0000	GOV10071 0001	KP215T13 6205	GOV1132S 0000	KLKT0102 2000	GOV190L0 0000	KP204T01 6204	KP215T03 6205	KP216T03 6206	GOV190S0 0000
GOV10071 0001	1	0	0	0	0	0	0	0	0	0
GOV10080 000	0	1	0	0	0	0	0	0	0	0
KP215T136 205	0	0	1	0	0	0	0	0	0	0
GOV1132S 0000	0	0	0	1	0	0	0	0	0	0
KLKT01022 000	0	0	0	0	1	0	0	0	0	0
GOV190L0 0000	0	0	0	0	0	1	0	0	0	0
KP204T016 204	0	0	0	0	0	0	1	0	0	0
KP215T036 205	0	0	0	0	0	0	0	1	0	0
KP216T036 206	0	0	0	0	0	0	0	0	1	0
GOV190S0 0000	0	0	0	0	0	0	0	0	0	1

# Table 8 Product-mold compatibility matrix

### **CHAPTER 5 : RESULTS**

Model-1 and model-2 were tested with real data to measure the accuracy. In both models, 1 time-period is equal to 3 hours. The purpose of the model is to minimize setup cost, inventory cost, backlog cost, regular maintenance cost and irregular maintenance cost by running according to 20 item, 20 mold and 2 alloy for timeframes of 20 periods, 30 periods, 40 period, 50 period and 60 periods.

The best solution for 60 periods shown in the table above is to decrease demand increase and installed capacity to a minimum and the number of mold presses to a constant value (100,000 pieces to 50,000 pieces). For the analysis, we used an optimization programming language, IBM ILOG CEPLEX 12.6. Results of this integer programming model is shown in the Appendix A.

- When demand does not exceed capacity, effect of backlog costume is not seen below in Table 10.
- When incoming capacity does not meet the capacity, inventory cost decreases in periods and a change in backlog is not observed. There is no change in regular maintenance costs and irregular costs below in Table 11 and Table 12.
- When the regular maintenance interval decreases without a change in demand (regular maintenance interval = 160, capacity = 180), no changes were observed in constraints below in Table 13.
- When the demand was the same, capacity was reduced (Capacity = 180 hour), regular maintenance interval was reduced (from T = 160 to 60), fixed number of mold press was reduced (from mn = 50,000 units to 100,000 units), reduction in regular maintenance

cost and inventory cost are observed below in Table 14 and Table 15.

- With the same demand, capacity was reduced, regular maintenance interval increased (from T=160 to 210), number of mold pressure constant was reduced (from mn=100,000 units to 50,000 units). Regular maintenance cost and inventory cost decreased below in Table 16.
- When setup capacity was minimized and capacity times were reduced against incoming demand, inventory cost decreased and backlog cost increased below in Table 17.
- When setup capacity was minimized and capacity times were reduced against incoming demand, and regular maintenance interval increased separately, while decrease in regular maintenance cost and inventory cost was observed, setup cost increased below in Table 18 and Table 19.

As capacity times decreased with setup capacity minimized against incoming demand, regular maintenance interval increased and fixed value of mold press decreased (mn=100,000k), it was observed that inventory cost, backlog cost values, regular maintenance cost values were also minimized.

The model was run according to 20 item, 20 mold and 2 alloy for timeframes of 60 periods. Besides, sensitivity range and low cost results are shown in Appendix B.

- Reduced cost of machine-mold compatibility is in the best solution set because its value is '0'. The value of reduced cost which is '0' is basic variable. The value which is between (0,1) and (0, ∞) shows the best solution in sensitivity interval below in Table 20.
- Reduced cost of product-period compatibility is 15 in between (0,0) and (0,∞). Coefficient of objective function should be decreased 5

units in order to do basic variable in range of  $(0, \infty)$  below in Table 21.

- Reduced cost is 0 in the range of (-∞,108) and (108, ∞) for product-period compatibility. It gives the best solution and values which are in the range are basic variables below in Table 22.
- The value of reduced cost is 0 in the sensitivity range of initial inventory for machine-mold compatibility, alloy-period compatibility and mold-item compatibility and it is in optimal solution below in Table 23, Table 24.
- The values which are in the range of (-∞,1)(1, ∞) are basic variables for item-mold compatibility and their reduced cost are 0. They are in optimal solution below in Table 25, Table 26 and Table 27.

Changes in constraints and results are discussed below in Table 9.

This problem was solved using IBM ILOG CPLEX Version 12.6 on a laptop PC with HP 15-BA010NT AMD A10-9600P CPU @ 2.4GHZ-8GB of RAM in 3:42:16 minutes. When the model was solved on the same PC with full scale real data, an "Out-of-memory" error was received.

	setup	capacity	inventory	backlog	setup	Regular	irregular	total	optimal
	capacity		cost	cost	cost	maintenance	maintenance	reduced	total cost
						cost	cost	cost	
1	2000	180	2.121.900	0	480	136.34	36038	363	2.259.083
2	500	90	2.121.900	0	480	13634	18800	352	2.258.878
3	500	60	2.121.900	0	180	13634	18800	363	2.258.896
4	500	120	2.121.900	0	180	13634	37600	352	2.259.084
5	500	90	4.714.600	0	480	13634	37600	336	4.851.819
6	500	90	4.754.700	727,31	534,8	0	37600		4.756.338
7	452	60	2.169.700	727,31	558,5	0	376.00		2.171.361
8	452	120	4.754.700	727.31	534.79	0	37600		4.891.040
9	452	90	4.754.900	727.31	534,8	0	37600		4.891.775
10	452	120	4.754.900	727,31	404	0	37600		4.756.407
11	452	60	4.754.900	885,45	484	0	37600		4.756.645

# Table 9 Performances of developed models

### **CHAPTER 7: CONCLUSION**

Consequently, the problem of foundry planning was explained in detail. The research discussed mathematical models and intuitive applications with a literature review. A mathematical model was developed, and all possible combinations were developed to find the optimal solution for probing. This model minimizes setup cost, inventory cost, maintenance cost and mold cost and it is developed as a first in the literature. However, in this thesis, additional mold maintenance costs were calculated for different die-foundry workshops in the literature. Thus, demands were met and the cost for production process was minimized. These studies were coded in CLPEX optimization programming language. Since the model could not solve the instance with full scale real data due to memory problems, a more efficient model must be developed or alternatively, heuristic methods should be tried.

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# **APPENDIX.A Initial Matrices for Optimal Solution**

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	2000	180	1.292.300	0	60	13634	36.038	0	1.342.032
for 30 period	2000	180	2.880.500	0	90	13634	36.038	0	2.258.878
for 40 period	2000	180	4.228.900	0	120	13634	36.038	0	2.258.896
for 50 period	2000	180	4.228.900	0	150	13634	36.038	0	2.259.084
for 60 period	2000	180	2.121.900	0	480	13634	36.038	363	2.259.083

 Table 10 Initial matrix for when the demand does not affect the capacity
	setup	capacity	inventory	backlog	setup	Regular	irregular	total	optimal
	capacity		cost	cost	cost	maintenance	maintenance	reduced	total cost
						cost	cost	cost	
for 20	500	90	1.388.700	0	60	13634	18782	infeasibilities	1.402.582
period									
for 30	500	90	3.077.200	0	90	13634	18782	0	3.091.112
period									
for 40	500	90	4.295.000	0	120	13634	18782	0	4.308.942
period									
for 50	500	90	4.568.500	0	150	13634	18782	0	4.582.472
period									
for 60	500	00	2 1 2 1 0 0 0	0	400	12624	10700	250	2 250 070
Deriod	500	90	2.121.900	U	400	13034	10/02	352	2.230.070
penou									

 Table 11 Initial matrix for when the incoming demand does not meet the capacity

**Table 12** Initial matrix for when the capacity of the same demand is reduced and the regular maintenance interval is reduced

	setup	capacity	inventory	backlog	setup	Regular	irregular	total	optimal
	capacity		cost	cost	cost	maintenance	maintenance	reduced cost	total cost
						cost	cost		
for 20	500	60	1.388.700	0	60	13634	18782	infeasibilities	1.525.288
period									
for 30	500	60	3.077.200	0	90	13634	18782	0	3.213.818
period									
for 40	500	60	4.295.000	0	120	13634	18782	0	4.431.648
period									
for 50	500	60	4.568.500	0	150	13634	18782	0	4.705.178
period									
for 60	500	60	2.121.900	0	180	13634	18782	363	2.258.896
period									

**Table 13** Initial matrix for demand is the same, capacity is reduced ,regular maintenance interval, and number of mold production is reduced

	setup	capacity	inventory	backlog	setup	Regular	irregular	total reduced	optimal
	capacity		cost	cost	cost	maintenance	maintenance	cost	total cost
						cost	cost		
for 20	500	120	1.466.200	0	60	13634	18.782	infeasibilities	1.602.788
period									
for 30	500	120	2.934.700	0	90	13634	18.782	0	3.071.318
period									
for 40	500	120	4.295.000	0	120	13634	18.782	0	4.431.648
period									
for 50	500	120	4.540.000	0	150	13634	18.782	0	4.676.678
period									
for 60	500	120	2.121.900	0	180	13634	18.782	363	2.258.896
period									

**Table 14** Initial matrix for the same demand was reduced and the regular maintenance interval, the number of mold production was reduced

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	500	90	1.461.600	0	60	13634	37.564	0	1.598.376
for 30 period	500	90	2.934.700	0	90	13634	37.564	infeasibilities	3.071.506
for 40 period	500	90	4.295.000	0	120	13634	37.564	0	4.431.836
for 50 period	500	90	4.616.000	0	150	13634	37.564	0	4.752.866
for 60 period	500	90	4.714.600	0	480	13634	37.564	336	4.851.819

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	452	60	1.600.000	260	140	10.539	37.564	infeasibilities	1.648.503
for 30 period	452	60	3.540.000	458	160.25	10.539	37.564	infeasibilities	3.558.561
for 40 period	452	60	4.470.000	680	256.95	13.629	37.564	infeasibilities	4.521.873
for 50 period	452	60	4.394.100	680	360	13.629	37.564	infeasibilities	4.446.333
for 60 period	452	60	2.169.700	727,31	558,5	0	37.564		2.208.550

# Table 15 Initial matrix for setup capacity can be minimized and when capacity times are reduced

**Table 16** Initial matrix for when the incoming demand is increased and the setup capacity is reduced and the capacity times are decreased

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	452	120	1.600.000	260	140	10.539	37.564	infeasibilities	1.648.503
for 30 period	452	120	3.540.000	458	188.67	10.539	37.564	infeasibilities	3.558.561
for 40 period	452	120	4.360.000	682	264.47	13.629	37.564	infeasibilities	4.521.873
for 50 period	452	120	4.394.100	682	311.4	13.629	37.564	infeasibilities	4.445.975
for 60 period	452	120	4.754.700	727.31	534.79	0	37.564		4.891.040

Table 17 Initial matrix for when the setup capacity is reduced and the regular maintenance interval is reduced

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	452	90	1.600.000	260	140	10.539	37.564	infeasibilities	1.611.315
for 30 period	452	90	3.540.000	458	188.67	10.539	37.564	infeasibilities	3.558.561
for 40 period	452	90	4.470.000	682	280	13.629	37.564	infeasibilities	4.521.873
for 50 period	452	90	6.707.600	682	324.25	13.629	37.564	infeasibilities	4.445.975
for 60 period	452	90	4.754.900	727.31	534,8	0	37.564		4.891.775

**Table 18** Initial matrix for demand increased and setup capacity minimize and when the regular maintenance interval value is increased

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	452	120	1.600.000	260	140	10.539	37.564	infeasibilities	1.611.315
for 30 period	452	120	3.540.000	458	188.67	10.539	37.564	infeasibilities	3.558.561
for 40 period	452	120	4.470.000	682	280	13.629	37.564	infeasibilities	4.521.873
for 50 period	452	120	6.707.600	682	324.25	13.629	37.564	infeasibilities	4.445.975
for 60 period	452	120	4.754.900	727,31	404	0	37.564		4.756.407

**Table 19** Initial matrix for demand increase and setup capacity minimize and when the number of mold production is reduced to a fixed value

	setup capacity	capacity	inventory cost	backlog cost	setup cost	Regular maintenance cost	irregular maintenance cost	total reduced cost	optimal total cost
for 20 period	452	60	1.600.000	260	140	10.539	37.564	infeasibilities	1.648.503
for 30 period	452	60	3.540.000	458	188.67	10.539	37.564	infeasibilities	3.558.561
for 40 period	452	60	4.470.000	682	280	13.629	37.564	infeasibilities	4.521.873
for 50 period	452	60	6.707.600	682	324.25	13.629	37.564	infeasibilities	4.445.975
for 60 period	452	60	4.754.900	727,31	404	0	37.564		4.793.595

## APPENDIX .B The Results of Sensitivity Range and Reduced Cost

### Table 20 Mold-period compatibility

		Dejele		*
mold (buyukluk 20)	(period (ouyukluk 60)	J Değer	Indirgenmis maliyet	Duyarlılık aralıçı
1	100 100 100 100 100 100 100 100 100 100	1	0	[-a 1] [1 a]
1	?	12	0	[01] [0]
1	3	5	0	[01] [0]
1	4	0	0	[01] [0]
1	5	0	0	[01] [0]
1	6	2	0	[01] [0]
1	1	5	0	[01] [0]
1	8	5	0	1011 [0]
1	9	Ŭ	0	[01] [0]
1	10	0	0	[01] [0]
1	11	D	0	[01] [0]
1	12	0	0	[01] [0]
1	13	î:	0	[01] [0]
1	(J14)	D:	0	[01] [020]
1	15	0	0	[01] [0]
1	16	0	0	[01] [0]
1	1/	Ð	0	[01] [0]
1	18	5	0	(01) (0)
1	19	5	0	101(10=)
1	20	D	0	[01] [0]
1	21	5	0	[01][0]
1	22	0	0	[01] [0
1	23	0	0	[01] [0]

#### Table 21 Item-period compatibility for initial backlog

📄 hable balonimed	📑 Falice bakimidat	🗍 SSM değeri	📄 🗄 SSP değer 🔄 🗐 Eminos değer (	23
		Degeder		
, itemm (bklok 20)	, period (bbyaklak 60)	, Değer	Indirgenmi; maliyet	Duyarlılık aralığı
1	1	Q	20	[0.22] [0.22]
1	2	6	25	[00] [00]
1	3	0	15	(03) (0*)
1	4	.0	15	[00] [0
1	5	0	15	[00] [0]
E	6	0	15	[00] [00]
î.	7	0	15	[00] [0]
1	8	0	15	[00] [0]
1	9	0	15	[00] [0∞]
1	10	0	15	[00] [0
1	11	0	25	[00] [0]
1	12	0	15	1031 [0]
1	13	0	15	10
1	24	0	15	[00] [00]
1	15	C	15	[00] [0]
1	16	0	15	[00] [0]
1	17	0	15	[00] [0]
1	18	0	15	[00] [0]
1	19	0	15	[00] [0]
1	1 20		15	[00] [0]
1	1 Z.		19	[00] [0]
1	1 22		15	1001 10
1	23	6	15	[00] [0]

a hatice_bakim mod	🔚 hatice_bakim dat	🚆 SSM deberi	📋 SSP değeri 🔄 İminus değeri	📋 lipius degeri 💥
		Degerier		*
, demm (b., klók 20)	period (böyöklök 60)	, Veĝe	İnda genimşi maliyet	Duyarlılık əral ğı
1	1	108	0	[+m,208][208,m]
1	2	0	10	[0.0][0.m]
1	3	0	5	[~, 0] (0, 0]
1	4	0	5	[0.0] [0]
I	5	0		[00] [0c]
I.	5	0	5	[co. 0] [0. 0]
1	7	0	5	[0.0] [0.0]
1	R	٥	-	[00] [00]
1	Э	0	3	[0.0] [0.0]
1	10	0	5	[00] (00]
1	11	U	3	10.0 [0.0]
1	12	Q	3	[U. 0] [U. M]
1	13	Q	- à,	10.0 (C.A)
1	14	0	5	[0.0] [0.2]
L	15	0	3	10.0110.011
1	15	0	5	[0.0] [0.~1]
1	17	0	5	[0.0] [0.0]
1	18	0		[0.0] [0.0]
1	19	0	5	[0.0] [0.0]
1	20	۵	5	[0.0] [0.0]
1	21	0	5	[0.0] [0.0]
1	22	0	5	[0.0] [0.0]
1	23	0	4	[0.0] [0.m]

Table 22 Item-period compatibility for initial inventory

ahatire_hakimmed		hatice_hak	im.dat 🛛 🗄 SSM değeri 😒	E SSP değer			
1			Değerler 🛠				
mach., k7)	, mol. 20)	, ellp 61)	, Değer	Indirgenniş məliyet	Doyarlılık aralığı		
3	17	35	0	0	[∞.0] [L.0]		
3	17	36	0	0	[0.1] [0.00]		
3	17	37	0	9	[01] [00]		
1	17	18	0	9	[01] [00]		
1	17	P	0.	0	[ea.0] [F.0]		
3	1/	40	6	3	[0,1] (0,10]		
3	17	41	C	0	(0.1) (D.s.s)		
3	17	42	0	0	[00 0270805] [0∞1		
3	17	43	0.00353264424063028	0	[ ∞.,0.00353264] [0.00353264.,∞]		
3	17	44	0.00350629847936328	0	[ 000.0035063] [0.0035063.00]		
٦	17	45	0.00150549495095768	D	[-@.0.00750649] [0.00750649		
1	1/	46	0.00 90549 4956451/	9	[+@.0.00 (50649] [0.00 (50649		
3	17	47	0.00386663947432795	9	[-m0.00686854] [0.00366854m]		
3	17	48	0	9	[0.1] D.m]		
3	17	-19	0	D	[0.1] [0.00]		
3	17	50	0	0	[0.1] [0.00]		
3	17	51	0	D	(01) (00)		
1	17	52	0	0	[01] [0os]		
1	17	51	0.00/16547515 (2981.1	0	[-@0.00 (16948) [0.00 (16948		
3	1/	24	0.00443508568520423	9	[-**0.00443808] [0.00443808*/		
3	17	55	0.00442011769480652	0	[0.00442612] [0.00442612]		
3	17	36	0.00142523056286537	0	[-∞0.00112623] [0.00112623∞]		
3	17	57	0 00442522549824864	þ	[ ∞0.00442623][0.00442623∞]		

### Table 23 Machine-mold compatibility

hative bakimmud		E halice bas	im.da.	🖽 \$5M değ	en 🔀 🗏 S	SP değeri		
			Değerle			4位	*	
mach. k7)	, mol. 20)	, ellp (i1)		Değer	Değer İndirgenmiş maliyet Duyarlılık aralığı	Duyarlılık aralığı	-	
1	1	0		0		0	[00] [00]	
1	1	1		Ð		0	[D1][D.∞]	
1	1	2		2		0	0 110	
1	1	3		5		0	[0 <b>1</b> ][0 ∞]	
1	1	4		D.		0	[D.J][D.co]	
1	1	3		5		U	(m, 0)]E. C	
1	1	6		0		0	[00][ <b>1</b> .∞]	
T	1	7		D.		0	[00] [10]	
1	1	8		Ð		0	[0]	
1	1	9		D		0	[0.1][0.∞]	
1	1	10		D.		0	[00] [0oo]	
1	1	11		U.		0	[0 1][0 m]	
1	1	12		5		0	[0.d][0.∞]	
1	1	13		D.		0	[00] [10]	
1	1	14		Ð		0	[0 ][[0 m]	
1	1	15		0		0	[] [D]	
1	1	16		0		0	[00] [1.0]	
1	1	1/		Ð		0	[0.1]{0.m]	
1	1	18		D		0	0.1][0]	
1	1	19		D		0	[0.1][0.00]	
1	1	70		D.		0	[0.1][[1.00]	
1	1	21		D		0	[w.0][L.0]	
1	1	22		0		0	[0.1] [0.∞]	
124		100		120		100		

### Table 24 Mold-item compatibility

💽 hat ce_ba	kimmed [	hatice_bakim.dat	🗇 😳 Midegeri	📃 🗄 SSP değeri 🕄	
		Değerler			**
mol. 20)	, itemm 20)	allperiJuk 61)	Drğrı	Indiagenmiş maliyet	Duyoridak aralığı
1	1	0	0	9	[00] [0]
1	1	1	D	Û.	[0.1][0.a]
1	1	2	. D	D	[][][]
1	1	3	0	9	[ <b>01</b> ] [ <b>0∞</b> ]
1	1	4	5	0	[0.1] [0.w]
1	1	5	b	D	[D1] [D]
1	1	6	5	0	[01] [0∞]
1	1	7	0	D	[01][0∞]
1	1	8	0	D.	[9.1][9.30]
I.	1	9	Ð	D	[][][]
1	1	10	0	D	[01] [0∞]
1	1	11	0	9	(0.1) (0)
1	1	12	D	0	[0.1][0]
1	1	13	0	D	[]_I][]_@]
1	1	14	0	0	[01] [0
1	1	35	10	0	[0.1][0.04
1	1	15	5	D	[][][]
1	1	17	0	0	[]1] []∞]
1	1	18	0	0	[01] [0]
1	1	19	0	9	[0.1][0]
1	1	29	0	3	[]1] []
1	1	21	0	0	[01][0∞]
1	1	22	5	9	(0.1)(0)

I namer na	amman	nonco_nakim.da	t 🖂 ssainegen	E 201 05351 59			
			Değerler		**		
1 mol20)	_ itemm 20)	Lallperiluk 51)	Deger	Indiagen mis maliyet	Duya blue are inc		
2	1	39	0	0	[01] [0∞]		
2	1	40	1	0	[ 0 1] [1 00]		
2	1	41	1	0	[ ∞ 1] [1 ∞]		
2	1	42	0.199226272108411	0	[-cc.0.199226] [0 199226cc]		
2	1	43	0.189534868205553	0	[-~.0189351] [0189335~]		
2	1	-14	0.1894086363635291	U			
2	1	45	0.189406086214.139	0	-m 0189406) 0 189408m)		
2	1	46	0_189400090017323	0	i-m. 0.189406] 10 109406m]		
2	1	47	0.00385063947432795	0	[+m0 00385864] [0 00386854 .m]		
2	1	48	10	0	[∞ 1] [ ∞]		
2	1	49	1	0	[ co 1] [1 co]		
2	1	50	1	٥	[ 00 1] [1 00]		
2	1	51	0	0	[01] [0]		
2	1	52	1	0	[-0,1] [1,0]		
2	1	53	0.190150605450517	0			
2	1	54	0185598500519778	0	-m 0.385599[ 0.186599m]		
2	1	55	0.185632015304145	0	0_185632] *D 186632		
2	1	56	0.18553169927372	0	[~m. 0.185632] [0.166632m]		
2	1	57	0.185531702254507	0	[-cc. 0.185512] [0.166512cc]		
2	1	82	0.186531702225365	٥	[ oc. 0.185522] [0.126632]		
2	1	59	0.186531702226544	٥	[ oc. 0.185632] [0.186632co]		
2	1	60	0.907388760700865	0	[ ∞ .0.907389] [0.007389∞]		
2	2	0	0	0	[00] [0v]		

and hat hat a set of the set of t

🛃 hatice bakim mod	[ hat de bakimidat	🗇 SSM değeri	🗐 SSP değer 🛛 🛛	🗄 W değeri 😥		
1	1		Degerier			
, comm (a. dik 7)	, mole (aŭyūklāk 20)	pened (hűyűklűk 90)	, Dejer	indirgenmis maliyet	Doya dok aralığı	
1	1.000	1	1	C	$[\times 1][1,\infty]$	
1	t	2	1	0	[-∞ 1] [1,∞]	
1	1	3	2	0	[-1.1][1.1]	
1	3	4	$T_{ij}$	0	[-cc 1] [1.cc]	
1	1	5	1	0	$[\infty, 1][1,\infty]$	
1	1	6	1	0	[-∞ f [1,∞]	
1	1	7	1	0	[·* 1][1.+]	
1	3	8	1	0	[-oc. 1] [1.oc]	
1	1	9	1	0	[x, 1][1, x]	
1	1	10	11	0	[-∞ 1] [1.∞]	
1	1	11	1	(	[-= 1][1.+]	
1	1	17	1	0	[-sc 1] [1.sc]	
1	1	13	1	0	[ se ][ []	
1	1	14	1	0	[-∞, 1] [1,∞]	
1	1	15	1	0	[-+ f][1.+]	
1	1	16	1	0	[-se 1] [] .se]	
1	1	17	1	0	[ = 1] [1.=]	
1	1	18	1	0	[-∞.1][1.∞]	
1	1	19	1	6	[-= 1][1.+]	
1	5	-11	4	0	[-ce. 1, [1.cc]	
1	1	21	1	(	[ × 1] [1 × ]	
1	1	22	11	0	[-× 1'[2.∞]	
1	1	23	1	6	[-+ 1][1,+]	

### Table 25 Mold-item compatibility

## Table 26 Mold-product for machine manufacturability

natice bakim mee	📄 hat de belam est	🗍 55M değen	🗟 55P dağan	🖫 x eigen 👸	-	
			Değerler			
, itemm (builduk 20)	_ mold (buyukleis20)	period (buyuiduk 60)	Deger	Indirgenmis maliyet	Duyarlı k aralığı	
10	1	1	ţ.	163 531	0.0 [0.m]	
			2.	107.851	[0, 0] [0.xe)	
1	1	3	1	153 031	(0.0) [0]	
Ť	9	4	2	15-8-1	0.0 [0.we]	
1	12	5	0	153 831	(0.0) [0.0]	
2	1	5	Ð	150 501	,0.0, [0.m]	
1 A	291	1	0	165.851	3.3 [0.44]	
1	1	8	0	153 831	(0, 0) [0,,⇔]	
1	1	3	2	152 521	0.0 [0.m]	
1	N.	10	5	157 831	[0.0] [0.00]	
1	1	11	0	153 031	[0.0] [0.0]	
1.	3	12	p.	He* 8-1	0-0 [0.av]	
1	1	Ľ	0	163 831	[0.0] [0.0]	
1	1	14	2	152 521	0.0 [0.m]	
±	4	15	5	165.851	0.01 [H.ue]	
1	1	16	1	153 831	(0.0) [0.00]	
1	1	1/	9	155 551	0.0 (0.m)	
7	1	15	5	107.851	ta .n; [0]	
1	1	19	6	153 831	[0 0] [0.0]	
1	4	x	5	Be 851	0.01 [0.00]	
1	1	21		153 831	[0.0] [0.0]	
2	1	22	D	152 531	0.0 [0.m]	
12		25	5	153.831	[cs0] [C. C'	

Table 27	Alloy-period	compatibility
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hatice_bekim mod	📑 batice_bakim dat	🗁 SSM degeni	🔲 SSP degeri 🗄 🗄 🗄 degeri 😫	
1	1	Değerler	*	
, alloy (böyüklük Z)	penod (böyöklök 60)	, Değer	İndugenmş maliyet	Duyarlılık asalığı
1	1	2	0	-m.1  1.m
1	2	1	0	[][1]
1	)	1	0	[-00.1][1.00]
1	4	1	0	[-20.1][120]
1	5	T	n	[ 001][100]
1	5	1	0	[ 201][120]
1	7	1	0	[ 001]["00]
1	8	1	0	[ 001][100]
1	9	1	0	[-20,,1] [1,,20]
1	10	1	0	[][1,]
1	11	1	6	[-00,1][1,00]
1	12	2	0	[-w.1] [1»]
1	13	1	6	[-m.1][1m]
1	14	2	U	[-10.1][1.10]
1	15	1	0	[-00.1][1.00]
1	15	2	0	[][]]
1	17	1	0	[-001][100]
1	18	1	0	[ 001][100]
1	19	1	6	[ 001][100]
1	20	10	.0	[ 201][120]
1	21	1	0	[ 00,,1][1,,00]
1	22	1	0	[-001][100]
1	23	1	0	[][[]