PRODUCTION PLANNING FOR FOUNDRY WORKSHOP

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JANUARY 2016

# PRODUCTION PLANNING FOR FOUNDRY WORKSHOP

A THESIS SUBMITTED TO

THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

OF

IZMIR UNIVERSITY OF ECONOMICS

BY

HATICE DOĞRAMACI

IN PARTICAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE

OF

MASTER OF SCIENCE

IN

THE GRADUATE OF NATURAL AND APPLIED SCIENCES

JANUARY 2016

Approval of theGraduate School of Natural andAppliedSciences

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# ABSTRACT

PRODUCTION PLANNING FOR FOUNDRY WORKSHOP

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M.Sc. in Industrial Engineering

Graduate School of Natural and Applied Sciences

Supervisor: Asst. Prof. Dr. Mahmut Ali Gökçe

December 2016, 81 pages

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

# ÖZ


DÖKÜM ATÖLYESİ İÇİN PLANLAMA

Doğramacı, Hatice

Endüstri Mühendisliği Yüksek Lİsans Programı

Fen Bilimleri Enstitüsü

Tez Danışmanı: Asst. Prof. Dr. Mahmut Ali Gökçe

Aralık 2016, 81 sayfa

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

## ACKNOWLEDGEMENTS

I would like to thank my project supervisor Asst. Prof. Dr. Mahmut Ali Gökçe, whowas always there when I needed help throughout my project study, whose invaluable ideas I benefited from and who always helped me to shape my project.

I would like to thank you my sisters; İpek Süğüt, Tuğçe Üstüner who have helped me during the master program.

Specially, I would like to thank you my family who has never stopped supporting and encouraging me. They are very important for me. They are the biggest chance of my life.

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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.

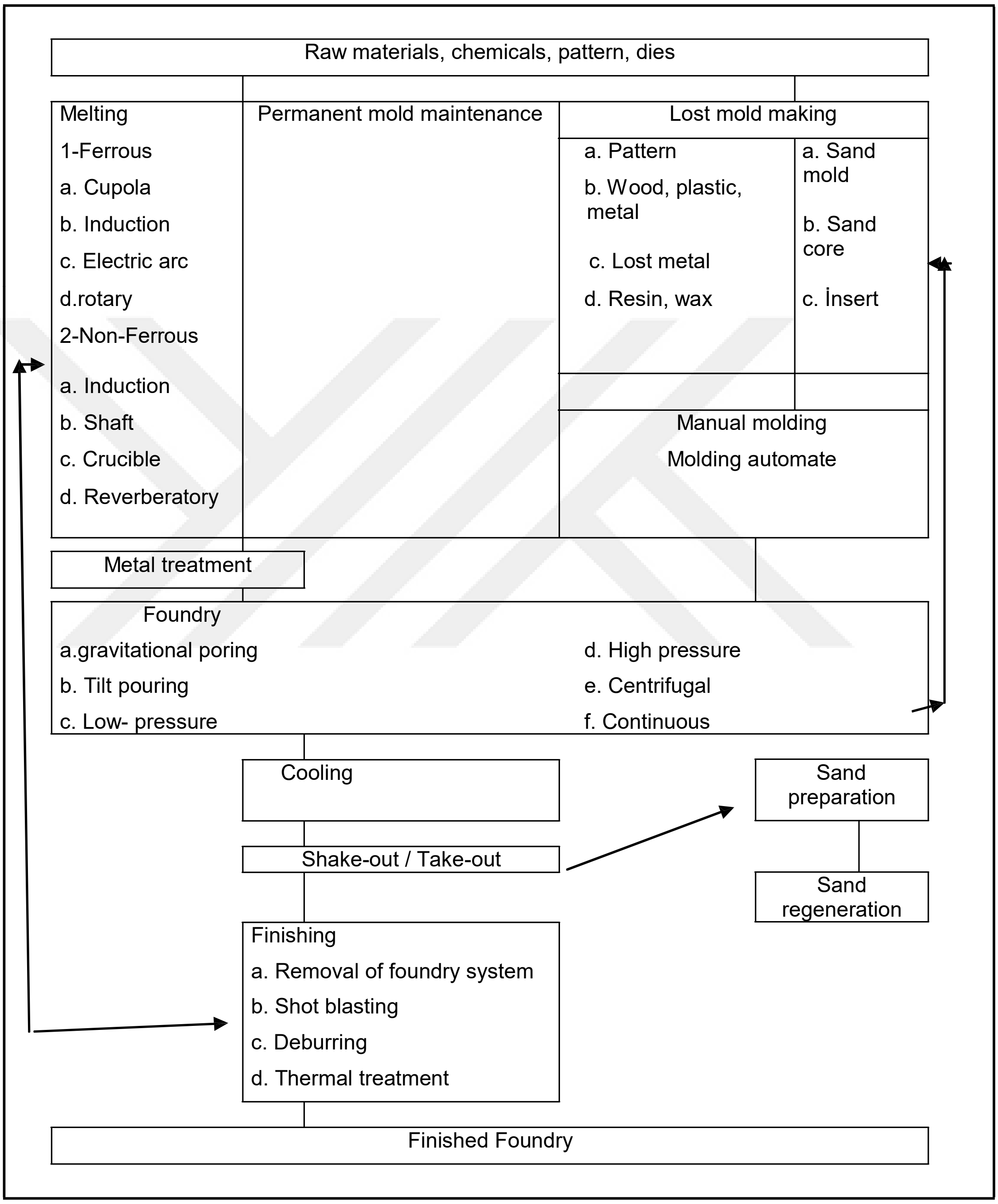


**Figure 1** Diagram of general foundry process (European Commission, 2005)

## 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, mold-item 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 real-time 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 ındustry 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 | Topic | Aim | Mathematical Model | Genetic Algorithm |
|---|---|---|---|---|
| Landmann *et al.* (2013) | Production scheduling optimization problem in the foundry industry. | Minimize the efficiency of the operator. | | □ |
| Sortrakul *et al.* (2005) | Genetic algorithms for integrated preventive maintenance planning and production scheduling for a single machine. | Minimize the integrated optimization model for production scheduling and preventive maintenance planning. | | □ |
| Yulan *et al.* (2007) | Multi-objective integrated optimization research on preventive maintenance planning and production scheduling for a single machine. | Minimize the maintenance cost, makespan, total weighted completion time of jobs, total weighted tardiness, and maximizing machine availability. | | □ |

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

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

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

| References | Topic | Aim | Mathematical Model | Genetic Algorithm |
|---|---|---|---|---|
| Stawawy *et al.* (2012) | Model and algorithm for planning and scheduling in foundry. | Minimize the cost and delivery time | ◻ | |
| Maticevic *et al.* (2006) | Production scheduling model in Aluminum foundry. | Minimize the delivery time | ◻ | |
| Cassady *et al.* (2005) | Integrating preventive maintenance planning and production scheduling for a single machine. | Minimize the total expected weighted completion time of jobs. | ◻ | |

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

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

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

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

# 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*

$\square_{it}$ demand of item *i* ordered in period *t*

$\square_{\square}$ 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*

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

??$_?$ setup loss of capacity (kg) due to a setup for alloy *a*

??ɩg??????ɩ??$_{ɩ?}$ binary variable,

??ɩg?????? = { 1 if item *i* can be produced in mold *k*, <br> 0 otherwise

ɩ??$_{ɩ?}$ =

??ɩg????? = { 1 if mold *k* can be used in machine *m*, <br> 0 otherwise

?? =

$M_?$ = { 1 if mold *k* available, <br> 0 otherwise

ɩ?r???$_i$ = Initial stock for item *i*

ɩ???????$_i$ = Initial backlog for item *i*

?$_i$ = Cycle time of mold *k*

?$_i$ = Cycle time of item *i*

$P$ = Period length (1 hour)

???$_?$ = Setup time of mold *k*

?$P_i$ = Setup time of item *i* on mold

$M_{?t}$ = { 1 if available mold *k* in period *t*, <br> 0 otherwise

**DECISION VARIABLES**

$?_{i?t}$ = 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*

$?_{i?t}$ Binary variable ,

$?_{i?t}$ = { 1 if item *i* can be produced with mold *k* in period *t*, 0 otherwise

$????_{??t}$ binary variable,

$????_{??t}$ = { 1 if machine *m* has mold *k* in period *t*, 0 otherwise

$????_{??t} - ????_{??(t-1)}$ binary variable,

$????_{??t} - ????_{??(t-1)}$ = { 1 means setup for machine *m* in period *t*, 0means no mold setup on machine to *m* in period *t*

$?_t^?$ binary variable,

$?_t^?$ = { 1 indicates that the furnace is set up for producing alloy *a* in period *t*, 0 otherwise

$?_t^?$ binary variable,

$?_t^?$ = { 1 if there is setup alloy *a* in period *t*, 0 otherwise

Thus $?_t^? = 0$ if $?_{t-1}^? = 1 \geq ?_t^?$ and $?_{t-1}^? < ?_t^?$.

$?_{?t}$ binary variable,

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

MIP model:

$$\underset{I_{it}}{Mi?i?????} \sum_{i=1}^{?} \sum_{t=1}^{?} (h_{it}^- + h_{it}^+ I_{it}^+) + \sum_{?=1}^{A} \sum_{t=1}^{?} (?_? ?_t^?) \quad (1)$$

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:

$$I_{it-1}^+ - I_{it-1}^- + \sum_{?\supset\{?:??i????i??\,?ty\}1}^{K} \sum_{t-?}^{?} ?_{i?t} - I_{it}^+ + I_{it}^- = ?_{it} \quad i = 1, \ldots I \quad t = 1, \ldots, T \quad (2)$$

$$\sum_{?=1}^{?} \sum_{i-?(?)}^{?} p_i ?_{i?t} + ??_t \leq ?_t ???? \quad , a = 1, \ldots, A \quad t = 1, \ldots, T \quad (3)$$

$$\sum_{?\varepsilon A} ?_t^? \leq 2 \quad ? = 1, \ldots, T \quad (4)$$

$$\sum ?_{i?t} = 1 \quad k = 1, \ldots, K \quad t = 1, \ldots, T \quad (5)$$

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.

[∑□▯▯▯▯ (▯▯▯▯▯▯t − ▯▯▯▯▯▯(t−1))] × ▯▯▯▯ + [∑□i▯▯ − ▯▯F▯▯▯(t−1)] ×

▯(▯▯F▯it

▯Fi + [∑□i ∑□▯ h × ▯i▯t] ≤ 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 × ▯▯▯▯▯▯t × M▯t ≥ ∑ □▯, □▯, □▯ (7)

▯i▯t

□i

M × ▯▯F▯it × M▯t ≥ ∑ □▯, □i, □▯ (8)

▯i▯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.

∑ ≤ 1 □▯, □▯ (9)

▯▯▯▯▯▯t

□▯

$$\sum_{\square i} \square\square F_{\square it} \leq 1 \quad \square\square, \square\square \qquad (10)$$

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.

$$\sum_{i \square I} \square_{i\square t} \leq M \times \square_{\square t} \quad \square\square, \square\square \quad (11)$$

$$\sum_{\square \square \{K \square \square i \square i \square ity\}1} \square_{\square t} \leq 1 \quad m = 1, \ldots, M \quad t = 1, \ldots, T \quad (12)$$

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.

$$\square_{i\square t} \leq \square \times \square_{i\square t} \quad \square_{i\square t} \quad (13)$$

$$\square_t^{\square} \geq \square_t^{\square} - \square_{t-1}^{\square} \quad \square = 1, \ldots, \square \quad \square = 1, \ldots, \square \quad (14)$$

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.

$$\sum_{\square=1}^{A} \square_t = 1 \quad \square = 1, \ldots, T \quad (15)$$

$$\square_t^{\square} \square \{0,1\} \square\square\square\square \square_{\square}^{\square} = 0, \quad \square = 1, \ldots, \square, \quad \square = \square, \ldots, \square \quad (16)$$

$$0 \leq \square_t^{\square} \leq 1, \quad \square = 1, \ldots, \square, \square = 1, \ldots, \square \quad (17)$$

$$\square_{i\square t} \geq 0 \square\square\square\, i \square\square\square g \square\square, i = 1, \ldots, I, \square = 1, \ldots \square \quad (18)$$

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.

$$I_{it}^{+} \square\square\square I_{it}^{-} \geq 0, i = 1, \ldots, I, \quad \square = 0, \ldots, \square \quad (19)$$

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**

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

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

[illegible]$_{it}$ demand of item *i* ordered in period *t*

[illegible] 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*

[illegible] setup penalty for alloy *a* (money)

[illegible] setup loss of capacity (kg) due to a setup for alloy *a*

[illegible] binary variable,

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

0 otherwise

[illegible] =

1 if mold *k* can be used in machine *m*,

[illegible] =

0 otherwise

$M_{?}$ = { 1 if mold *k* available,
0 otherwise

$i?r???_i$ = Initial stock for item *i*

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

$?_i$ = Cycle time of mold *k*

$?_i$ = Cycle time of item *i*

$P$ = Period length (1 hour)

$???_?$ = Setup time of mold *k*

$?P_i$ = Setup time of item *i* on mold

$M_{?t}$ = { 1 if available mold *k* in period *t*,
0 otherwise

$???_?$ = cost of regular maintenance

$??_?$ = ($???_? \leq cr_k$) cost of carry out irregular maintenance

$\tau$= duration of planning period

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

**DECISION VARIABLES**

$?_{i?t}$ = 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

$??_?$ = Total production of units for mold

$\square_{i\square t}$ binary variable,

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

$\square\square\square\square_{\square\square t}$ binary variable,

$$\square\square\square\square_{\square\square t} = \begin{cases} 1 \text{ if machine } m \text{ has mold } k \text{ in period } t, \\ 0 \text{ otherwise} \end{cases}$$

$\square\square\square\square_{\square\square t} - \square\square\square\square_{\square\square(t-1)}$ binary variable,

$$\square\square\square\square_{\square\square t} - \square\square\square\square_{\square\square(t-1)} = \begin{cases} 1 \text{ means setup for machine } m \text{ in period } t \\ 0 \text{ means no mold setup on machine to } m \text{ in period } t \end{cases}$$

$\square_t^{\square}$ binary variable,

$$\square_t^{\square} = \begin{cases} 1 \text{ indicates that the furnace is set up for producing alloy } a \text{ in period } t \\ 0 \text{ otherwise} \end{cases}$$

$\square_t^{\square}$ binary variable,

$$\square_t^{\square} = \begin{cases} 1 \text{ if there is setup alloy } a \text{ in period } t \\ 0 \text{ otherwise} \end{cases}$$

Thus $\square_t^{\square} = 0$ if $\square_{t-1}^{\square} = 1 \geq \square_t^{\square}$ and $\square_{t-1}^{\square} < \square_t^{\square}$.

$\square_{\square t}$ binary variable,

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

MIP model:

$$M\iota□\iota□□□□□ \sum_{i=1}^{□} \sum_{t=1}^{□} (h_{it}^{-} I_{it}^{-} + h_{it}^{+} I_{it}^{+}) + \sum_{□=1}^{A} \sum_{t=1}^{□} (□_{□} □_{t}^{□}) +$$

$$\sum_{□□K} \left( \frac{(\sum_{i□I} \sum_{t=1}^{□} □_{i□t})}{□□□} \times □□□_{□} \right) + \left( \int_{□_{□}}^{□_{f}} □(□)\, □□ \right) \times □□□_{□} \quad (1)$$

The 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:

$$I_{it-1}^{+} - I_{it-1}^{-} + \sum_{□□\{□:□□\iota□□□□\iota□□\ □ty\}1}^{K} \sum_{t□□}^{□} □_{i□t} - I_{it}^{+} + I_{it}^{-} = □_{it} \quad i = 1, \ldots I$$

$$t = 1, \ldots, T \quad (2)$$

$$\sum_{i□\{□:□□\iota□\iota□\iota□□y\}1} □_{i□t} = 1 \quad k = 1, \ldots, K \quad t = 1, \ldots, T \qquad (3)$$

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.

$$[\sum_{□□□□□} (□□□□_{□□t} - □□□□_{□□(t-1)})] \times □□□_{□} + [\sum_{□i□□} □(□□F_{□it} - □□F_{□□□(t-1)})] \times □F_{i} + [\sum_{□i} \sum_{□□} h\, □_{i□t}] \leq P \quad (4)$$

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 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.

$$M \times ????_{??t} \times M_{?t} \geq \sum_{\square i} ?_{i?t} \quad \square?, \square?, \square? \quad (5)$$

$$M \times ??F_{?it} \times M_{?t} \geq \sum_{\square i} ?_{i?t} \quad \square?, \square i, \square? \quad (6)$$

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.

$$\sum_{\square ?} ????_{??t} \leq 1 \quad \square?, \square? \quad (7)$$

$$\sum_{\square i} ??F_{?it} \leq 1 \quad \square?, \square? \quad (8)$$

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.

$$\sum_{i \square I} ?_{i?t} \leq M \times ?_{?t} \quad \square?, \square? \quad (9)$$

$$\sum_{? \square \{K \square ?? i ? i ? i ? ity\}1} ?_{?t} \leq 1 \quad m = 1, \ldots, M \quad t = 1, \ldots, T \quad (10)$$

$$?_{i?t} \leq ? \times ?_{i?t} \quad \square_{i?t} \quad (11)$$

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 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.

$$\sum_{i\in I}\sum_{?\in ?} p_i \times ?_{i?t} \le ?(?)\ ?\ ?\quad (12)$$

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.

$?_{i?t} \ge 0\ ???\ i???g??,\ i = 1, \ldots, I,\ ? = 1, \ldots ?$

(13)

$I^{+}_{it}\ ???\ I^{-}_{it} \ge 0,\ i = 1, \ldots, I,\quad ? = 0, \ldots, ?$ (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.

$$\sum_{?=1}^{?}\ \sum_{i\in ?(?)} p_i\, ?_{i?t} + ??_t^{?}\ \ ?_t^{?}???? ,\quad a = 1,\ldots,A\ \ t = 1,\ldots,T\quad (15)$$

$$\sum_{?\varepsilon A} ?_t^{?} \le 2\quad ? = 1,\ldots,T\quad (16)$$

$$?_t^{?} \ge ?_t^{?} - ?_{t-1}^{?}\quad ? = 1,\ldots,?\quad (17)$$

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.

$$\sum_{\square=1}^{A} \square_{\square} = 1 \quad \square = 1, \dots, A \quad (18)$$

$$\square_{t}^{\square} \; \square \; \{0,1\} \; \square\square\square\square h_{\square^{\square}} = 0 , \qquad \square = 1, \dots, \square , \qquad \square = \square, \dots, \square \quad (19)$$

$$0 \le \square_{t}^{\square} \le 1 , \qquad \square = 1, \dots, \square , \square = 1, \dots, \square \quad (20)$$

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.

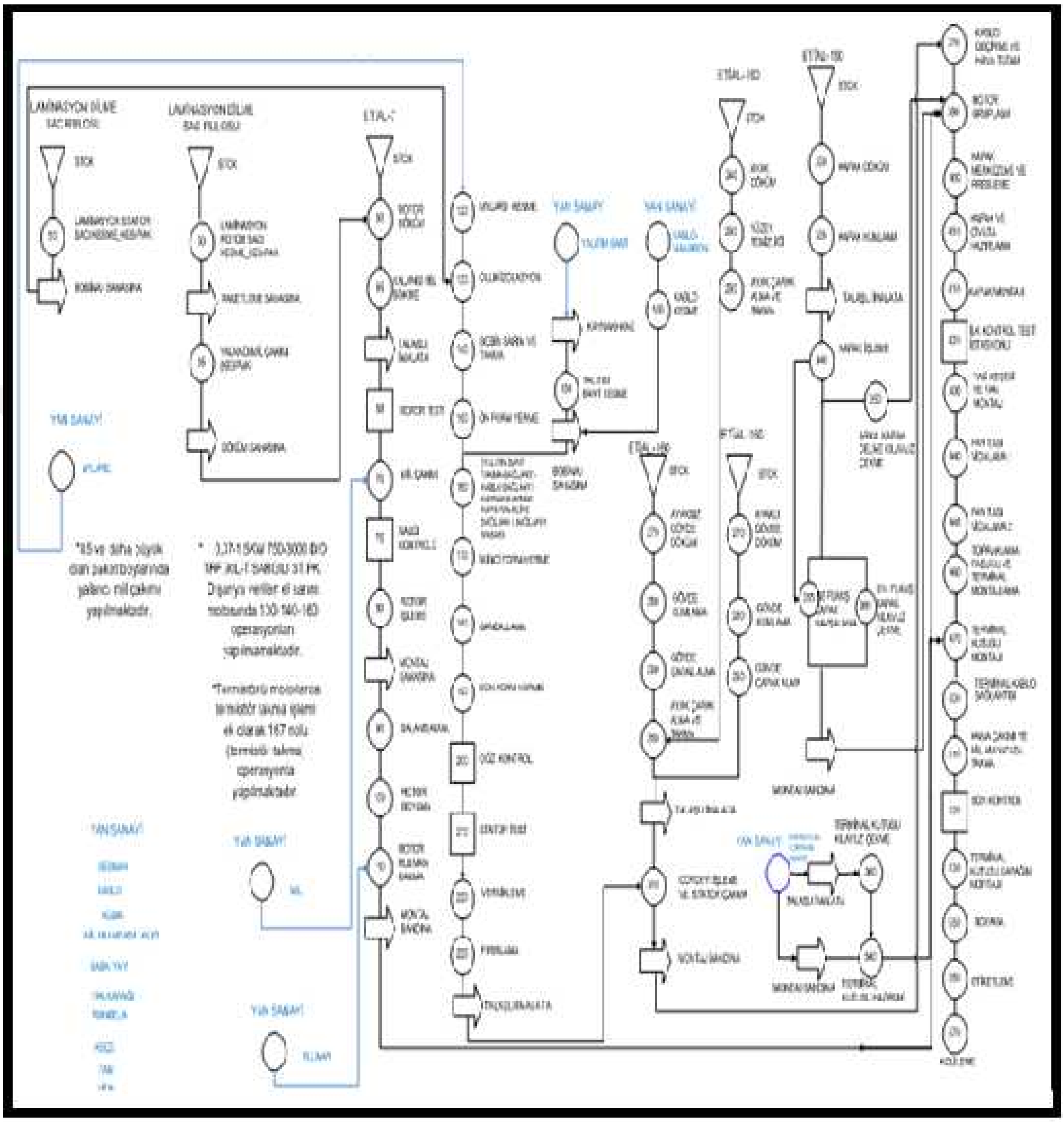

**Figure 2** Production foundry study

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.

**Table** 2 Injection machine park

| 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.

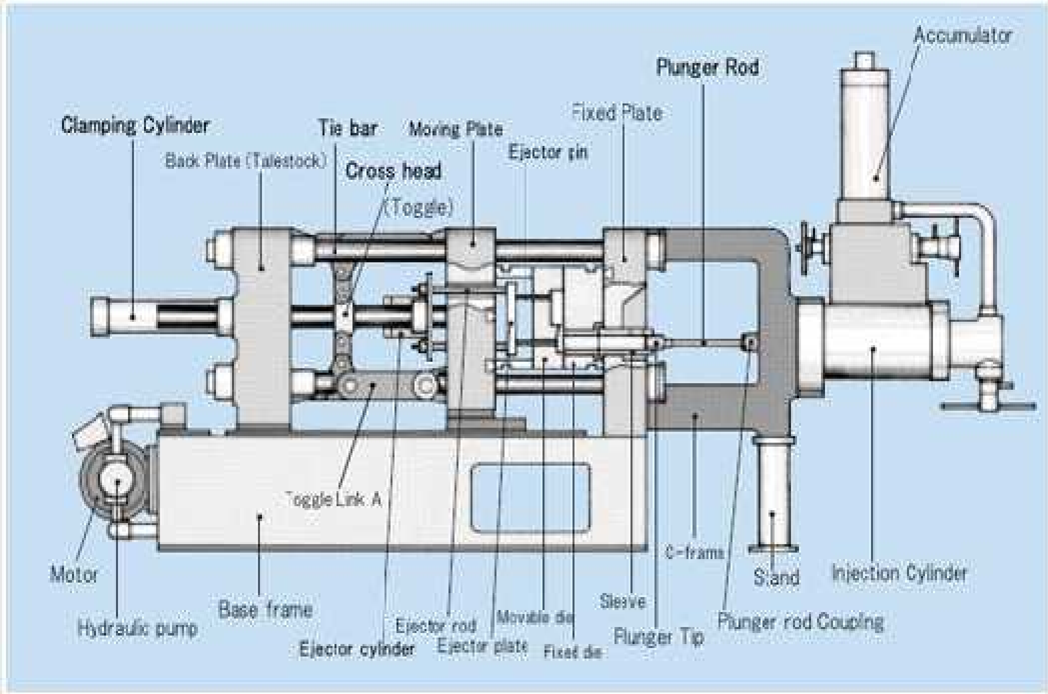


**Figure 3** Horizontal injection machine mechanism

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:

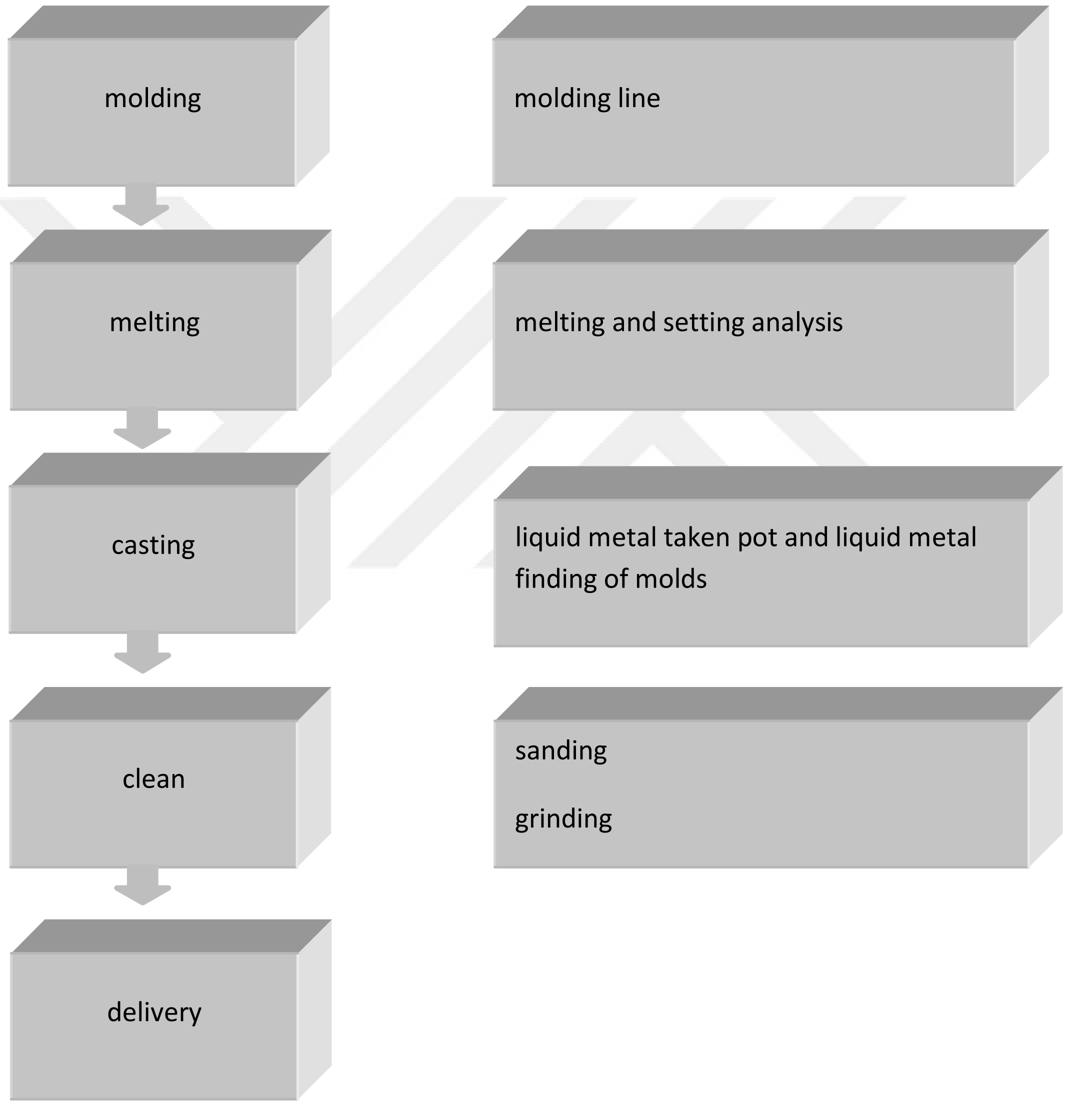


**Figure 4** Flow chart of the foundry production process

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.

**Table 3** Product group for item

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

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.

**Table 5** Demand and  item ordered for period

| 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 |

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.

**Table 6** Cycle time of item and setup time of mold

| Product Code | Product Description | Cycle time of item *i* (dk) | Setup time of mold *k* (dk) |
|---|---|---|---|
| AYAK60000000 | 80 GÖVDE AYAĞI | 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 |

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.

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

| 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 |

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

**Table 8** Product-mold compatibility matrix

| 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 |

**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,∞ ) 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.

**Table 9** Performances of developed models

| | setup capacity | capacity | inventory cost | backlog cost | setup cost | Regular maintenance cost | irregular maintenance cost | total reduced cost | optimal total 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 |

# 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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# APPENDICES

## APPENDIX.A Initial Matrices for Optimal Solution

**Table 10** Initial matrix for when the demand does not affect the capacity

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

| | 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 | 1.388.700 | 0 | 60 | 13634 | 18782 | infeasibilities | 1.402.582 |
| for 30 period | 500 | 90 | 3.077.200 | 0 | 90 | 13634 | 18782 | 0 | 3.091.112 |
| for 40 period | 500 | 90 | 4.295.000 | 0 | 120 | 13634 | 18782 | 0 | 4.308.942 |
| for 50 period | 500 | 90 | 4.568.500 | 0 | 150 | 13634 | 18782 | 0 | 4.582.472 |
| for 60 period | 500 | 90 | 2.121.900 | 0 | 480 | 13634 | 18782 | 352 | 2.258.878 |

**Table 12** Initial matrix for when the capacity of the same demand 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 | 500 | 60 | 1.388.700 | 0 | 60 | 13634 | 18782 | infeasibilities | 1.525.288 |
| for 30 period | 500 | 60 | 3.077.200 | 0 | 90 | 13634 | 18782 | 0 | 3.213.818 |
| for 40 period | 500 | 60 | 4.295.000 | 0 | 120 | 13634 | 18782 | 0 | 4.431.648 |
| for 50 period | 500 | 60 | 4.568.500 | 0 | 150 | 13634 | 18782 | 0 | 4.705.178 |
| for 60 period | 500 | 60 | 2.121.900 | 0 | 180 | 13634 | 18782 | 363 | 2.258.896 |

**Table 13** Initial matrix for demand is the same, capacity is reduced ,regular maintenance interval, and number of mold production 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 | 500 | 120 | 1.466.200 | 0 | 60 | 13634 | 18.782 | infeasibilities | 1.602.788 |
| for 30 period | 500 | 120 | 2.934.700 | 0 | 90 | 13634 | 18.782 | 0 | 3.071.318 |
| for 40 period | 500 | 120 | 4.295.000 | 0 | 120 | 13634 | 18.782 | 0 | 4.431.648 |
| for 50 period | 500 | 120 | 4.540.000 | 0 | 150 | 13634 | 18.782 | 0 | 4.676.678 |
| for 60 period | 500 | 120 | 2.121.900 | 0 | 180 | 13634 | 18.782 | 363 | 2.258.896 |

**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 |

**Table 15** Initial matrix for setup capacity can be minimized and when capacity times are 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 | 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 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

hatice_bakim.mod | hatice_bakim.dat | SSM değeri | SSP değeri | b değeri

| | | Değerler | | |
|---|---|---|---|---|
| mold (büyüklük 20) | period (büyüklük 60) | Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
| 1 | 1 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 2 | 0 | 0 | [0..1] [0..∞] |
| 1 | 3 | 0 | 0 | [0..1] [0..∞] |
| 1 | 4 | 0 | 0 | [0..1] [0..∞] |
| 1 | 5 | 0 | 0 | [0..1] [0..∞] |
| 1 | 6 | 0 | 0 | [0..1] [0..∞] |
| 1 | 7 | 0 | 0 | [0..1] [0..∞] |
| 1 | 8 | 0 | 0 | [0..1] [0..∞] |
| 1 | 9 | 0 | 0 | [0..1] [0..∞] |
| 1 | 10 | 0 | 0 | [0..1] [0..∞] |
| 1 | 11 | 0 | 0 | [0..1] [0..∞] |
| 1 | 12 | 0 | 0 | [0..1] [0..∞] |
| 1 | 13 | 0 | 0 | [0..1] [0..∞] |
| 1 | 14 | 0 | 0 | [0..1] [0..∞] |
| 1 | 15 | 0 | 0 | [0..1] [0..∞] |
| 1 | 16 | 0 | 0 | [0..1] [0..∞] |
| 1 | 17 | 0 | 0 | [0..1] [0..∞] |
| 1 | 18 | 0 | 0 | [0..1] [0..∞] |
| 1 | 19 | 0 | 0 | [0..1] [0..∞] |
| 1 | 20 | 0 | 0 | [0..1] [0..∞] |
| 1 | 21 | 0 | 0 | [0..1] [0..∞] |
| 1 | 22 | 0 | 0 | [0..1] [0..∞] |
| 1 | 23 | 0 | 0 | [0..1] [0..∞] |

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

hatice_bakim.mod | hatice_bakim.dat | SSM değeri | SSP değeri | Iminus değeri

| | | Değerler | | |
|---|---|---|---|---|
| itemm (büyüklük 20) | period (büyüklük 60) | Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
| 1 | 1 | 0 | 20 | [0..∞] [0..∞] |
| 1 | 2 | 0 | 15 | [0..0] [0..∞] |
| 1 | 3 | 0 | 15 | [0..0] [0..∞] |
| 1 | 4 | 0 | 15 | [0..0] [0..∞] |
| 1 | 5 | 0 | 15 | [0..0] [0..∞] |
| 1 | 6 | 0 | 15 | [0..0] [0..∞] |
| 1 | 7 | 0 | 15 | [0..0] [0..∞] |
| 1 | 8 | 0 | 15 | [0..0] [0..∞] |
| 1 | 9 | 0 | 15 | [0..0] [0..∞] |
| 1 | 10 | 0 | 15 | [0..0] [0..∞] |
| 1 | 11 | 0 | 15 | [0..0] [0..∞] |
| 1 | 12 | 0 | 15 | [0..0] [0..∞] |
| 1 | 13 | 0 | 15 | [0..0] [0..∞] |
| 1 | 14 | 0 | 15 | [0..0] [0..∞] |
| 1 | 15 | 0 | 15 | [0..0] [0..∞] |
| 1 | 16 | 0 | 15 | [0..0] [0..∞] |
| 1 | 17 | 0 | 15 | [0..0] [0..∞] |
| 1 | 18 | 0 | 15 | [0..0] [0..∞] |
| 1 | 19 | 0 | 15 | [0..0] [0..∞] |
| 1 | 20 | 0 | 15 | [0..0] [0..∞] |
| 1 | 21 | 0 | 15 | [0..0] [0..∞] |
| 1 | 22 | 0 | 15 | [0..0] [0..∞] |
| 1 | 23 | 0 | 15 | [0..0] [0..∞] |

**Table 22** Item-period compatibility for initial inventory

hatice_bakim.mod | hatice_bakim.dat | SSM değeri | SSP değeri | Iminus değeri | Iplus değeri

| itemm (büyüklük 20) | period (büyüklük 60) | Değerler | | |
|---|---|---|---|---|
| | | Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
| 1 | 1 | 108 | 0 | [-∞..108] [108..∞] |
| 1 | 2 | 0 | 10 | [0..0] [0..∞] |
| 1 | 3 | 0 | 5 | [0..0] [0..∞] |
| 1 | 4 | 0 | 5 | [0..0] [0..∞] |
| 1 | 5 | 0 | 5 | [0..0] [0..∞] |
| 1 | 6 | 0 | 5 | [0..0] [0..∞] |
| 1 | 7 | 0 | 5 | [0..0] [0..∞] |
| 1 | 8 | 0 | 5 | [0..0] [0..∞] |
| 1 | 9 | 0 | 5 | [0..0] [0..∞] |
| 1 | 10 | 0 | 5 | [0..0] [0..∞] |
| 1 | 11 | 0 | 5 | [0..0] [0..∞] |
| 1 | 12 | 0 | 5 | [0..0] [0..∞] |
| 1 | 13 | 0 | 5 | [0..0] [0..∞] |
| 1 | 14 | 0 | 5 | [0..0] [0..∞] |
| 1 | 15 | 0 | 5 | [0..0] [0..∞] |
| 1 | 16 | 0 | 5 | [0..0] [0..∞] |
| 1 | 17 | 0 | 5 | [0..0] [0..∞] |
| 1 | 18 | 0 | 5 | [0..0] [0..∞] |
| 1 | 19 | 0 | 5 | [0..0] [0..∞] |
| 1 | 20 | 0 | 5 | [0..0] [0..∞] |
| 1 | 21 | 0 | 5 | [0..0] [0..∞] |
| 1 | 22 | 0 | 5 | [0..0] [0..∞] |
| 1 | 23 | 0 | 5 | [0..0] [0..∞] |

**Table 23** Machine-mold compatibility

| mach...k 7) | mol. 20) | allp... 61) | Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
|---|---|---|---|---|---|
| 3 | 17 | 35 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 36 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 37 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 38 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 39 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 40 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 41 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 42 | 0 | 0 | [0..0.0270805] [0..∞] |
| 3 | 17 | 43 | 0.00353264424063928 | 0 | [-∞..0.00353264] [0.00353264..∞] |
| 3 | 17 | 44 | 0.00350629847336328 | 0 | [-∞..0.0035063] [0.0035063..∞] |
| 3 | 17 | 45 | 0.00150649496096768 | 0 | [-∞..0.00150649] [0.00150649..∞] |
| 3 | 17 | 46 | 0.00150649349564517 | 0 | [-∞..0.00150649] [0.00150649..∞] |
| 3 | 17 | 47 | 0.00386863947432795 | 0 | [-∞..0.00386854] [0.00386854..∞] |
| 3 | 17 | 48 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 49 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 50 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 51 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 52 | 0 | 0 | [0..1] [0..∞] |
| 3 | 17 | 53 | 0.0017694751579811 | 0 | [-∞..0.00176948] [0.00176948..∞] |
| 3 | 17 | 54 | 0.00443808568820423 | 0 | [-∞..0.00443808] [0.00443808..∞] |
| 3 | 17 | 55 | 0.00442011769480652 | 0 | [-∞..0.00442612] [0.00442612..∞] |
| 3 | 17 | 56 | 0.00442623056286537 | 0 | [-∞..0.00442623] [0.00442623..∞] |
| 3 | 17 | 57 | 0.00442622549524864 | 0 | [-∞..0.00442623] [0.00442623..∞] |
| 1 | 1 | 0 | 0 | 0 | [0..0] [0..∞] |
| 1 | 1 | 1 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 2 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 3 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 4 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 5 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 6 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 7 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 8 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 9 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 10 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 11 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 12 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 13 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 14 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 15 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 16 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 17 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 18 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 19 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 20 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 21 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 22 | 0 | 0 | [0..1] [0..∞] |

**Table 24** Mold-item compatibility

hatice_bakim.mod | hatice_bakim.dat | SSM değeri | SSP değeri

| mol...20) | itemm...20) | allperi...lük 61) | Değerler: Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
|---|---|---|---|---|---|
| 1 | 1 | 0 | 0 | 0 | [0..0] [0..∞] |
| 1 | 1 | 1 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 2 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 3 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 4 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 5 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 6 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 7 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 8 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 9 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 10 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 11 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 12 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 13 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 14 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 15 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 16 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 17 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 18 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 19 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 20 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 21 | 0 | 0 | [0..1] [0..∞] |
| 1 | 1 | 22 | 0 | 0 | [0..1] [0..∞] |

hatice_bakim.mod | hatice_bakim.dat | SSM değeri | SSP değeri

| mol...20) | itemm...20) | allperi...lük 61) | Değerler: Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
|---|---|---|---|---|---|
| 2 | 1 | 39 | 0 | 0 | [0..1] [0..∞] |
| 2 | 1 | 40 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 41 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 42 | 0.199226272106411 | 0 | [-∞..0.199226] [0.199226..∞] |
| 2 | 1 | 43 | 0.189334868205553 | 0 | [-∞..0.189335] [0.189335..∞] |
| 2 | 1 | 44 | 0.189408663636292 | 0 | [-∞..0.189409] [0.189409..∞] |
| 2 | 1 | 45 | 0.189408086214139 | 0 | [-∞..0.189408] [0.189408..∞] |
| 2 | 1 | 46 | 0.189408090017123 | 0 | [-∞..0.189408] [0.189408..∞] |
| 2 | 1 | 47 | 0.00386063947432795 | 0 | [-∞..0.00386064] [0.00386064..∞] |
| 2 | 1 | 48 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 49 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 50 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 51 | 0 | 0 | [0..1] [0..∞] |
| 2 | 1 | 52 | 1 | 0 | [-∞..1] [1..∞] |
| 2 | 1 | 53 | 0.190150605460517 | 0 | [-∞..0.190151] [0.190151..∞] |
| 2 | 1 | 54 | 0.186698520519778 | 0 | [-∞..0.186699] [0.186699..∞] |
| 2 | 1 | 55 | 0.186632015304145 | 0 | [-∞..0.186632] [0.186632..∞] |
| 2 | 1 | 56 | 0.18663169927372 | 0 | [-∞..0.186632] [0.186632..∞] |
| 2 | 1 | 57 | 0.186631702254307 | 0 | [-∞..0.186632] [0.186632..∞] |
| 2 | 1 | 58 | 0.186631702226365 | 0 | [-∞..0.186632] [0.186632..∞] |
| 2 | 1 | 59 | 0.186631702226544 | 0 | [-∞..0.186632] [0.186632..∞] |
| 2 | 1 | 60 | 0.907388760700865 | 0 | [-∞..0.907389] [0.907389..∞] |
| 2 | 2 | 0 | 0 | 0 | [0..0] [0..∞] |

**Table 25** Mold-item compatibility

| itemm (büyüklük 20) | mold (büyüklük 20) | period (büyüklük 60) | Değerler: Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 2 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 3 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 4 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 5 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 6 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 7 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 8 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 9 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 10 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 11 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 12 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 13 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 14 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 15 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 16 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 17 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 18 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 19 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 20 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 21 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 22 | 1 | 0 | [-∞,1] [1,∞] |
| 1 | 1 | 23 | 1 | 0 | [-∞,1] [1,∞] |

**Table 26** Mold-product for machine manufacturability

| itemm (büyüklük 20) | mold (büyüklük 20) | period (büyüklük 60) | Değerler: Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
|---|---|---|---|---|---|
| 1 | 1 | 1 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 2 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 3 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 4 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 5 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 6 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 7 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 8 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 9 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 10 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 11 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 12 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 13 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 14 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 15 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 16 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 17 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 18 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 19 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 20 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 21 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 22 | 0 | 162.831 | [0,0] [0,∞] |
| 1 | 1 | 23 | 0 | 162.831 | [0,0] [0,∞] |

**Table 27** Alloy-period compatibility

batice_bakim mod | batice_bakim de | SSM değeri | SSP değeri | z değeri

| alloy (büyüklük 2) | period (büyüklük 60) | Değerler | | |
|---|---|---|---|---|
| | | Değer | İndirgenmiş maliyet | Duyarlılık aralığı |
| 1 | 1 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 2 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 3 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 4 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 5 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 6 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 7 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 8 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 9 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 10 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 11 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 12 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 13 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 14 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 15 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 16 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 17 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 18 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 19 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 20 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 21 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 22 | 1 | 0 | [-∞..1] [1..∞] |
| 1 | 23 | 1 | 0 | [-∞..1] [1..∞] |