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M.Sc. in Industrial Engineering
ABDULLAH AKMAN DEMİRKAN

REPUBLIC OF TURKEY
GAZİANTEP UNIVERSITY
GRADUATE SCHOOL OF NATURAL & APPLIED SCIENCES

PRODUCTION PLANNING APPLICATION FOR A PET RESIN PRODUCTION PLANT

M.Sc. THESIS
IN
INDUSTRIAL ENGINEERING

BY
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M.Sc. Thesis
in
Industrial Engineering
Gaziantep University

Supervisor
Assoc. Prof. Dr. Zeynep Didem UNUTMAZ DURMUŞOĞLU

by
Abdullah Akman DEMİRKAN
September 2019

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Abdullah Akman DEMİRKAN

ABSTRACT

PRODUCTION PLANNING APPLICATION FOR A PET RESIN PRODUCTION PLANT

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PET (Polyethylene terephthalate) is one of the most important aromatic polyester commercially. Therefore, number of PET production sites has increased at a great pace all around the world as time passes due to its extensive usage. Subject of this thesis is developing a production planning model for one of bottle grade PET production plants in Turkey. Production planning is very critical for PET resin production facilities especially in Turkey, because there are only three manufacturers and sum of their production quantity is lower than actual market demand. According to the actual data of the year in which the planning was made, the amount of PET resin imported in bottles is 49.1% of the total PET resin consumption in bottles. Facilities of the study alone is capable to do the Turkey's bottle grade PET production of 47.5%. As shown by these data, an improper production planning would affect especially domestic consumers and sectoral current deficit would be increased due to rising imported PET quantity. This kind of plan must be prepared considering sustainability to decrease environmental impact by sufficient production and effective use of resources. For these purposes, a deterministic multi-period multi-product single level mixed-integer linear programming (MILP) model is presented. The objective is to maximize profit. The proposed model is applied for different choices in inventory policy, energy resources policy and capacity policy. It was seen that significant improvements were achieved according to obtained results. According to findings profit increases by 6.0% and total cost decreases by 6.8%.

Key Words: PET Resin, Continuous Multi-grade Production, Production Planning,
Capacitated Lot Sizing, GAMS

ÖZET

BİR PET REZİN TESİSİNDE ÜRETİM PLANLAMA UYGULAMASI

DEMİRKAN, Abdullah Akman
Yüksek Lisans Tezi, Endüstri Mühendisliği
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PET (Polietilen tereftalat) ticari olarak en önemli aromatik polyesterlerden biridir. Geniş çaplı kullanımı nedeniyle PET üretim tesislerinin sayısı tüm dünyada büyük bir hızla artmaktadır. Bu çalışmanın konusu Türkiye'de bulunan şişe sınıfı PET üretim tesislerinden birinin üretim planlamasıdır. PET üretim tesislerinde üretim planlama özellikle Türkiye'de çok kritiktir. Çünkü yalnızca üç üretici vardır ve üretim miktarlarının toplamı gerçek piyasa talebinden düşüktür. Planlamanın yapıldığı yılın gerçek verilerine göre ithal edilen şişe cinsi PET rezin miktarı, toplam şişe cinsindeki PET rezin tüketiminin % 49.1'idir. Çalışmanın yapıldığı tesis ise tek başına Türkiye'nin şişe sınıfı PET üretiminin %47.5'unu yapabilecek kapasitededir. Bu verilerin ışığında böyle bir tesiste üretim planının düzgün olmaması özellikle yerli tüketicileri etkileyecek ve ithal edilen şişe sınıfı PET miktarının artması nedeniyle sektörel cari açık artacaktır. Böyle bir planlama programı uygun üretim miktarı ile çevresel etkinin azaltılması ve kaynakların daha verimli kullanılmasını sağlamak için sürdürülebililirliği de göz önüne alarak hazırlanmalıdır. Bu amaçlarla belirlenimli (deterministik) çok dönemli çok ürünlü tek seviyeli bir karışık tamsayılı doğrusal programlama (KTDP) modeli sunulmuştur. Hedef karın en yüksek düzeye çıkarılmasıdır. Önerilen model, stok politikası, enerji kaynakları politikası ve kapasite politikasındaki farklı seçimler için uygulanmıştır. Model uygulamasının sonuçlarına göre önemli iyileştirmeler sağlandığı görülmüştür. Bu verilere göre, kar % 6.0 oranında artarken toplam maliyet ise % 6.8 oranında azalmıştır.

Anahtar Kelimeler: PET Resin, Sürekli Çok Sınıflı Üretim, Üretim Planlama, Kapasiteli Öbek Büyüklüğü Belirleme Problemi, GAMS

To my parents and my friends

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LIST OF ABBREVATIONS

t/d	Ton per Day
d	day
t	ton
PET	Polyethylene Terephthalate
LDPE	Low-Density Polyethylene
PP	Polypropylene
HDPE	High-Density Polyethylene
PVC	Polyvinyl Chloride
PS	Polystyrene
IV	Intrinsic Viscosity
SSP	Solid-state Polycondensation Process
MTR	Melt-to-resin Polycondensation Process
CAGR	Compound Annual Growth Rate
DCS	Distributed Control System
MPS	Master Production Schedule
MRP	Material Requirement Planning
MRP II	Manufacturing Resources Planning
ERP	Enterprise Resource Planning
SCP	Supply Chain Planning
APP	Aggregate Production Planning
HPP	Hierarchical Production Planning
BOM	Bill of Materials
MILP	Mixed Integer Linear Programming
MOP	Multi-objective Programming
NLP	Non-linear Programming
DP	Dynamic Programming
MP-based	Mathematical Programming Based
EOQ	Economic Order Quantity
SILSP	Single Item Lot Sizing Problem

ULS	Uncapacitated Lot Sizing Problem
CLSP	Capacitated Lot Sizing Problem
CSILSP	Capacitated Single Item Lot Sizing Problem
PSE	Process Systems Engineering
ARIMA	Auto Regressive Integrated Moving Average Forecasting Method
HW	Holt-Winter Forecasting Method
SSA	Singular Spectrum Analysis Method
MAE	Mean Absolute Error
MAD	Mean Absolute Deviation
MSE	Mean Squared Error
RMSE	Root Mean Squared Error
MAPE	Mean Absolute Percentage Error
MASE	Mean Absolute Scaled Error
SMAPE	Symmetric Mean Absolute Percentage Error
CSD	Carbonated Soft Drinks
BW	Bottled Water

CHAPTER I

INTRODUCTION

Production planning is defined as the planning (that is the acquisition, time of usage, quantity used etc.) of the resources required to perform these transformation steps, in order to satisfy the customers in the most efficient or economical way (Pochet, 2001). The goal of production planning is to make planning decisions optimizing the trade-off between economic objectives such as cost minimization or maximization of contribution to profit and the less tangible objective of customer satisfaction. (Pochet & Wolsey, 2006).

Assume a single facility where different items are produced. The production of a single item requires the facility (actually some or all of the machines within the facility) to be setup for that item. Continuous production of equivalent items requires no intermediates setups and this continuous sequence is called a lot. The number of items in a lot is called lot size (Brahimi, 2004). Lot sizing problems are production planning problems with setups between production lots (Brahimi et al., 2006). This problem considers the tradeoff between the setup and inventory holding costs to determine the minimal cost of a production plan for one (or several) machine(s) in order to meet the demand for each item (Melega et al., 2018). Making the right decisions in lot sizing will affect directly the system performance and its productivity, which are important for a manufacturing firm’s ability to compete in the market (Karimi et al., 2003). The problem class is very wide. There are many variations of lot sizing problems along with the needs of related process. Problems could be solved for basic requirements (minimize cost, maximize profit) and much more complex cases. If a suitable lot sizing model which is determined to solve problematic issues could be developed and applied for a production facility, visible improvements could be seen soon. There would be economical, social and environmental benefits according to problem scope and obtained results.

There are several production management systems in the literature and in practice. Among the systems where lot sizing arises are Material Requirement Planning (MRP), Manufacturing Resource Planning (MRP II), Optimized Production Technology and more recently Enterprise Resource Planning (ERP) (Brahimi, 2004). It can be said that lot sizing could be applied from shorter time periods (weeks etc.) to longer time periods (months). Although production is planned appropriately according to production management systems mentioned above, planning data should be updated periodically to handle competitive market conditions. This process can be done much easier than before with the help of softwares such as SAP. This is also due to the proper functioning of the planning units of most companies.

There are many examples of real-world applications of lot sizing problems. Enormous savings in cost or increase in profit is taken with these practices. That kind of optimization activities are applied extensively in many corporations as a part of normal production or sevice process. Also numerous studies are published regularly on this issue.

Implementations of lot sizing are carried out in many industrial areas. Plastics industry (and naturally PET production) is among these areas. However there are not many applications about this subject in the literature. Subject of the study is developing a production planning model of one of bottle grade PET production plants in Turkey. This plant is located in Gaziantep and it is capable of 47.5% of total bottle grade PET production quantity of Turkey. For that purpose a capacitated MILP model is presented. Resources for production is limited and it means that model is capacitated. Production takes place in one stage and it is assumed a single-level problem according to literature. The objective is to maximize profit. This target is very closely related to minimizing total cost. Setup process is grade changeover in this plant and it is unlike from most manufacturing facilities due to different production process. PET resin production process is based on conversion of raw materials and additives to end-product and this production process is a chemical production process. Grade changeovers are necessary in order to meet dynamic customer demand on time but are undesirable, because they last a significant amount of time and cause variations in base resin properties and processing conditions during the transition period (Liberopoulos, et al., 2010). There are excess production setups without proper planning. It doesn’t cost much owing to specialty of production process but after every setup a transition material is produced equivalent time of setup. This material has lower quality than normal end product (off spec) and sales price of this product is lower than normal end product. Less number of setup means less transition material as a result of this income will increase.

Three different end-products are produced in this plant and IV is the characteristic of these end-products. Intrinsic viscosity (IV) is the measure of quality of end-product and according to IV end-product is classified on different product grades. IV is related to the length of the polymer chains; the higher the IV, the stiffer the material (Liberopoulos et al., 2010). End-product can be obtained by three different grades: 0.76 IV, 0.80 IV and 0.84 IV. Product grade of 0.76 IV is primarily used for water bottles. Product grade of 0.80 IV or 0.84 IV is used for carbonated soft drink bottles. Two PET grades now dominate the global market, i.e. fibre-grade PET and bottle-grade PET. These standard grades differ mainly in molecular weight or intrinsic viscosity (IV), respectively, optical appearance and the production recipes (Scheirs & Long, 2004).

General introduce and main motivation of study is presented in the first chapter. Main methodology and literature survey is done on the second chapter. That chapter contains basic production planning definitions, lot sizing equations and classification of lot sizing problems, key factors for production planning (sustainability, lean production and policies implemented in model) and basic information about forecasting and related techniques. In the third chapter, main concepts about PET production are mentioned. That chapter could be segregated to three parts: First part include general definition of chemical production, process of PET production and characteristic properties of PET. Second part contains statistics and future trends about worldwide PET production. Last part contains basic production process diagram of production facility where the study is made. In the fourth chapter, problem is defined and the development of the model is explained. Assumptions and parts of model (sets, parameters, variables, constraints and equations) are also given in this chapter. Implementation of model is evaluated on fifth chapter. At first results obtained from model run is mentioned. This section consists of forecasting accuracy and evaluation of results. Evaluation of results consists of interactions between obtained results, interactions between improvements and interactions between improvements by different models. Last section of this chapter is interpretation of results. Conclusions and suggestions are given in sixth chapter.

CHAPTER II

METHODOLOGY AND LITERATURE SURVEY

Methodology and literature survey is examined together in this section. An extensive literature review is done on classification of lot sizing problems and key factors for production planning. The methodology used in the thesis is based on the studies selected from the literature review. Proposed model is designated according to used methodology.

This chapter contains basic production planning definitions, lot sizing equations and classification of lot sizing problems, key factors for production planning (sustainability, lean production and policies implemented in model) and basic information about forecasting and related techniques.

2.1 Production Planning

Production planning is defined as the planning (that is the acquisition, time of usage, quantity used etc.) of the resources required to perform these transformation steps, in order to satisfy the customers in the most efficient or economical way. In production planning and operations management, the financial objectives are usually represented by production costs for machines, materials, manpower, startup costs, overhead costs and inventory costs like opportunity costs of the capital tied up in the stocks and insurances. Customer service objectives are represented by the ability to deliver the right product, in ordered quantity, at the promised date and place (Pochet, 2001). The goal of production planning is to make planning decisions optimizing the trade-off between economic objectives such as cost minimization or maximization of contribution to profit and the less tangible objective of customer satisfaction (Pochet & Wolsey, 2006).

Production planning typically encompasses three time ranges for decision making: long-term, medium-term and short-term. In long-term planning usually the focus is on anticipating aggregate needs and involves such strategic decisions as product, equipment and process choices, facility location and design, and resource planning. Medium-term planning often involves making decisions on material requirements planning (MRP) and establishing production quantities or lot sizing over the planning period, so as to optimize some performance criteria such as minimizing overall costs, while meeting demand requirements and satisfying existing capacity restrictions. In short-term planning, decisions usually involve day-to-day scheduling of operation such as job sequencing or control in a workshop (Karimi et al., 2003). Master production scheduling expresses the overall plans in terms of specific end items or models that can be assigned priorities. It is useful to plan for the material and capacity requirements (Buffa, Sarin, 2007).

General definitions and problem types can be found from (Rand et al., 1993). Deterministic production planning problems, models, their formulations and extensions (backlogging, constant capacity etc.) are analyzed on this article (Pochet, 2001). Uncapacitated and capacitated models according to their properties (number of items, number of periods, number of levels, shared resources, product structures, demand and setup choices) are explained briefly. Some reformulations are given on consistent with relaxation methods and algorithms to run models with higher performance and solve more complex problems.

Scheduling is the other way to solve planning problems used production processes usually. Production planning and scheduling is one of the most challenging subjects for the management. It appears to be an hierarchical process ranging from long-term to medium-term to short-term decisions (Drexl & Kimms, 1997). In the context of chemical processing systems, the scheduling problem generally consists of the following components: production recipes, which specify the sequences of tasks to be performed for manufacturing given products; available processing/storage equipment; intermediate storage policy; production requirements; specifications of resources, such as utilities and manpower; and a time horizon of interest. The goal is to determine a schedule which includes the details of the sequence of tasks to be performed in each piece of equipment; the timing of each task; and the amount of material to be processed (i.e., batch-size) by each task. The performance of a schedule is measured with one or more criteria, for example, the overall profit, the operating costs, and the makespan (Floudas & Lin, 2005). It depends on planning objectives. Even the time scales and way of modeling different, scheduling of multi-grade continuous chemical processes according to market conditions is studied on (Tousain & Bosgra, 2006). Advanced controlling of operations integrated with scheduling on chemical production systems is analyzed on (Engell & Harjunkoski, 2012). Production planning and design problems on chemical production processes are reviewed from cases on (Kallrath, 2002) and (Kallrath, 2005). Simultaneous strategic and operational planning is done for the supply chain management of a multisite production network in which production units are subject to purchase, opening or shut-down decisions leading to an MILP model based on a time-indexed formulation on first article. Successful implementations in real world consisting supply chain optimization for PP plant, a LP-based planning system for the Petro-Chemical industry, web-based production optimization tool and scheduling under uncertainity and special features in planning in the process industry is given on second article.

Extensive research by industrial applications of production scheduling with the help of case studies is given on (Harjunkoski et al., 2014) and (Fuchigami & Rangel, 2018).

2.2 Lot Sizing Problem

Lot-sizing problems are production planning problems in which the periods are fixed a priori, and production of an item in a given period implies some discrete event such as payment of a fixed cost or the loss of a fixed amount of production capacity, due to placement of an order, or the setup, start-up, or changeover of a machine. Problems typically involve the satisfaction of demand for a number of items over a time horizon consisting of several periods (Belvaux & Wolsey, 1998). Lot sizing models determine the optimal timing and level of production. Making the right decisions in lot sizing will affect directly the system performance and its productivity, which are important for a manufacturing firm’s ability to compete in the market (Karimi et al., 2003).

Lot sizing problems are reviewed generally on papers such as (Drexl & Kimms, 1997; Wolsey, 2003; Brahimi, 2004; Jans & Degraeve, 2008). Capacitated models are reviewed on (Gicquel et al., 2008) and some extensions (backlog, sequencing etc.) on model is given on (Quadt & Kuhn, 2008). Joint economic lot sizing problems are reviewed on (Glock et al., 2014).

2.2.1 Lot Sizing Problem Models

Lot sizing problems are classified according to related production environment. Fundamental distinction is about production capacity. There are not limit on production capacity basically in uncapacitated models. This model is more suitable for theoretical inferences than real-world applications. On the other hand, capacitated models are limited by maximum production capacity. Capacitated lot sizing problems are more realistic than uncapacitated lot sizing problems, because to our knowledge, no source in the universe is infinite. Classification of lot sizing problems is given more broadly on section 2.2.2.

2.2.1.1 Uncapacitated Single Item Lot Sizing Problem

The uncapacitated SILSP is a lot sizing problem where a single (or aggregate) product is considered and the production capacity is assumed to be high enough to never be binding in an optimal solution (Brahimi et al., 2006). This model is the core sub problem in production planning because it is the problem solved repeatedly for each item from end products to raw materials in the material requirements sequential planning system (Pochet, 2001).

We define the index t =1, ⋯, n to represent the discrete time periods, and n is the final period at the end of the planning horizon. The purpose is to plan the production over the planning horizon (i.e. fix the lot size in each period) in order to satisfy demand, and to minimize the sum of production and inventory costs. Classically, the production costs exhibit some economies of scale that are modelled through a fixed charge cost function. That is, the production cost of a lot in decomposed into a fixed cost independent of the lot size, and a unit cost incurred for each unit produced in the lot. The inventory costs are modelled by charging an inventory cost per unit held in inventory at the end of each period. Any demand in a period can be satisfied by production or inventory, and backlogging is not allowed. The production capacity in each period is not considered in the model, and therefore assumed to be infinite.

For each period t =1, ⋯, n, the decision variables are x_t, y_t and s_t. They represent respectively the production lot size in period t, the binary variable indicating whether or not there is a positive production in period t ($y_t = 1$ if $x_t > 0$) and the inventory at the end of period t. The data are p_t, f_t, h_t and d_t modelling respectively, and for each period t, the unit production cost, the fixed production cost, the unit inventory cost, and the demand to be satisfied. For simplicity $d_t \geq 0$ for all periods t is supposed.

The natural formulation of this uncapacitated lot sizing problem can be written as follows.

$$min \sum_{t=1}^{n} (p_t x_t + f_t y_t + h_t s_t) \tag{2.1}$$

$$s_{t-1} + x_t = d_t + s_t \quad for\ all\ t \tag{2.2}$$

$$s_0 = s_n = 0 \tag{2.3}$$

$$x_t \ \leq M * y_t \quad for\ all\ t \tag{2.4}$$

$$x_t, s_t \ \geq 0, y_t \in \{0, 1\} \quad for\ all\ t \tag{2.5}$$

Constraint (2.2) expresses the demand satisfaction in each period, and is called the flow balance or flow conservation constraint. Constraint (2.3) says there is no initial inventory. Constraint (2.4) forces the setup variable in period t to be 1 when there is positive production (i.e. $x_{it} > 0$) in period t. M is a large positive number and it must be large enough to force production. It can be maximum production capacity. Constraint (2.5) imposes the nonnegativity and binary restrictions on the variables. The objective function defined by (2.1) is simply the sum of unit production, fixed production and unit inventory costs (Pochet, 2001).

2.2.1.2 The Capacitated Multi item Lot Sizing Problem

The capacitated lot sizing problem can be seen as an extension of the lot sizing problem under dynamic demand to the multi-item case under capacity constraints (Glock et al., 2014).

The capacitated single item lot sizing problem is characterized by the fact that the production quantity is limited by a given capacity. In most production facilities, it is not realistic to assume that production capacity is infinite (or large enough to accommodate all the demands). Instead, this capacity has to be calculated for each period, or approximated to an average constant value. The complexity of the CSILSP depends mainly on the capacity parameter structure (variable or time independent); but it is generally NP-hard even for several special cases (Brahimi et al., 2006).

Multi item capacitated lot-sizing model is an extension of single item problem. As written main difference is number of items: Multiple items are the subject of production planning.

The purpose is to plan the production of a set of items, usually finished products, over a short term horizon corresponding to the total production cycle of these items. For each item, the model is the same as the ULS model in terms of costs and demand satisfaction. In addition, the production plans of the different items are linked through capacity restrictions coming from the common resources used to produce the items. We define the indices i =1, ⋯, N to represent the set of items whose production has to be planned, k =1, ⋯, K to represent the set of shared resources with limited capacity, and t =1, ⋯, N to represent the time periods. The variables x, y, s, and the data p, f, h, d, have the same meaning for each item i as in the model ULS. A superscript i has been added to represent the item i for which they are each defined. The data L_t^k represents the available capacity of resource k during period t. The data α_{ik} and β_{ik} represent the amount of capacity of resource k consumed respectively per unit of item i produced, and for a setup of item i. The coefficient β_{ik} is often called the setup time of item i on resource k, and represents the time spent to prepare the resource k just before the production of a lot of item i. Together with α_{ik}, it may also be used to represent some economies of scale in the productivity factor of item i on resource k. The natural formulation of this multi item capacitated lot-sizing model, or basic MPS model, can be written as follows where M is a large positive number.

$$min \sum_i^N \sum_t^N \{p_t^i x_t^i + f_t^i y_t^i + h_t^i s_t^i\} \tag{2.6}$$

$$s_{t-1}^i + x_t^i = d_t^i + s_t^i \quad for\ all\ i,t \tag{2.7}$$

$$x_t^i \le M * y_t^i \quad for\ all\ i,t \tag{2.8}$$

$$\sum_i \alpha^{ik} * x_t^i + \sum_i \beta^{ik} * y_t^i \le L_t^k \quad for\ all\ t,k \tag{2.9}$$

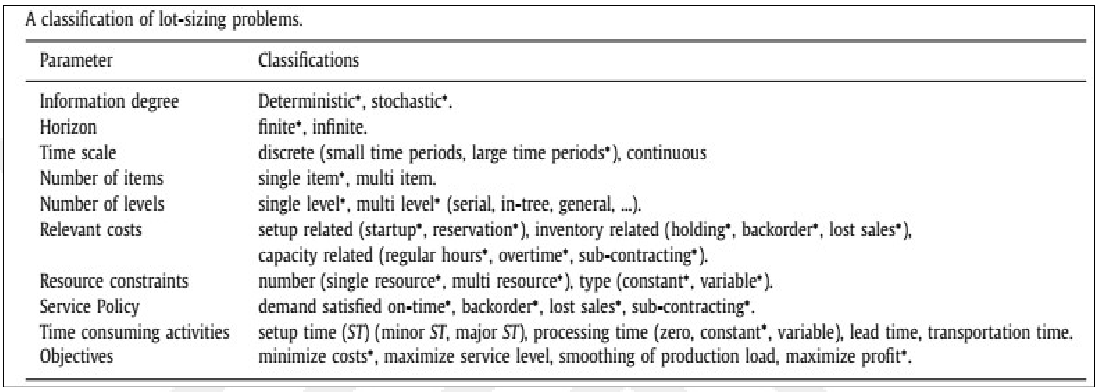
$$x_t^i,\ s_t^i \ge 0,\ y_t^i \in \{0,1\} \qquad for\ all\ i,t \tag{2.10}$$

Constraints (2.6), (2.7), (2.8) and (2.10) are the same as for the ULS model, and constraint (2.9) expresses the capacity restriction on each resource k in each period t (Pochet, 2001).

Model considered in this thesis resources are not shared as expressed as (2.9) constraint. Resource usage is limited by maximum consumption of resource according to determined capacity, so this constraint is used as modified format in model considered in this thesis. Binary variable of setup is substracted from that constraint and L_t^k is different for every resource. More detailed description is given on Chapter IV, model development.

2.2.2 Lot Sizing Problem Classification

Lot sizing problems can be classified according to their time scale, the demand distribution and the time horizon (Jans & Degraeve, 2008). More extensive classification can be done based on several criteria or characteristics such as: Nature of data (deterministic or stochastic), nature of the time scale (continuous or discrete), number of machines, number of production stages (levels), capacity constraints and their nature (fixed or variable), length of production periods, etc. (Brahimi et al., 2017). This classification is shown on Figure 2.1. Also most of these parameters are examined points below Figure 2.1. Information degree is explained on nature of demand. Planning horizon can be finite or infinite. It depends to time scale: if there is a defined time period (discrete) horizon is finite, otherwise time scale is continuous and planning horizon is infinite. More information about time scale is given in time period, third point below. Number of items and number of levels are explained in second point below. Problems classified for relevant costs include different approaches of cost function. Cost function can be convex or concave according to programming algorithm. Conventional problems can be solved with concave functions. On the other hand dynamic programming algortihms and heuristic methods are used for convex functions due to their complexity. Relevant cost of lot sizing problem can be setup related, inventory related or capacity related. It is chosen according to problem environment and objective. More information about resorce contraints is given in fifth point below. Problems of service policy are specific to demand. It is explained further in sixth point (extensions) and sub-point on demand. Information about time consuming activities is given in sixth point (extensions) and sub-points on setups and production time. Different objectives are defined according to problem type and related process or requirements. It can be achieved by different programming methods one by one (single objective) or more than one objective (multi-objective). According to target programming method is changed. Single objectives can be achieved by most programming methods such as linear programming, non-linear programming, mixed integer programming etc. On the other hand multi-objectives can be achieved with multi-objective or goal programming. Complexity of problems with multi-objectives is higher than problems with single-objectives.



A classification of lot-sizing problems.

Parameter	Classifications
Information degree	Deterministic*, stochastic*.
Horizon	finite*, infinite.
Time scale	discrete (small time periods, large time periods*), continuous
Number of items	single item*, multi item.
Number of levels	single level*, multi level* (serial, in-tree, general, ...).
Relevant costs	setup related (startup*, reservation*), inventory related (holding*, backorder*, lost sales*), capacity related (regular hours*, overtime*, sub-contracting*).
Resource constraints	number (single resource*, multi resource*), type (constant*, variable*).
Service Policy	demand satisfied on-time*, backorder*, lost sales*, sub-contracting*.
Time consuming activities	setup time (*ST*) (minor *ST*, major *ST*), processing time (zero, constant*, variable), lead time, transportation time.
Objectives	minimize costs*, maximize service level, smoothing of production load, maximize profit*.

Figure 2.1 Classification of lot sizing problems (Brahimi et al., 2017)

Problem classification could be expressed more elaborated as below to define model considered in this thesis better (Díaz-madroñero et al., 2014).

1. Problem type: This category consist of five main production planning areas. These areas are MPS, MRP, SCP, APP and HPP (Mula et al., 2006). The MPS establishes an optimal production plan which meets customers' orders and provides release dates and amounts of final products to manufacture by minimizing production, holding and setup costs. Typically, components production planning is dealt the MRP using BOM and the results obtained by MPS calculations. The purpose of MRP is to optimize simultaneously the production and purchase of all items from raw materials to finished products, in order to satisfy for each item the external or independent demand coming from customers and the internal or dependent demand coming from the production of other items, over a short term horizon. The dependency between items is modelled through the definition of the product structure, also called the bill of materials (BOM) (Pochet, 2001). On the other hand, aggregate production planning (APP) is the medium term capacity planning that determines minimum cost, workforce

and production plans required to meet customer demands (Cheraghalikhani et al., 2019). APP problems are reviewed and classified generally on (Cheraghalikhani et al., 2019).

In model both APP and MRP/MPS approaches is used. Workforce level is not subject of optimization strategy unlike APP approach. Model structure doesn’t fit APP approach exactly due to specialty of process. However except of manpower and labor figures remaining ones are not enough to solve whole problem. On the other hand resources are sparse and it could be overcame by MRP approach. The limited resources is shared by all end-product grades as used on APP and MRP models. All resources used in model are different and there is not only one limit for them. In another words, all resources used in model have different upper bound due to their unit consumption for production are different from each other. That kind of use is different from APP and MRP approaches. By the help of hybrid approach of these two models both monthly and daily production plans run better.

2. Number of products and number of levels: In terms of number of products, single-item models are considered as which production is planned for only a single final product, and also multi-item models that provide the production planning of several items, which may be end products, parts or components. Single-level and multi-level problems is considered based on production stages. The former corresponds to production systems where only final products are manufactured according to the demand obtained directly from customer orders or market forecasts. In multi-level production planning models, BOM establishes a parent/component relationship among the items and define the number of levels in the product structure.

Model consists of multi item products and production line is assumed as single level. There are three end-products of production system and it is a multi-item model. There are not intermediate sections in production line like assembly lines where different parts must be joined to product to finish production process. Chemical reaction goes on during production and production is done on single level.

Single-item and multi-item lot sizing problems are surveyed on different papers such as (Staggemeier & Clark, 2001; Brahimi, 2004). Single item lot sizing problems are surveyed on different papers such as (Pochet, 2001; Brahimi et al., 2006; Brahimi et al., 2017). Multi-item lot sizing problems are surveyed on different papers (Bahl et al., 1987; Karimi et al., 2003; Jans & Degraeve, 2008; Buschkühl et al., 2010; Díaz-madroñero et al., 2014) and textbooks (Pochet & Wolsey, 2006).

3. Time period: According to period length, big time bucket problems and small time bucket problems could be mentioned. Small time buckets problems have short production periods, which normally consist of several hours. Big time bucket problems consist of longer time periods, normally of the order of a few days or weeks. The latter can be seen as a time aggregation of the former. This leads to the consideration of hierarchical planning problems (Brahimi et al., 2006).

Model considered in this thesis assumed as big bucket model because planning horizon is one year. Every month is a discrete time period.

4. Nature of demand: Demand acts as a typical parameter of production planning models and its nature can affect their complexity. If demand levels are known exactly, demand is called deterministic. Yet if demand is not known, it can be termed uncertain. In production planning models, uncertainty is modelled by using probability distributions, fuzzy sets, stochastic approaches based on stochastic values, or several scenarios and robust approaches.

Demand is assumed as deterministic on model considered in this thesis. Forecasted demand is calculated according to last year data.

5. Capacities or resource constraints: It refers to the capacities of the available resources in the production system. A production system can be characterized by restrictions imposed by the available resources. Capacity constraints may increase the complexity of the production planning models and their resolution, but enable more realistic models. Constraints related to inventory limitations, supply of parts and raw materials from suppliers, productive resources such as machines and workforce and transportation resources are identified. Such constraints may be included in the models in isolation or in combination with others. In this sense, some of these constraints can be included in more than one capacity constraints class. For example, a model may

have only production capacity constraints, while another might also include limitations related to inventory capacity constraints and/or supply from suppliers.

Model considered in this thesis is capacitated. The most important constraint of our model is production capacity constraint. There are certain unit consumption of raw and additive materials for producing one unit of end-product and these figures used as unit consumption parameters on model. Resources used in model (raw material, additive material, utility and energy resources) are limited by maximum production and processing capacity. Productive resource limitation is related with maximum production and processing capacity. It means that only end-product quantity less than maximum production quantity can be produced. End-product inventory is limited by maximum warehouse capacity, however it is hardly possible to reach storage limit because there is also a certain degree of inventory turnover. Planned quantity of end-product safety stock is stored by every grade of production according to safety stock calculation as decided on inventory policy. Raw materials are stored in storage silos for certain days of inventory according to planned production capacity. Additive materials are prepared regularly as solutions. Utility resources are used directly.

Multi-item lot-sizing problems with limited resource and end-product capacity is mentioned on (Drexl & Haase, 1995; Hung & Hu, 1998; Karimi et al., 2006; Brandimarte, 2006; Erromdhani & Rebaï, 2017; Sung & Chang, 1986). Same problem with multiple resources is mentioned on (Katok et al., 2008; Chen et al., 2009; Jodlbauer & Reitner, 2012). Energy constraints are added and energy consumption is mentioned on (Rapine et al., 2018; Goisque et al., 2018).

6. Extensions

a. Demand: In order to obtain production planning models that come closer to reality, in addition to considering price-dependent demand levels, several extensions related to demand are identified. For instance, the ability to meet demand through product substitution, the existence of time windows, the option of backlogs to meet demand in following periods, and modelling lost sales if demand cannot be met during the corresponding period or during the subsequent one.

Only one extension on demand is used in our model: backlogging. Customer satisfaction is the one of the priorities for production planning. There is a risk to unmet demand with varying probability so backlogging is used in model in order to control it better. Backlogging with deterministic uncapacitated single-item single-level lot sizing problem is mentioned on (Aksen et al., 2003; Toledo & Shiguemoto, 2005; Van Vyve, 2006; Absi et al., 2011). Both single-item and multi-item problems with backlogging extension are reviewed on (Küçükyavuz & Pochet, 2009). Multi-item problem with backlogging extension is examined on (Karimi et al., 2006). Deterministic capacitated multi-item problem with shortage costs is examined on (Absi & Kedad-sidhoum, 2003; Absi & Kedad-Sidhoum, 2006; Absi & Kedad-Sidhoum, 2009). There is not backlogging extension on these three models but shortage cost is mentioned. Last two of these three articles include safety stock extension in their model. Backlogging with safety stock for an uncapacitated model is given on (Loparic et al., 2001). A framework for capacitated multi-level lot sizing problem with backlogging is given on (Wu et al., 2011). Backlogging and lost sales for uncapacitated lot sizing problem is examined on (Absi et al., 2011).

High customer service level is one of the targets of the production planning. There are different descriptions for service level. These definitions are classified as α, β, γ and λ letters according to considered points. Backlog can be seen as the depth of the unserved demand on one of the definitions (Gruson et al., 2018). Service level is defined as equation below (Helber et al., 2010) and this approach is used in model.

$$\gamma_t = 1 - \left(\frac{expected\ backlog\ in\ period\ t}{expected\ demand\ in\ period\ t}\right) \qquad (2.11)$$

The impact of service level for both capacitated and uncapacitated deterministic problem is mentioned on (Gruson et al., 2018). Service levels with extensions of safety stocks and backlogging is examined on a stochastic lot sizing problem (Helber et al., 2010). Service level variable is added to model considered in this thesis according to (Boulaksil, 2016).

b. Setups: Generally, setup activities are included in production planning models by considering the setup costs and/or setup times which model the production changeovers between different products. The inclusion of setup times involves reducing the production capacity available per period and increases the models' complexity because they are usually modelled by introducing zero-one variables. Three other setup types of complex setups can be contemplated: setup carry-overs; sequence-dependent setups; family setups.

Setup in our model could be defined as a product quality changeover. As mentioned before there are three end-products. Before production of end-products with different quality, grade transition must be done. One of the motivations of PET production planning is to minimize the amount of off-spec material during the transitions for given production targets for the different grades within a certain period of time. The amount of off-spec product in each transition is minimized by solving a dynamic optimization problem and simultaneously the due date violations and the overall production costs are optimized through scheduling aspects (Engell & Harjunkoski, 2012). However scheduling is not considered in this thesis. It could be achieved same target by decreasing number of setup times. It can be possible by assignment to production quantity to different grades on determined time horizons. Idea of this kind of solution is very similar to Heijunka which is one of the lean production tools used in manufacturing. The task of Heijunka is multiple: to connect the total value chain from customers to suppliers, make what customers want and when they want, and smooth the system pulse. The production volume is streamlined as smooth as possible, but product mix is similarly spread out as evenly as possible. The result of this policy is that in each moment the sequence structure of different model types in the assembly line reflects the volume and the structure of the monthly and smoothed daily demand (Vörös & Rappai, 2016).

c. Production time: In order to adjust the capacity usage level of productive resources, production planning models include overtime, subcontracting and under time decisions. If production capacity is less than customer demand in a particular period, the decision-maker may choose to produce in overtime or to outsource part of the production to meet demand without backlogs. If, however, production capacity is higher than demand, production resources may be idle for sometime, which can be modelled with under time variables.

This extension is not used in model considered in this thesis because production quantity is same whether manpower is considered as a predictive factor or not. Production process is almost independent from manpower because production continues by chemical conversion. There is no need for extra manpower or overtime to increase productivity in such kind of production plants.

d. Multiple and parallel machines: Standard production planning models can represent the existence of parallel machines by augmenting the production variables and the capacity parameters by an additional index indicating the individual machines. However, there is an alternative way of modelling parallel machines without including the additional index in the production variables.

This extension is not used in model considered in this thesis. There are multiple equipments in production line and some of them run parallel in some sections of process. In order to simplify production plan, these are not considered as a part of the problem. Capacity expansion plans could include increment of number of equipments and number of production lines, so in future that kind of extensions can be done.

e. Multisite: Monosite production planning models can be extended to multisite ones by considering several manufacturing plants and/or by incorporating the suppliers, warehouses, distribution centers and customers constituting a supply chain.

This extension is not used in model considered in this thesis. There are different kind of plastic production plants which are part of facilities of the study in different places of Turkey. However these are preform production plants. Our planning is only done for PET resin production in Gaziantep. If all parts are considered, it would be a supply chain problem and it is out of our scope. For future works, this model can be extended for this.

f. Remanufacturing activities and/or quality issues: In recent years, manufacturers have started to integrate remanufacturing activities into the traditional production environment. For example, remanufacturing returned products is a common practice in production plants of high valued products like computers, copiers or medical equipment. Thus, customers' demand can be met with new products or returned remanufactured products. Remanufacturing returned products, however, creates many new operations management problems. These include the collection of used products, dismantlement or disassembly of returned products, incorporation of remanufacturing activities into the overall production planning, and the recycling or disposal of unused products.

The quality of the returned products to be remanufactured is an important aspect to consider when organizing and planning remanufacturing activities. A common way of considering the quality of returned products is by assigning different degrees of quality and, depending on which, the necessary remanufacturing operations to which they must be submitted to meet customers demand may vary.

Environmental awareness was raised popularity first on 70’s due to increasing side effects of conventional industrialization. Life quality of a human being is dramatically rise since first industrial revolution. The average life expectancy has more than doubled during this period and people's lives have been made easier by factors such as the use of white goods and the development of plastic technology. However, average amount of waste per person is increased much higher in the same period: the content of thrash is also increased drammatically. Concepts of remanufacturing and recycling became popular due to rapidly increasing environmental pollution, waste of natural resources, and scarcity of resources.

In the past there were no restrictions on the recycling of end products. However, most countries had taken a step and they applied some charges about it. This extension is not used in model now, but in future it may be considered.

7. Modelling approach: The typical mathematical programming approaches considered in production planning problems are linear programming, integer linear programming, mixed integer linear programming and quadratic programming, if there is a quadratic objective function of several variables subject to linear constraints in these variables. However, the need to optimize more than one objective simultaneously and to express the nonlinear relationships among the different variables of a production system involves the use of multiobjective programming and nonlinear programming respectively.

Mixed integer linear programming is the approach of model considered in this thesis. Modeling lot sizing problems with mixed integer programming with some extensions of original problem (start-up, changeover, number of setups) is given on (Belvaux & Wolsey, 2003). Different cases from chemical industry using MILP is mentioned on Kallrath (2000) and (Kallrath, 2002). The most useful resource which covers problem types, extensions and cases of production planning by MIP is reviewed on Pochet & Wolsey (2006).

8. Solution approach: According to Buschkühl et al. (2010), the approaches to solve different types of production planning or capacitated lot-sizing models can be classified into five groups: mathematical programming based (MP-based) approaches, Lagrangian heuristics, decomposition and aggregation heuristics, metaheuristics, problem-specific and greedy heuristics. Among the MP-based approaches, it is possible to distinguish between exact methods, which stop after an optimal solution has been found regardless of efforts made in terms of required computation time and memory, and MP-based heuristics, which only explores parts of the solution space and attempts to find a good feasible solution in a reasonable time. This work considers exact methods as those embedded in default solvers, such as the typical branch-and-bound algorithm for solving mixed-integer programs to optimality. MP-based approach is used in this thesis.

9. Development tool: This refers to the commercial or non-commercial software tools needed to implement and solve the proposed models. These software tools can be solvers (CPLEX, LINGO, Xpress-MP, Gurobi, LP-Solve, GLPK, etc.), programming languages (C, C++, Visual C, Java, Basic, Fortran, etc.), optimization modelling languages (GAMS, AMPL, OPL, AIMMS, MPL, Matlab, Xpress-MOSEL, etc.) and simulation systems (Anylogic, Arena, FMS.net, AutoSchedAP, etc.).

GAMS was used as modelling language for model considered in this thesis. CPLEX solver which was integrated by GAMS language was used. Model was tried to run by different solvers and CPLEX solver was chosen thanks to its better performance.

10. Application: The proposed models can be validated by using data from real-world production systems or by carrying out numerical experiments based on artificially generated instances.

One of the applications on plastic industry is given on Van Wassenhove & De Bodt (1983). It is about injection moulding of a plastics production plant. Optimization of production in bottle grade PET resin plant is target of model considered in this thesis and it is a real-world application. Some of the recent studies on bottle grade PET resin are given on Liberopoulos et al. (2010) and Hatzikonstantinou et al. (2012). These articles are about production scheduling of a PET resin plant according to defined quality range. Inventory management of planned end product quantity is done according to market conditions. Case studies are surveyed on Fuchigami & Rangel (2018). General review of methodologies and applications in different production processes especially in the chemical industry is given on Harjunkoski et al. (2014).

11. Limitations: Some of the limitations pointed out by the authors of the proposals are related to the solution method used, the considered production systems, demand issues, capacities, the non-consideration of uncertain parameters, product properties, applications in non-real-world environments, supply chain issues and costs. These limitations are possibly improvements of the proposed models, and they identify future lines of work for academic researchers and practitioners.

12. Benefits: Possible benefits are classified into six groups: solution method, improvements, application, uncertainty, extensions and demand. One of the objectives of solving a lot sizing problem is obtaining benefits somehow. These benefits may be more useful in enhancing the theoretical aspect, more useful for real-world applications or useful for both ways.

2.3 Key Factors For Production Planning

Basic information about production planning is given on section 2.1. However some other factors must be considerered to establish and keep an appropriate production plan. Not only numerical data but also general standards and social obligations should be considered when creating such a plan. One of the most powerful challenges is sustainability concept. It is a must for enterprises for many reasons. Waste of resources and environmental pollution have been dramatically increasing as mentioned before. With unplanned industrialization and urbanization, living spaces are decreasing. In addition, the working culture in most existing workplaces is far from meeting the expectations of employees. Therefore, the solution of environmental and social problems has become an urgent need. It is not possible for enterprises that work only for profit to ignore these problems and grow. Sustainability is a concept that addresses economic, environmental and social needs and aims to continue economic growth with an understanding that protects people and nature. Lean production is a concept that aims to minimize all kinds of waste in the workplaces. With the active implementation of these two concepts, there will be a more harmonious interaction between industry, environment and people. For this purpose, production capacity, energy and stock policies are formed and their relations are examined in the model mentioned in the thesis.

2.3.1 Sustainability and Lean Manufacturing

Sustainable manufacturing is the creation of manufactured products through economically sound processes that minimize negative environmental impacts while conserving energy and natural resources (US EPA, n.d.). Concept of triple bottom line sets out the objectives of sustainable production in a short and clear way (Elkington, 1998). As stated by this concept sustainability consists of economic, environmental and social dimensions. Economic dimension focuses on the financial expectations of the customers, employees, suppliers, and investors. Environmental side of the sustainability considers minimizing waste, reducing the carbon emission and other pollution, and protecting natural resources. Social aspect matters for human rights, diversity, employment quality with opportunities for training and development, and health and safety conditions of workers (Kazan, 2018).

Recently, several authors addressed lot-sizing with different environmental constraints. Carbon emissions constraints deal with several new legislative constraints that aim at reducing the overall environmental impact. These constraints were addressed with different point of views. Some authors considered carbon emission constraints that limit the unitary carbon emission following several concepts. They propose four types of carbon emission constraints: periodic carbon emission constraint, cumulative carbon emission constraint, global carbon emission constraint, and rolling carbon emission constraint (Absi et al., 2013). These constraints impose a maximum value not on the total carbon emission, but on the average carbon emission per product. This type of constraints is particularly relevant to the firms who want to display the carbon footprint of their products (Brahimi et al., 2017). An application with periodic carbon emission constraint is implemented on Absi et al. (2016). One of the lot sizing problems with emission constraint is examined on Retel Helmrich et al. (2015). Carbon emission with economical effect directly related with lot sizing according to EOQ principle and relations between emission with order quantity and total cost is analyzed on Hua et al. (2011). Relation between total cost and carbon emission if there is a carbon price is examined on (Hua et al., 2011). Interactions between total profit and emission (and some others) is reviewed on (He et al., 2012). Interactions between cycle service level, total cost and inventory level is examined on (Purohit et al., 2015).

Cognitive concepts based on consumer psychology and behavior in order to environmental design is analyzed on this remarkable work (Macdonald & She, 2015). Interaction between lean implementation and organizational culture in enterprises is studied on (Bortolotti et al., 2015).

Success and current development of sustainable systems are followed by some performance indicators according to triple bottom line classification. A survey which performance indicators are classified by general standards and guidelines according to triple bottom line is given on (Saeed & Kersten, 2017). Frequently used metrics are given on (Thomé et al., 2012). In addition to performance measures, the process industries are attempting to undertake significant transformations and will need to face new challenges in the future. These include: changing market circumstances and increased competition, with shorter product life cycles; improved sustainability and environmental and social impacts throughout the supply chain; future regulation and compliance requirements (for example the responsibility to recover and recycle consumer products at end-of-use) (Papageorgiou, 2009). Success is not only achieving the aims but also to ‘sustain’ sustainability process steadily.

PET resin production plant is a chemical production plant and polyester production is a part of chemical industry. Chemical industry, as a huge materials and energy consumer, and with a strong ecological impact, could not remain outside of sustainability requirements. It is imperative to consider all three dimensions of sustainability in all stages of process development. As a consequence, process optimization evolves to multi-objective optimization. In traditional process optimization the objective function is a scalar one. In multi-objective optimization of sustainable processes the objective function is a vectorial one, with economical, ecological and social components (Woinaroschy, 2016). PSE is the field that encompasses the activities involved in the engineering of systems involving physical, chemical, and/or biological processing operations (Stephanopoulos & Reklaitis, 2011). A comparative study is done between PSE perspective and operations research (lot sizing and scheduling) for a single-level continuous production process is examined on (Amorim et al., 2013). Different perspectives of PSE is given on (Klatt & Marquardt, 2009). Process synthesis perspective is also a chemical engineering concept which its awareness increase. It is related with sustainable production. One of the study on this topic is given on (Barnicki & Siirola, 2004).

Reflections on the manufacturing system has been developing since first serial assembly production. After the 60’s lean production idea was born in Japan and spread around the world. Lean manufacturing is an integrated socio-technical system, whose main objective is to eliminate waste by concurrently reducing or minimizing supplier, customer, and internal variability (Almanei et al., 2017). It has been a reliable standard for top companies for almost sixty years. The paths of production planning and lean production converge in many areas. Integration of these two ideas are evaluated on some studies. MRP and JIT integration is analyzed on (Benton & Shin, 1998). Work for a production environment with JIT principles is mentioned on (Vörös & Rappai, 2016). Number of integrated modeling practices rises regularly by the pressure of strict rules and actual needs. Aggregate planning with sustainability view is studied on (Türkay et al., 2016).

Lean manufacturing is analyzed with environmental management and relations between not only environmental outcomes but also market and financial performance on a different work (Yang et al., 2011). Lean practices make visible effects on the system where applied to. Performance of lean production on processes could be seen on different works. Inventory turnover is one of the successful examples with the help of JIT (Demeter & Matyusz, 2011). Inventory turnover is seen on another work

(Marodin et al., 2018). ROA and some other key results with using JIT is seen on (Maiga & Jacobs, 2009). On the other hand lean manufacturing is not a magic wand. In some applications expected results didn't occur. Waste elimination is not affected from lean implementation in a factory in Poland (Wyrwicka & Mrugalska, 2017). Lean manufacturing is very beneficial for most factors but putting it into practice is not easy. It is a part of the company's vision and implementation is not for single time. It is a continuous process which must be learned and applied up and down in an enterprise. There would be some contradictions during application. Production plan has to be strong and flexible enough to handle that kind of problems. It depends how it is implemented on production facility where the study is made.

Lean manufacturing is one of the source inspirations of sustainability. In some works relation between lean manufacturing and sustainability is reviewed. One of them is on supply chain management, but it gives a comprehensive approach for the overall operations management (Martínez-Jurado & Moyano-Fuentes, 2014). An extensive literature review on two ideas is given on (Hartini & Ciptomulyono, 2015). Performance of lean tools in large organizations by selected measures is analyzed on (Bhasin, 2012). JIT implementations by different critical success factors and benefits are reviewed on local Mexican companies is analyzed on (Alcaraz et al., 2014).

2.3.2 Energy Policy

Lot sizing problems could be used to decrease energy usage except of main objectives. Some applications are done to reduce electrical consumption by pricing of electricity in different time periods of day (Masmoudi, Yalaoui, Ouazene, & Chehade, 2015).

2.3.3 Capacity Policy

Sufficient production quantity by demanded product grade is the main area of study of lot sizing problems. However production capacity is usually kept in the background to meet frequently used objectives like maximizing profit or minimizing cost. Some earlier studies are given on (Ritzman & Bahl, 1984) and (Helber, 1995). The relation between MRP and capacity planning is seen on more recent review (Jodlbauer & Reitner, 2012). Batch size is fixed on some works to see effect on optimal result (Tempelmeier & Hilger, 2015), (Li & Meissner, 2011). Additionally there is cost of capacity adjustment on given model (Ou & Feng, 2019). However in this case production quantity is not enough to handle demand. Utilization and capacity planning is given on by a stochastic non-linear model on (Erenay et al., n.d.). In this work utilization level and cost is compared.

Studies on lot sizing problems with resource constraints and capacity issue is reviewed on (Bahl et al., 1987). It is one of the early review on this subject and very useful. Multi-level multi-item capacitated lot sizing problem with capacity constraints is examined on (Buschkühl et al., 2010). Similar work to model considered in this thesis could be seen with a generalized theory as known as advanced resource planning on (Vandaele & De Boeck, 2003). An application for food industry is given on (Kopanos et al., 2011).

2.3.4 Inventory Policy

Inventory is one of the challenging problems for enterprises since the idea of lean production became widespread. Lean principles force workplaces to decrease and eliminate their stocks in the long run. In production system, it represent as solution of 'waste' problem. Without inventory, one of the waste sources is being disposed of and cost of inventory is disappeared. On the other hand, there is always a risk of stock outs due to many reasons: fluctuating demand, problems in supply chain etc. Required amount of end-products must be sent to customers by reliable and quick way. A certain degree of safety stock must be stored to protect production environment from these problems.

If it is assumed a deterministic replenishment time and a stochastic or random consumption the safety stock calculation can be done with the equation:

$$Safety\ Stock = \sigma_D * SF * \sqrt{\left(\frac{LT}{T}\right)} \tag{2.12}$$

where:

σ_D: Standard deviation of demand;

SF: Service level factor;

LT: Total lead time;

T: time used for calculating standard deviation of demand.

SF (z score) is found from standard normal distribution table according to expected service level percentage.

$$Reorder\ Point = Lead\ Time\ Demand + Safety\ Stock \tag{2.13}$$

Safety stock issue for capacitated multi-item lot sizing problem is mentioned on (Absi & Kedad-Sidhoum, 2009) basically. Accord between forecasted demand and safety stock is reviewed on (Boulaksil, 2016) and (Prak et al., 2017). Relation between service level and safety stock is reviewed on (Rădăşanu, 2016) and (Nenni et al., 2005).

2.4 Forecasting

A forecast is a prediction of future events used for planning purposes. Planning, on the other hand, is the process of making management decisions on how to deploy resources to best respond to the demand forecasts (Krajewski et al., 2011).

Demand forecasting is an important task given its impact on decisions at many different levels within firms. Companies in general pay relevant attention on how to obtain a prompt and accurate forecast of future demand (Kalchschmidt, 2012).

2.4.1 Forecasting Methods

Forecasting methods may be based on mathematical models that use available historical data, or on qualitative methods that draw on managerial experience and judgments, or on a combination of both (Krajewski et al., 2011).

Choosing the appropriate forecasting method depends largely on what data are available. If there are no data available, or if the data available are not relevant to the forecasts, then qualitative forecasting methods must be used. These methods are not purely guesswork there are well-developed structured approaches to obtaining good forecasts without using historical data.

Quantitative forecasting can be applied when two conditions are satisfied:

1. Numerical information about the past is available;

2. It is reasonable to assume that some aspects of the past patterns will continue into the future.

Most quantitative prediction problems use either time series data (collected at regular intervals over time) or cross-sectional data (collected at a single point in time) (Papalambros & Wilde, 2018).

A study on selecting forecasting methods is given on (Armstrong, 2001). General review on forecasting methods and a remarkable study is done on (Kalchschmidt, 2012). Commonly used variables are compared between forecasting method results and according to their performance proper method is chosen. One of the different approaches on forecasting accuracy is given on (Barrow & Kourentzes, 2016). According to this study forecasting effectiveness increases by combinations of selected forecasting methods. Performance of forecasting methods by their outcomes on industry specialized on inventory performance is studied on (Petropoulos et al., 2019).

2.4.1.1 Time Series Methods

Time series methods use historical data as the basis of estimating future outcomes. When forecasting past time and future demand Holt-Winter and ARIMA methods are used in proposed model due to higher accuracy along with the real data. There are same comparisons with same methods of their performance on different industries. These works are on food industry (Da Veiga et al., 2014), tourism sector (Sood & Jain, 2017), information technology (Yakovyna & Bachka, 2018). One of the works of forecasting demand is done by moving average, Holt-Winter, ARIMA methods on plastic industry (Udom, 2014). Scope of some works are very extensive. European industrial production is forecasted by Holt-Winter, ARIMA and a new technique called Singular Spectrum Analysis Method (SSA) and performance of these methods are compared based on data from Germany, France and the UK, Europe's most powerful producers. Forecasting European industrial production of biggest players (Germany, United Kingdom and France) is done by Holt-Winter, ARIMA and a new technique called SSA and performance of these methods are compared on (Hassani et al., 2009).

2.4.1.2 Holt-Winters' Method

Holt-Winter method is one of the exponential forecasting methods. Exponential smoothing was proposed in the late 1950s and has motivated some of the most successful forecasting methods. Forecasts produced using exponential smoothing methods are weighted averages of past observations, with the weights decaying exponentially as the observations get older. This framework generates reliable forecasts quickly and for a wide range of time series, which is a great advantage and of major importance to applications in industry.

The Holt-Winters seasonal method comprises the forecast equation and three smoothing equations one for the level ℓ_t, one for the trend b_t, and one for the seasonal component s_t, with corresponding smoothing parameters α, β^* and γ. m is used to denote the frequency of the seasonality, i.e., the number of seasons in a year.

The component form for the additive method is:

$$\hat{y}_{t+h|t} = l_t + hb_t + s_{t+h-m(k+1)} \tag{2.14}$$

$$l_t = \alpha(y_t - s_{t-m}) + (1-\alpha)(l_{t-1} + b_{t-1}) \tag{2.15}$$

$$b_t = \beta^*(l_t - l_{t-1}) + (1-\beta^*)b_{t-1} \tag{2.16}$$

$$s_t = \gamma(y_t - l_{t-1} - b_{t-1}) + (1-\gamma)s_{t-m} \tag{2.17}$$

where k is the integer part of (h−1)/m, which ensures that the estimates of the seasonal indices used for forecasting come from the final year of the sample. The level equation shows a weighted average between the seasonally adjusted observation ($y_t - s_{t-m}$) and the non-seasonal forecast ($l_{t-1} + b_{t-1}$) for time t. The trend equation is identical to Holt's linear method. The seasonal equation shows a weighted average between the current seasonal index, ($y_t - l_{t-1} - b_{t-1}$), and the seasonal index of the same season last year (i.e., m time periods ago).

The equation for the seasonal component is often expressed as

$$s_t = \gamma^*(y_t - l_t) + (1-\gamma^*)s_{t-m} \tag{2.18}$$

If we substitute l_t is substituted from the smoothing equation for the level of the component form above, this equation is obtained

$$s_t = \gamma^*(1-\alpha)(y_t - l_{t-1} - b_{t-1}) + \big(1 - \gamma^*(1-\alpha)\big)s_{t-m} \tag{2.19}$$

which is identical to the smoothing equation for the seasonal component is specified here, with $\gamma=\gamma^{*}(1-\alpha)$. The usual parameter restriction is $0 \leq \gamma^{*} \leq 1$, which translates to $0 \leq \gamma \leq 1-\alpha$ (Papalambros & Wilde, 2018).

2.4.1.3 ARIMA Method

If differencing with auto regression and a moving average model is combined, a non-seasonal ARIMA model is obtained. The full model can be written as

$$y'_t = c + \emptyset_1 y'_{t-1} + \cdots + \emptyset_p y'_{t-p} + \theta_1 \varepsilon_{t-1} + \cdots + \theta_q \varepsilon_{t-q} + \varepsilon_t \tag{2.20}$$

where y'_t is the differenced series (it may have been differenced more than once). The "predictors" on the right hand side include both lagged values of y_t and lagged errors. This is called an ARIMA(p,d,q) model, where

p = order of the autoregressive part;

d = degree of first differencing involved;

q = order of the moving average part.

Changing the parameters $\phi_1, \ldots, \phi_p$ results in different time series patterns. The variance of the error term ε_t will only change the scale of the series, not the patterns.

2.4.2 Forecasting Error and Forecasting Accuracy

A forecast "error" is the difference between an observed value and its forecast. Here "error" does not mean a mistake, it means the unpredictable part of an observation (Papalambros & Wilde, 2018).

The following terminology is used: if $y_1, \ldots, y_n$ represents a time series, then $\hat{y}_i$ represents the i^{th} forecasted value, where $i \leq n$. For $i \leq n$, the i^{th} error e_i is then

$$e_i = y_i - \acute{y}_i \tag{2.21}$$

Finding a forecast that minimize the errors is one of the goals of a proper production plan. A number of measures are commonly used to determine the accuracy of a forecast, including Mean Absolute Error (MAE), Mean Squared Error (MSE) and Root

Mean Squared Error (RMSE). Note that MAE is also commonly called Mean Absolute Deviation (MAD) (Zaiontz, 2013).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|e_i| \tag{2.22}$$

$$MSE = \frac{1}{n}\sum_{i=1}^{n} e_i^2 \tag{2.23}$$

$$RMSE = \sqrt{MSE} \tag{2.24}$$

Some other measurements are Mean Absolute Percentage Error (MAPE), Mean Absolute Scaled Error (MASE) and Symmetric Mean Absolute Percentage Error (SMAPE).

$$MASE = \frac{\frac{1}{n}\sum_{i=1}^{n}|e_i|}{\frac{1}{n-1}\sum_{i=1}^{n}|y_i - y_{i-1}|} \tag{2.25}$$

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{e_i}{y_i}\right| \tag{2.26}$$

$$SMAPE = \frac{1}{n}\sum_{i=1}^{n}\frac{|e_i|}{\left(\frac{|y_i| + |\hat{y}_i|}{2}\right)} \tag{2.27}$$

If decision has to be made according to forecasting error, it has to be chosen right measure for production environment considered in this thesis. When these methods are compared it can be seen that kind of results: MAD is the easiest to compute, but weights errors linearly. MSE squares errors, thereby giving more weight to larger errors, which typically cause more problems. MAPE should be used when there is a need to put errors in perspective (Stevenson, 2011).

Forecasting accuracy is crucial for production planning. Although the estimate is not exactly accurate, it is very helpful for planning. It is a popular topic due to its high importance. Relation between forecasting accuracy and inventory management is examined on Ali et al. (2012) and Gundavarapu et al. (2018). One work on safety stock as a part of inventory management is done specially (Prak et al., 2017).

RMSE, MAE and MAPE methods are the most common methods for forecasting accuracy. All three metrics measure the forecasting error when compared to the actual values and so report on the performance of each model. Smaller values would indicate better performance. The RMSE criterion is the most popular criterion for time series comparison. It depends on the scale of the variable of interest, thus is suitable for comparing different models across the same time series. Because of its quadratic nature large errors weigh higher and this fact makes RMSE more suitable when large errors are particularly undesirable. All errors are weighted equally on MAE method due its linear nature and as a consequence is less sensitive to large errors. MAE on the other hand, depends also on the scale of the variable, but due to its linear nature all errors are weighted equally, and as a consequence is less sensitive to large errors. Finally, MAPE is another popular measure of accuracy because it is scale independent and also because it can be interpreted and understood better. Reported disadvantages of MAPE are associated with instabilities, when the original time series carries small values, and with asymmetrical penalties applied to positive errors compared to the negative ones (Katris & Daskalaki, 2015).

CHAPTER III

MAIN CONCEPTS ON PET PRODUCTION

This study is a real-world application and as mentioned before production facility where the study is made is a bottle grade PET resin facility. In this chapter firstly production of chemicals is briefly explained. Then production of bottle grade PET is mentioned. This section consists of PET production processes, properties of PET, PET products, statistics on bottle grade PET usage and future trends. Retail/off-trade trends of PET products worldwide and for Turkey, consumption by use and general statistics about manufacturing figures are given on statistics on bottle grade PET usage. Some aspects and ideas are given on future trends. Basic information about production process of production facility where the study is made is given on last part.

3.1 Production of Chemicals

A chemical plant is an industrial process plant that manufactures (or otherwise processes) chemicals, usually on a large scale (Ellison-Taylor et al., 1970). The general objective of a chemical plant is to create new material wealth via the chemical or biological transformation and or separation of materials (Douglas & Siirola, 2000). Chemical processes may run in continuous or batch production.

3.1.1 Batch Processing

Batch processing is the industry standard for efficiently producing small batches of chemicals that meet unique end user requirements. In many cases, the manufacturer produces a sample solution, forwards it to the customer, and awaits feedback regarding what must be done to perfectly customize the product for the application. Consequently, small batch chemical manufacturing is commonly associated with the production of custom chemical products.

3.1.2 Continuous Processing

Continuous processing is the industry standard for producing large volumes of chemicals, which are typically designed to meet the needs of a broad range of end users. For example, in terms of efficiency and cost, it may make more sense to use continuous processing to create a dielectric solvent that is widely used by companies in the aerospace industry. In continuous processing, supply and demand are key considerations. The manufacturer often refers to production data from the previous year, as well as industry trends, to gauge production (Mancuso, n.d.).

3.2 Production of Bottle Grade PET

Polyethylene terephthalate is the most widely used thermoplastic polymer resin of the polyester family and is used in fibres for clothing, containers for liquids and foods, thermoforming for manufacturing, and in combination with glass fibre for engineering resins. It is also the most commercially important aromatic polyester. PET is a white or light cream material, has high heat resistance and chemical stability and is resistant to acids, bases, some solvents, oils and fats.

The majority of the world's PET production is for synthetic fibers (in excess of 60%) with bottle production accounting for around 30% of global demand. The increasing demand for PET gave rise to the development of continuously operated large-scale plants. The capacity of continuous PET plants has grown since the late 1960s from 20 t/d to presently 600 t/d in a single line, with the tendency to still higher capacities (Scheirs & Long, 2004).

3.2.1 PET Production Processes

Bottle grade PET resin can be produced both in a batch process as well as continuous process. For continuous production there are two types of processes: SSP and MTR. After polymerization in the melt phase the molecular weight of polyester can be further increased in the solid-state. This process is known as solid-state polycondensation. Continuous SSP plants are characterized by longer residence times and larger product hold-ups compared to the melt phase (Scheirs & Long, 2004). MTR® is a proven technology for producing PET resin from the feedstocks PTA (purified terephthalic acid) and EG (ethylene glycol), including conventional co-monomers and additives, in a melt-phase polymerization process (Thyssenkrupp, n.d.). MTR® process is used for bottle grade PET resin production in the facility where the study is carried out. Production in this facility is continuous. Continuous processing for production is used in production facility where this study is made.

3.2.2 Properties of PET

The properties of PET and its copolymers are determined basically by their chemical composition and molecular structures. The polyesters have been used in a variety of applications because of their versatility and excellent physical properties.

Molecular weight and molecular weight distribution are fundamental properties that determine end-use applications. The polymers are produced to various molecular weights and are available in amorphous, semi-crystalline or highly crystalline states. In the polyester industry, molecular weights have been characterized IV measurements in dilute solutions (Zein et al., 2010).

There are three main quality grades for PET resin specialized for usage: 0.76, 0.80 and 0.84. Product grade of 0.76 IV is primarily used for water bottles. It has low IV, because water bottles need not be as stiff as bottles for carbonated soft-drinks, which are under higher pressure. Carbonated soft drinks, on the other hand, are stored in 0.80 IV or 0.84 IV bottles (Liberopoulos et al., 2010).

3.2.3 PET Products

Bottle grade pet products are separated basically to bottles and jars. The demand for bottles is much higher than the demand for jars due to especially difference of usage areas of these products.

3.2.3.1 PET Bottles

PET bottles are available in a wide range of sizes and span all industries. They can be cylindrical or shaped but all have a narrow neck for pouring. PET bottles are usually clear and have a high shine finish.

PET bottles are common in soft drinks, mineral water and edible oil and are also heavily used in non-food categories like hand dishwashing products, household cleaners, shampoos, shower gels and other personal care products. PET bottles can also come in squeezable varieties (Euromonitor, 2013). PET has taken market share in the bottled water market due to its good clarity and not leaving any taste in the water.

PET has good barrier properties against oxygen and carbon dioxide. Its chemical inertness and physical properties made it particularly suitable in food packaging applications especially in beverages and drinking water (Ji, 2013). Some applications of pet bottle is seen on Figure 3.1.

Figure 3.1 PET bottle applications (Euromonitor, 2013)

3.2.3.2 PET Jars

PET jars differ from PET bottles as the mouth of the container is wider to enable consumers to "dip into" the jar. PET jars are typically blow molded (Euromonitor, 2013). Some applications of pet jar is seen on Figure 3.2.

Figure 3.2 PET jar applications (Euromonitor, 2013)

3.2.4 Statistics on Bottle Grade PET Usage

Some statistics about bottle grade pet usage is analyzed on this section. End-product demand, general overview of manufacturing and future trend is given basically. The market volume is very wide, and some of its features make PET indispensable and unrivaled for the time being.

3.2.4.1 End Product Demand and Retail Volume

According to EUROMONITOR statistics demand for PET bottle and PET jar requirement increases every year regularly. It can be seen on Figure 3.3.

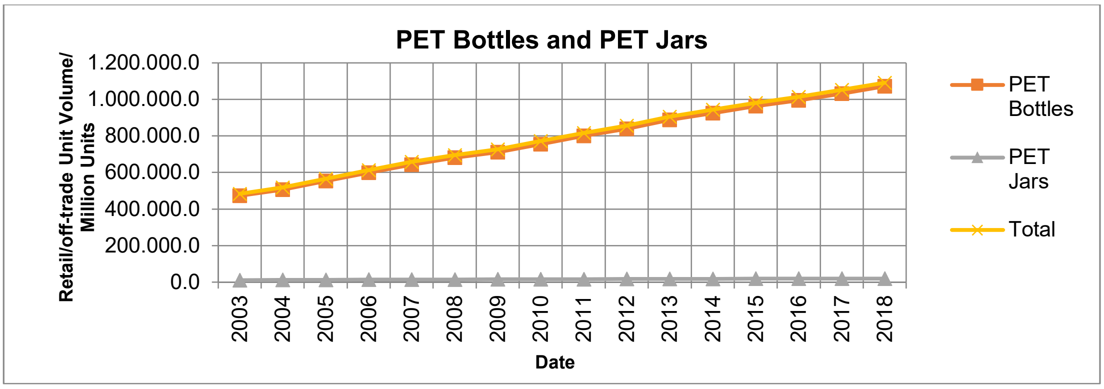


Figure 3.3 Worldwide PET applications retail/off-trade trend (Euromonitor, 2018)

PET bottle consumption raised more than 118% from 2003 to 2017 worldwide. Trend of this can be seen on Figure 3.4. Upward trend of PET jar consumption rate can be seen on Figure 3.5. Sector retail figure rise every year by an average of 5.7% from 2004 to 2017. End of 2018 forecast shows that it will increase by 3.8% compared to the last year.

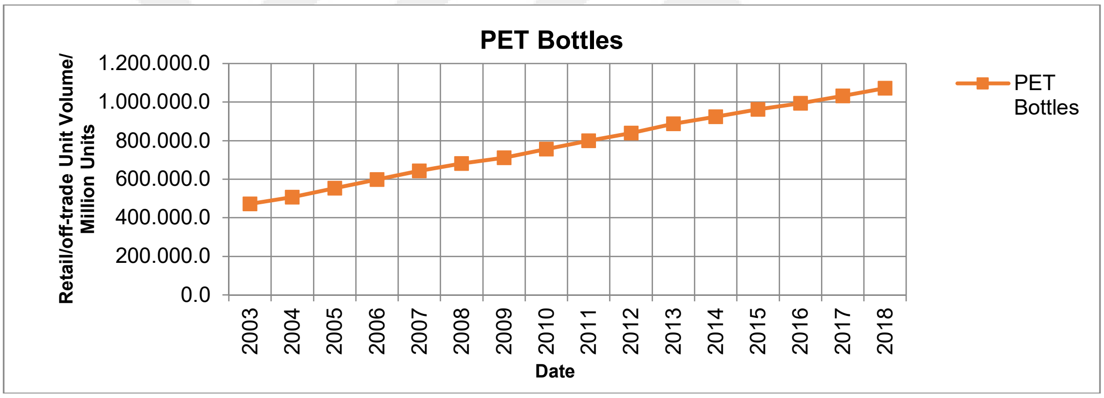


Figure 3.4 Worldwide PET bottle retail/off-trade trend (Euromonitor, 2018)

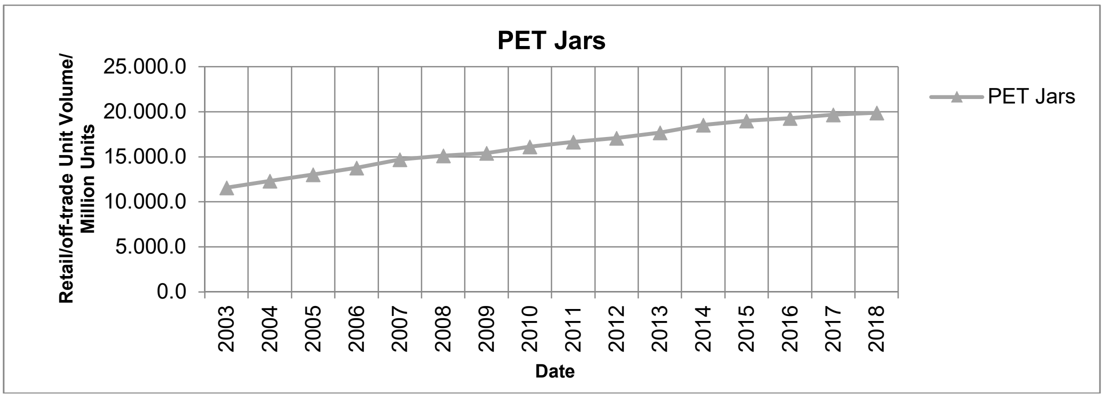


Figure 3.5 Worldwide PET jar retail/off-trade trend (Euromonitor, 2018)

Trend of sectoral distribution of PET bottle usage can be seen on Figure 3.6. There are many sectors using PET bottle but five sectors with the highest share is chosen. PET bottle applications mainly consist of beverages and soft drinks packaging worldwide. Worldwide retail figures are given on Table 3.1. Total retail figure of these two sectors is 910337.5 million units for 2017 PET bottle retail-off trade data 2017. Total packaging retail figure is 1032073.5 million units for 2017, so only these two sectors cover more than 88% of total PET bottle packaging. Other sectors in demand are dairy packaging, edible oil packaging and food packaging. Worldwide retail figures are given on Table 3.1.

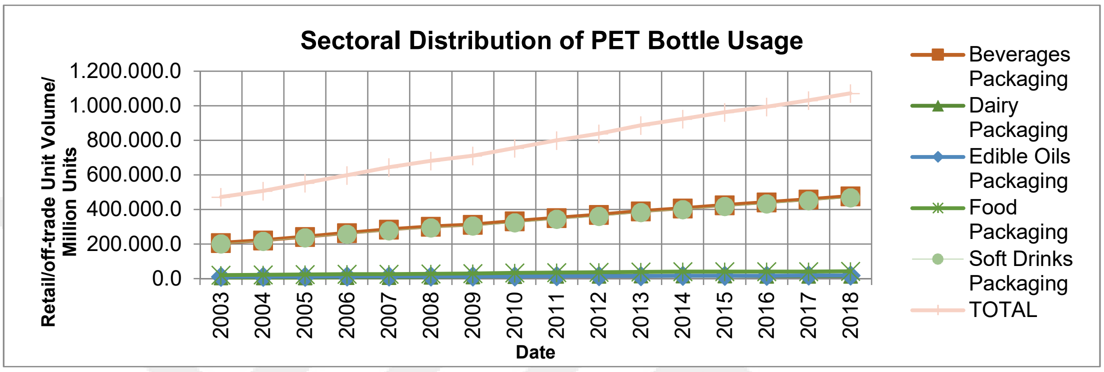


Figure 3.6 Worldwide PET bottle applications trend (Euromonitor, 2018)

Table 3.1 Worldwide PET bottle applications share-1 for 2017 (Euromonitor, 2018)

SECTOR	**Retail/off-trade Unit Volume / million unit**	**Share / %**
Beverages Packaging	459425.9	44.51
Dairy Packaging	15220.1	1.47
Edible Oils Packaging	17552.5	1.70
Food Packaging	40876.8	3.96
Soft Drinks Packaging	450911.6	43.69
Others	48086.6	4.66
TOTAL	1032073.5	100.00

Worldwide retail figures of other sectors can be seen briefly below on Table 3.2.

Table 3.2 Worldwide PET bottle applications share-2 for 2017 (Euromonitor, 2018)

SECTOR	**Retail/off-trade Unit Volume / million unit**	**Share / %**
Alcoholic Drinks Packaging	8514.3	0.825
Home Care Packaging	8088.5	0.784
Beauty and Personal Care Packaging	7534.5	0.730
Sauces, Dressings and Condiments Packaging	7448.9	0.722
Dishwashing	4573.3	0.443
Hair Care Packaging	2518.7	0.244
Bath and Shower Packaging	2231.5	0.216
Surface Care	2220.5	0.215
Oral Care Packaging	1223.9	0.119
Laundry Care	1183.6	0.115
Baby and Child-specific Products Packaging	727.2	0.070
Skin Care Packaging	619.3	0.060
Spreads Packaging	585.6	0.057
Men's Grooming Packaging	224.1	0.022
Fragrances Packaging	81.9	0.008
Deodorants Packaging	80.2	0.008
Baby Food Packaging	62.2	0.006
Air Care	51.2	0.005
Polishes	40.7	0.004
Adult Sun Care Packaging	30.1	0.003
Color Cosmetics Packaging	19.7	0.002
Toilet Care	16.9	0.002
Soup Packaging	7.4	0.001
Home Insecticides	2.3	0.000
Depilatories Packaging	0.1	0.000
TOTAL	48086,6	4.660

Trend of PET bottle and PET jar consumption for Turkey can be seen on Figure 3.7.

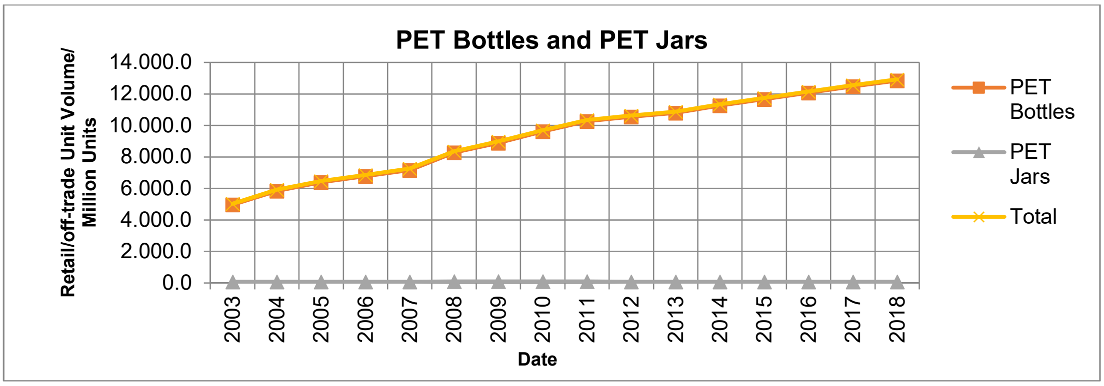


Figure 3.7 Turkey PET applications retail/off-trade trend (Euromonitor, 2018)

PET bottle and PET jar consumption increased more than 151% from 2003 to 2017 for Turkey. Trend of this can be seen on Figure 3.8. Upward trend of PET jar consumption rate can be seen on Figure 3.9. Sector retail figure rise every year with an average of 6.9% from 2004 to 2017. End of 2018 forecast show that it will increase by 3.0% compared to the previous year. It can be seen that which sector is more logical to make more studies to increase market share with the help of this figures.

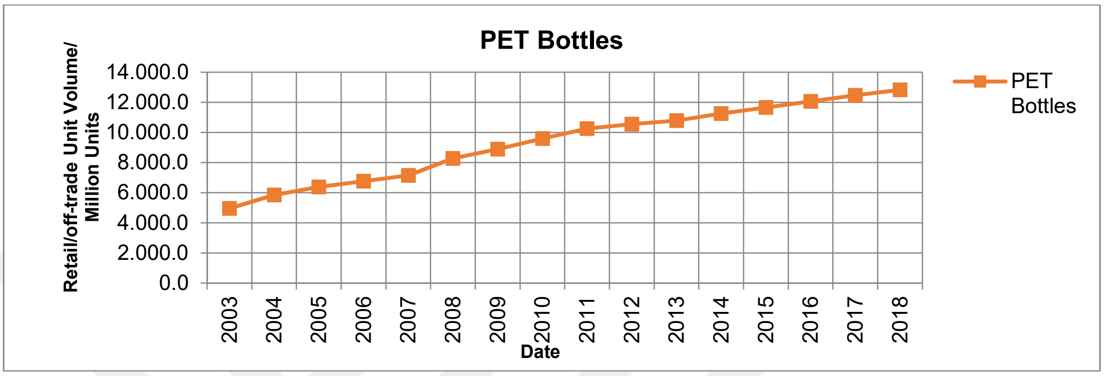


Figure 3.8 Turkey PET bottle retail/off-trade trend (Euromonitor, 2018)

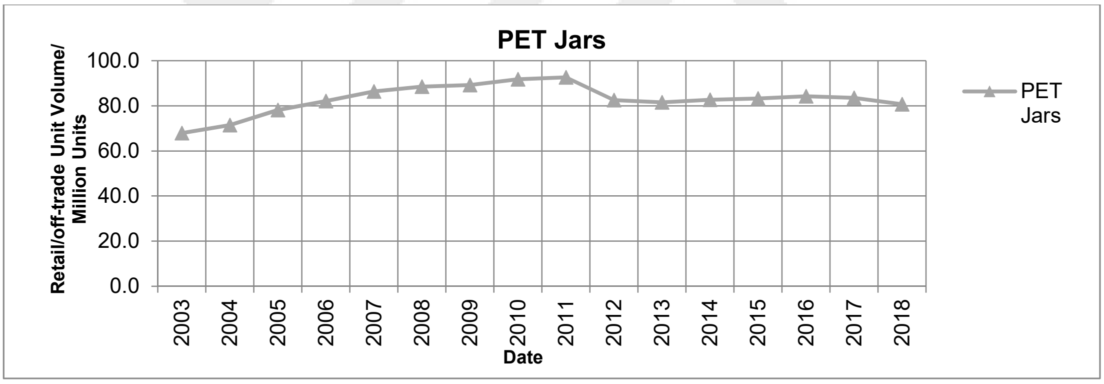


Figure 3.9 Turkey PET jar retail/off-trade trend (Euromonitor, 2018)

Trend of sectoral distribution of PET bottle usage for Turkey can be seen on Figure 3.10. Beverages packaging sector has the highest market share in Turkey along with the worldwide trend. However remaining sectors are different from worldwide usage. There is not enough data to cover all packaging sectors for PET bottle usage data for Turkey. Retail figures for Turkey are given on Table 3.3.

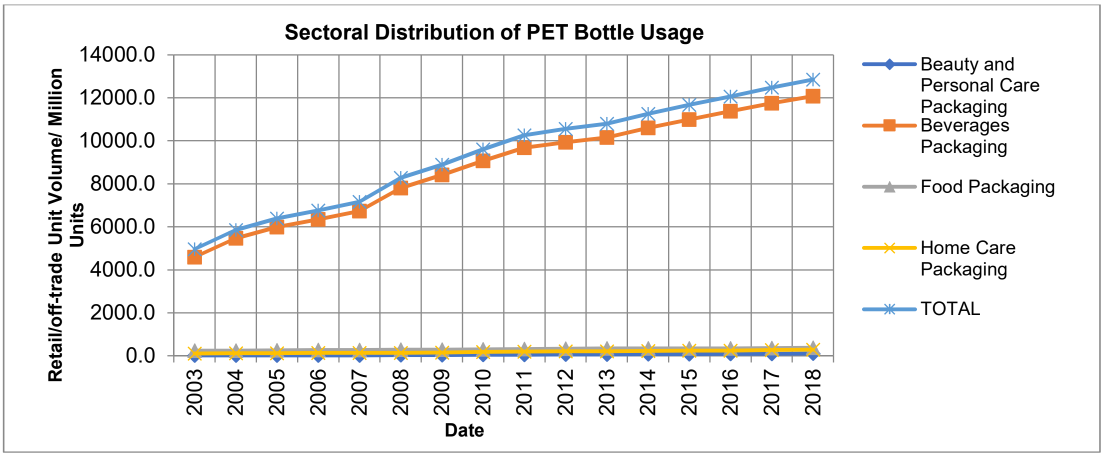


Figure 3.10 Turkey PET bottle applications trend (Euromonitor, 2018)

Table 3.3 Turkey PET bottle applications share for 2017 (Euromonitor, 2018)

SECTOR	**Retail/off-trade Unit Volume / million unit**	**Share / %**
Beauty and Personal Care Packaging	95.6	0.77
Beverages Packaging	11739.5	94.13
Food Packaging	368.3	2.95
Home Care Packaging	268.4	2.15
TOTAL	12471.8	100.00

Asia is the largest consumer of PET followed by Europe. The demand for PET is the highest in Asia. China is driving the majority of the demand for PET in the world. The demand in advanced countries like Japan has largely stabilized. With the large population in countries such as India and China, there is a huge consumption potential. The Asian demand by volume for PET in 2009 was nearly 4.7 million tons. The unparalleled growth of Carbonated Soft Drinks (CSD) and Bottled Water (BW) industries and thus the packaging industry can be primarily attributed to the changing lifestyles of people in the developing countries. Taking into account that India and China are heavily populated, it does not come as a surprise that these economies are key regional drivers for the global PET demand. Not considering the fabrics production, the largest PET consuming markets are CSD and BW. CSD is the largest market for PET globally. Because of its light weight, toughness and clarity, PET is the most preferred material for CSD bottles. BW is the second biggest PET consuming market globally. However, the packaged food segment is also a very important and growing market for PET. The beer market is largely untapped but has strong potential for growth with regard to PET applications (Ji, 2013).

PAGEV is one of the plastics manufacturers associations in Turkey. According to their sectoral report dated 2016, PET has the biggest share of 34 % among other types of plastics (LDPE, PP, HDPE, PVC and PS) on plastics raw material consumption. Besides PET has the highest share of 74 % in terms of quantity of plastic thermoform consumption among other types of thermoform plastics (PP, PVC and PS). Thermoforming in the manufacturing industry is to mold the plastic plate by heating.

An average of 300 kt of PET resin is produced annually in Turkey. Approximately 75 % of the total production is made up of bottles and 25 % is made of textile type PET. According to planning period of model (2017) PET production plant where this thesis is performed is capable of 47.5% of total bottle grade PET production quantity of Turkey. Imported bottle grade PET resin quantity is 49.1% of real bottle grade PET resin consumption in the same period (PAGEV, 2016).

3.2.4.2 Manufacturing View

Many polyester manufacturing plants have started production recently and many more are scheduled to start production in the future. Global polyester capacity greatly exceeds consumption. With the exception of South America and Western Europe, all other regions produce more polyester than they consume, leading to a surplus of 4 million t (Deopura et al., 2008). A more recent study gives more idea about market conditions of PET. World PET capacity will increase slower than demand bringing the market to balance. With average annual growth of 3.5% global capacity will reach 24.4 million tons/year by 2015. The global demand for PET was growing fast over the last decade. The effect of the economic slowdown has adversely affected the consumption of various commodities in many countries globally. Hence, demand for PET has also slowed down over the past two years. The global PET market in 2009 was 15.3 million tons. As the economies recover from the slowdown, the consumption of commodities will rise again and the global demand for PET will grow at CAGR of 4.9% up to 2020 (Ji, 2013).

3.2.4.3 Future Trends

Among polyesters, PET will continue to be in the leading position for applications in packaging and textiles with more applications in ‘Technical Textiles’ in sectors of agriculture, building, geo, home, medical, packaging, etc. Quality improvements such as increased barrier capabilities, softness and loft will be further improved. An increased demand for renewable raw materials and disposable materials for environmental and cost reasons will be a central issue in the future. Growth in today’s booming markets will be influenced by a shortage of raw materials and energy. Polyester will continue to find newer applications because of its undisputable performance and properties. According to a study on process industry supply chains a comprehensive approach must be taken for future (Shah, 2005).

At the current consumption rates, the current world crude oil reserves will be exhausted by the year 2043, unless new oil stocks are discovered. If, as predicted, the global population doubles in the next 50 years, the requirement for polyester resin at the current usage rate will also double. This will have a huge bearing on crude oil consumption. Therefore, the future of the polyester industry, in particular commodity resin, depends on how effectively the industry recycles polyester scrap and how quickly the industry moves from oil-based resources to renewable resources. The effective recycling of polyester resin will also reduce carbon dioxide emission, which in turn will minimize global warming (Deopura et al., 2008).

3.3 Pet Resin Plant Production Process

PET resin production is based on chemical conversion. Resin production is a result of chemical reactions between raw materials and it is operated continuously.

Operation of PET resin plant is controlled via Distributed Control System (DCS). DCS is a kind of automation system and all process including important parameters about physical properties (temperature, pressure, level percentage, speed of equipments etc.) can be tracked. In the DCS both supervisory control and regulatory (feedback) control are implemented using digital computers (Edgar et al., 2001).

Production process can be viewed generally on Figure 3.11.

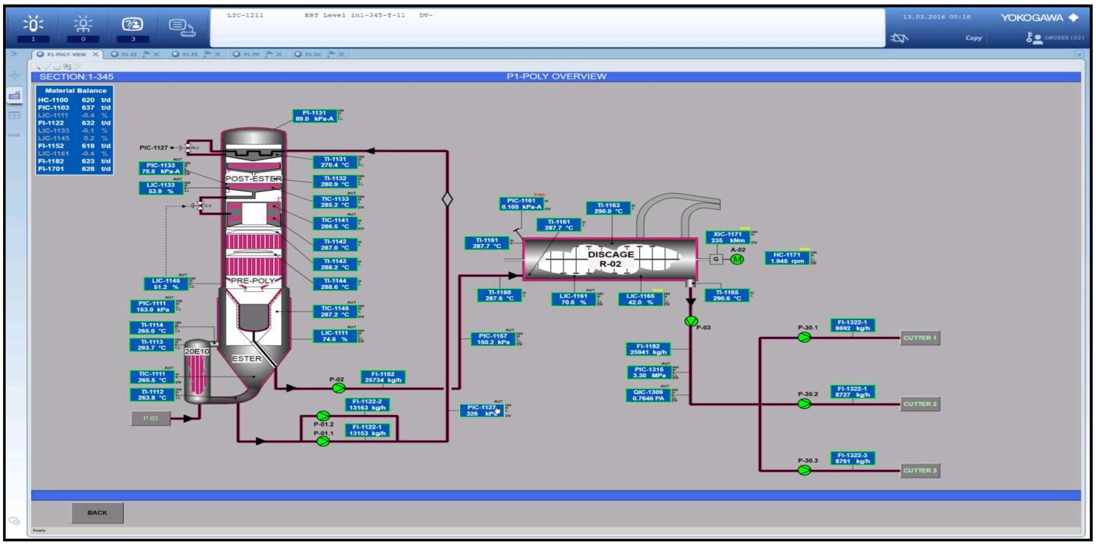


Figure 3.11 PET resin plant production process

There are two reactors and two reactions on that production environment. Before entering first reactor (R-01) raw materials are mixed in an agitated mixing tank. Then a mixture called ‘paste’ is occurs. Paste is feed to R-01 by paste pumps. After that reaction (first phase of esterification) takes place. Paste tank and line to R-01 is seen on Figure 3.12. Equipment labeled with D-03 is paste tank and equipment labeled with ESTER is R-01.

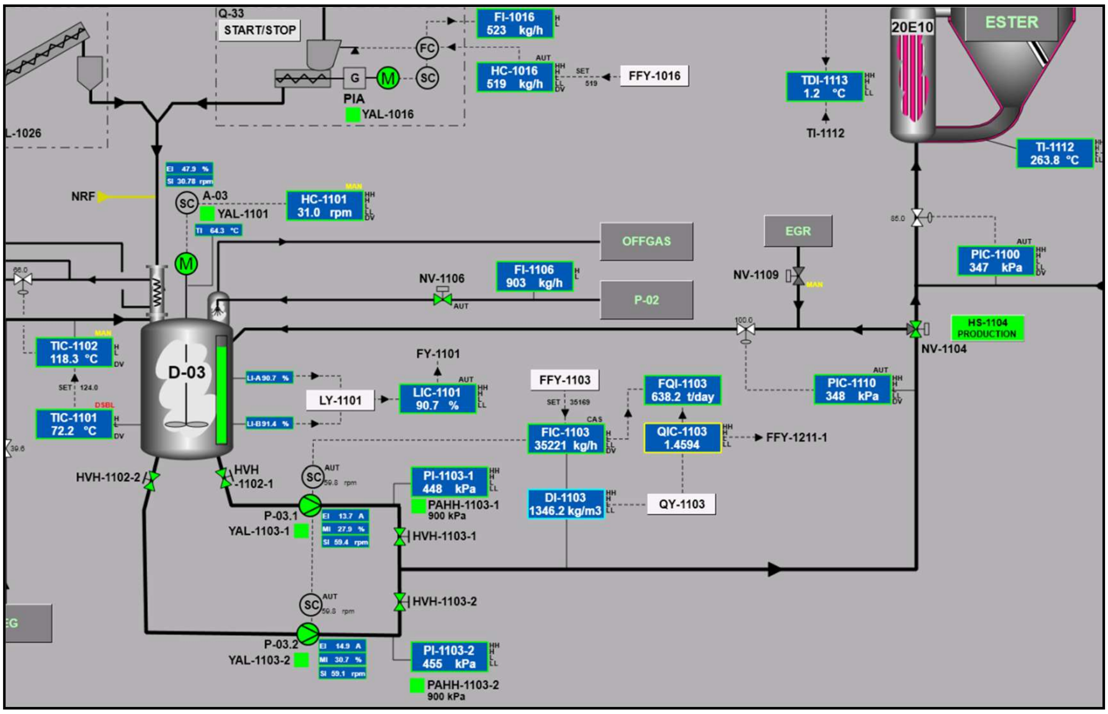


Figure 3.12 Paste Tank, R-01 and the line between them

There are three parts in R-01 reactor. First phase of esterification reaction takes place on first part, and a product called ‘monomer’ occurs. Afterward monomer is feed to second part by monomer pumps (P-01.1/2 on figure). Second and last phase of esterification (post-esterification) has effect on second part. Subsequently monomer is fed to third and last part of reactor: Prepolymerization. In that part, first phase of polymerization reaction is taken place, and a product called ‘prepolymer’ occurs. R-01 reactor and mentioned equipments (P-01.1/2) can be seen on Figure 3.13. All parts where reaction takes place is labeled with related reaction on R-01.

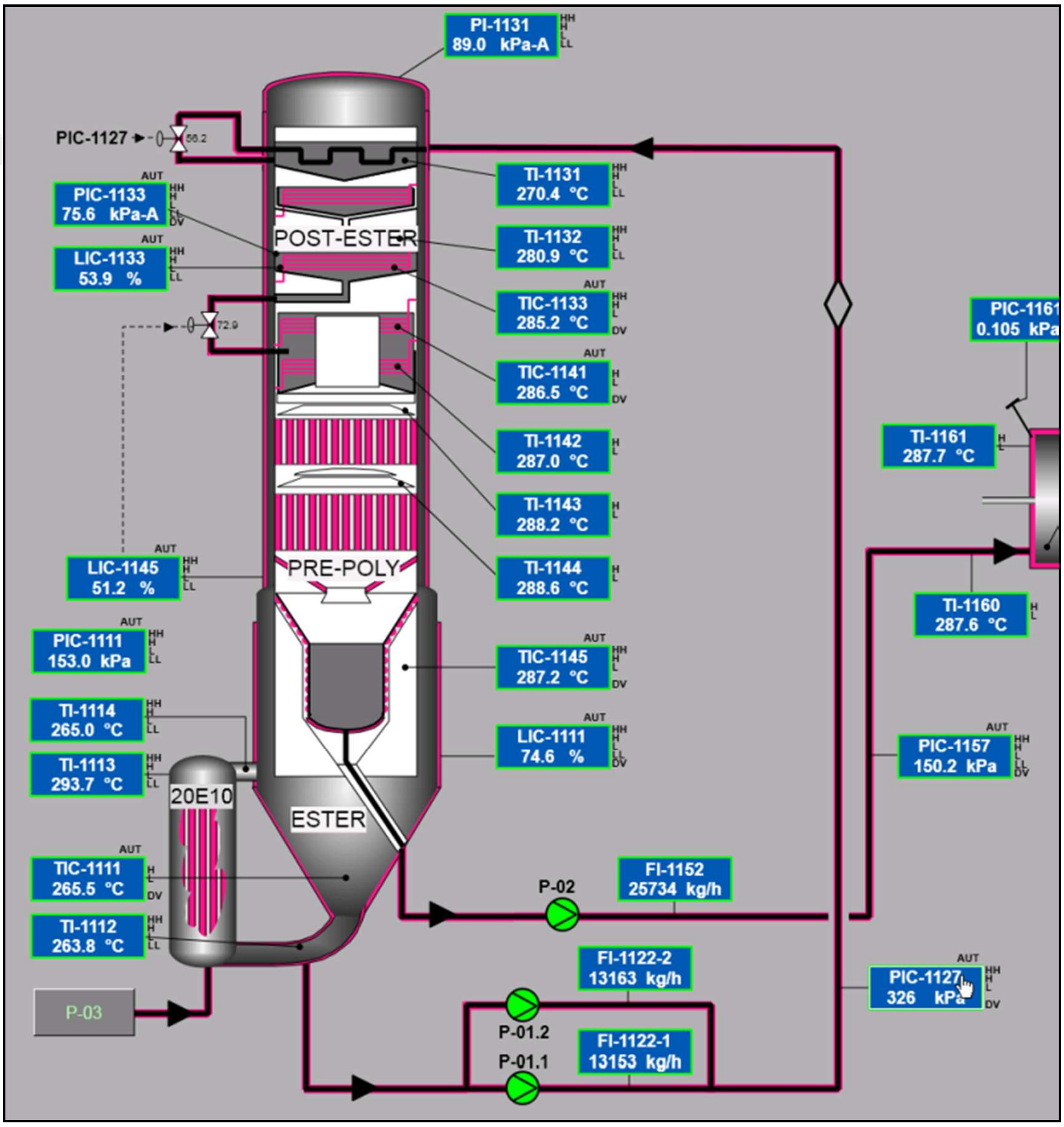


Figure 3.13 R-01 Reactor, parts of reactor and pre-product pumps

Next it is fed to second reactor (R-02) by prepolymer pump (P-02 on figure). On this reactor last phase of polymerization is occurs and last product (polymer) is supplied to booster pumps (P-30.1/2/3 on figure) by polymer pump (P-03 on figure). After booster pumps, polymer goes on cutters and it is granulated to very small particles as pellets. Then it feed to final conveying silos after conditioning. R-02 reactor and mentioned equipments (P-03/P-30) can be seen on Figure 3.14. As seen from Figure 3.14 every booster pump is along with the related cutter.

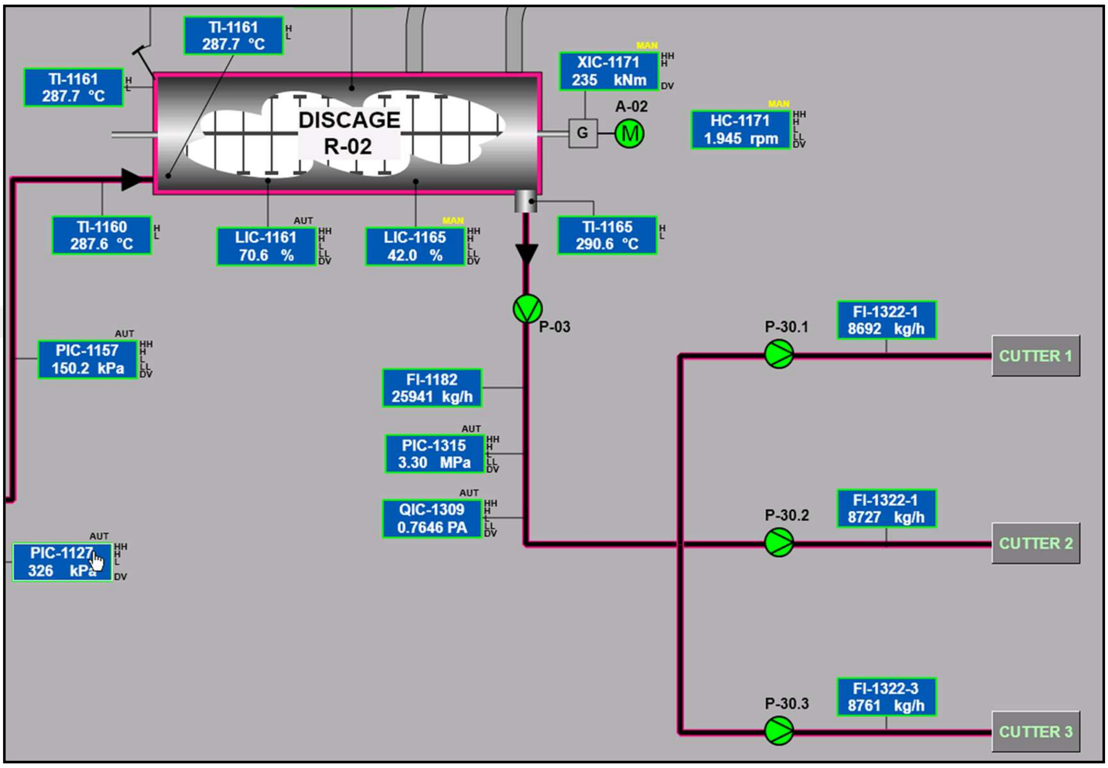
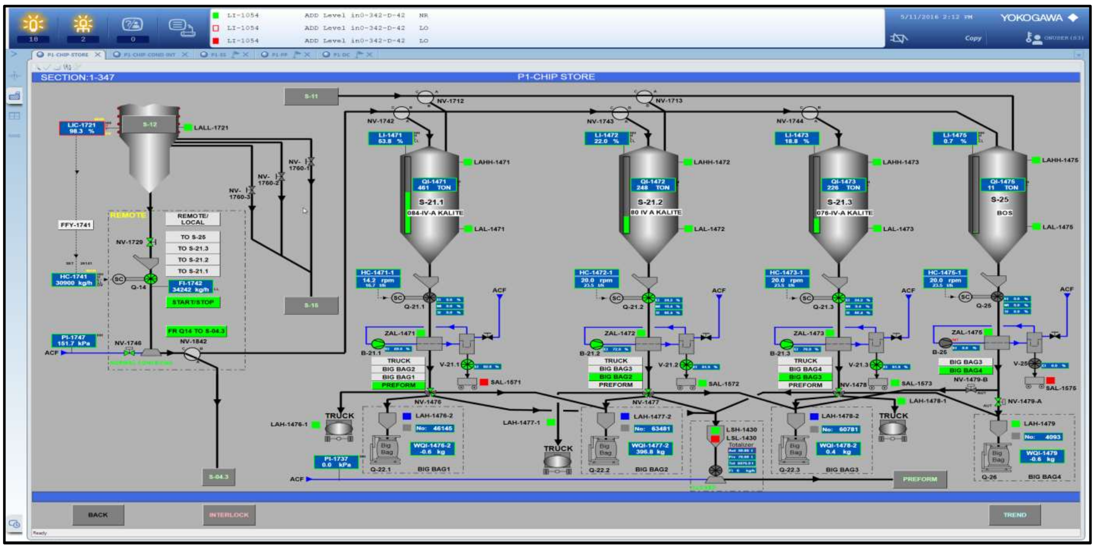


Figure 3.14 R-02 Reactor, polymer pump and booster pumps

During production process some physical properties are changed to get required quality product. Temperature increases and pressure comes down to vacuum conditions, so we product on preferred range of IV could be obtained.

External and internal consumers are defined to classify consumers. End-product is sold only to external consumers. They are consist of companies originated from abroad or domestic. Internal consumer is defined to plant facility where PET resin manufacturing facility is also one part of it. That plant facility is integrated with other plastic production plants. These are preform, bottle cap and film production plants.

End product can be conveyed from silos to three main points as described below. This points can be seen generally from Figure 3.15. More detailed view can be seen from Figure 3.16.



```
LI-1054        ADD Level in0-342-D-42   NR
LI-1054        ADD Level in0-342-D-42   LO
LI-1054        ADD Level in0-342-D-42   LO
```

Figure 3.15 PET resin plant end-product final conveying

- Truck/Silobus: If it is chosen product can be emptied to container or silobuses. Both vehicles are kind of trucks. Containers are used for external customers; however silobuses are used for internal needs of company (for producing pet resin caps and bottles).

- Bigbag: If it is chosen product can be emptied to bigbags. Bigbags are huge packages and standard weight of it is 1 t per one unit. After packaging, bigbags could be hold on warehouse, sent to external customers or are used for internal needs of company (for producing pet resin caps and bottles).

- Preform: If it is chosen product can be conveyed to preform plant. Pet resin is injection molded into a "mini bottle," complete with threads, called a preform. Preform plant is another plant of the company, so when it is chosen that product is used for internal needs of company (for producing pet resin caps and bottles.

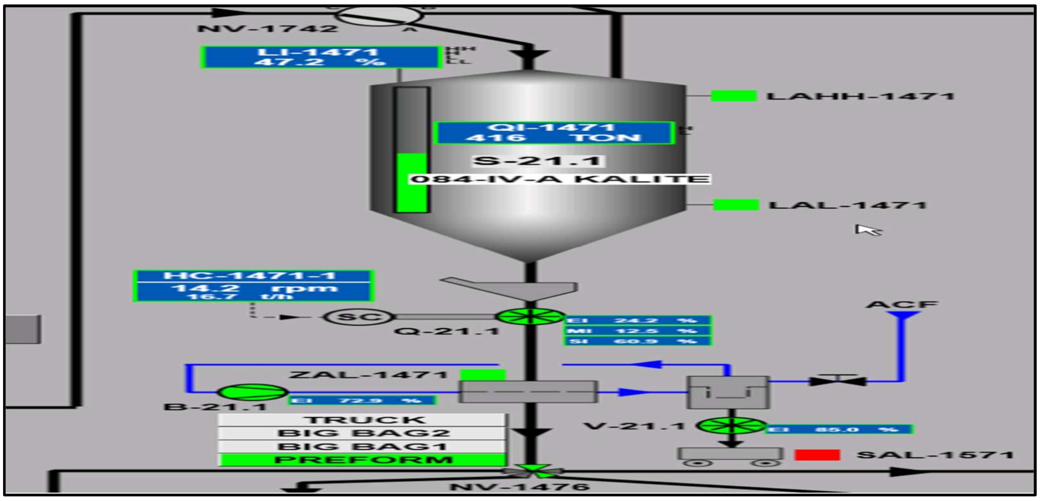


Figure 3.16 End product silo and packaging system

CHAPTER IV

PROBLEM DEFINITION AND MODEL DEVELOPMENT

In this chapter, problem is defined and the development of the model is explained. Assumptions and parts of model (sets, parameters, variables, constraints and equations) are also given on this chapter.

Proposed model is designed as a capacitated lot sizing problem. In addition to original problem equation, there are some significant resources to be taken into account. These are raw materials, additive materials and utility resources. Resources are limited therefore model equation is designed as capacitated model.

PET resin production process is based on conversion of raw materials and additives to end-product. Production process is basically chemical production process, hence production logic is different from traditional MRP idea. There are certain unit consumption values of resources for producing one unit of end-product and these figures used as unit consumption parameters on model. Average unit consumption figures for utility resources and average unit carbon emission generation figures are selected from previous year total consumption and production data. Model is implemented for a bottle grade PET resin production plant in Turkey along with 2016 data. This facility started production in November 2013. In the last two years before 2016, production quality has settled on the track and this product has become a reliable brand in the market. Since 2016 is considered as the most suitable year for the implementation of the proposed model in production planning as the reasons mentioned above, the implementation of the model was made according to the data of this year. Carbon emission generation is calculated to see direct effect of energy resource usage and as used one of the indicator of sustainable production. Unit emission generation figures are taken from (Döğerlioğlu, 2010) and (Güllü, 2011).

Two main raw material, four additive material and three utility resource are included in model. Generated carbon emission is defined as by-product. In order to see the cost and environmental impacts resulting from the use of the relevant resource, the energy policy has been implemented in the form of the use of two different energy sources, either separately or in half, in the model.

Unit prices and purchase costs are taken according to 2016 average data. There is not any correction factor about dynamic financial events like inflation or rate fluctuation for these values. Cost types are briefly explained one by one below.

Contrary to lot sizing problem definition, setup cost of PET resin production is lower than most processes because of characteristics of production process. Setup in PET resin production could be denoted as grade changeover process. Production changeover is done by adjusting main quality parameters of related IV and capacity conditions. Before or after grade changeover there is no need to change any equipment layout, additional operations like cleaning or anything else because production cycle is continuous and based on chemical conversion. It is sufficient to prepare production process to changeover as adjusting quality parameters. After every setup a transition material is produced equivalent time of setup. This material has lower quality than normal end product. By the help of production planning only required quantity of end-product is produced for all grades over the planning horizon. For example it could be sufficient to make three setups in one month. Consequently number of setups would decrease. Less number of setup means less transition material. For these reasons setup cost is specified as very low value.

Production cost is specified as very low value as setup cost. Except of production cost, Raw material, additive and utility costs which are assumed as normal parts of production cost are defined in model considered in this thesis.

Inventory cost is calculated according to average inventory quantity in model considered in this thesis. This cost is supposed between 10% and 30% of sales price in most of existing studies (Richardson, 1995). It is assumed as 25% of sales price in model considered in this thesis.

Capacity policy allows to see the change in model results such as total cost and production amount, especially the objective function value, with the regular increase of capacity between the selected minimum and maximum capacities. The production facility is a continuous-flow process. It means that it runs continuously without interruption except of extensive maintenance or shutdowns. Production rate differs between 360 t/d and 725 t/d. There are two reactors and seven pumps on production line and there are four storage silos for end product. Different grades of products could be stored on these silos along with the existing demand. These equipments are suitable for operation at a capacity of 725 t/d. Capacity range used in model run from 600 t/d to 725 t/d. However, this range must be narrowed from 655 t/d to 725 t/d if there would be not backlog on planning horizon for forecasted demand data. Interactions between selected parameters by obtained results is given on Chapter V. Backlog quantity and utilization rate are among of these parameters. Backlog quantity and utilization rate decrease by increasing capacity as it seen from Figure 5.11. Backlog quantity is zero after reaching 655 t/d capacity. There is not backlog on higher capacities. Detailed evaluation is given on Chapter V.

Inventory policy includes safety stock decisions by different expected consumer service levels. There is an extension of demand on backlogging as a result of fluctuating demand. Even if developed technology and know-how, there is always a risk about meeting demands on time in real life. There may be lots of reasons about it: forecasting errors, general economic environment, problems on production plant etc. In order to handle these kind of troubles, keeping safety stock must be thought. On the other hand excess production is one of the wastes according to lean manufacturing, so consequently systems are designed to have less stock (if possible stockless) to minimize economic effects of inventories (Hofer et al., 2012). Though it force factories to have almost zero inventory, it is also risky policy because of potential stock out on rising demand periods. As it can be seen there is a tradeoff between expected service level by safety stocks and inventory holding cost. Optimum inventory policy must balance these two points (Rădăşanu, 2016).

Safety stock calculations are based on forecasted demand predictions by ARIMA method. Three alternatives were designated for safety stock. Safety stock is calculated for 90% customer service level for all products on the first alternative. Safety stock is calculated for 95% customer service level for all products on second alternative. Higher service level is better but it effects inventory holding cost concurrently.

According to the results inventory turnover ratio is affected too. Third alternative includes different service level shares for all three grades. Supposed service level percentages are chosen from past three year (2014 – 2016) real demand data as seen on Table 4.1. Third alternative is based on market shares and supposed service level ratios are chosen in line with average rate of customer share (Rădăşanu, 2016). This kind of perspective is both flexible to market conditions and cheaper than second alternative.

Constraints are based on daily production capacity. Every constraint value is defined consistent with maximum end-product quantity of capacity policy.

Table 4.1 Demand rate and supposed service level percentages

YEAR	DEMAND RATES FOR ALL GRADES / %		
	0.76	0.80	0.84
2014	58.5	17.4	24.1
2015	56.8	9.0	34.3
2016	58.5	11.3	30.1
AVERAGE RATE	57.9	12.6	29.5
SUPPOSED SERVICE LEVEL	95.0%	85.0%	90.0%

Maintenance and labor costs are not included, because these activities are not directly related with production. Production process is based on chemical conversion, so labor only needed to control and other routine operation works. Labor is directly used for most plants usually because of direct effect to production: For example in an assembly unit number of finished or semi-finished product dependent to performance of workers in that job station. Maintenance cost is one of the direct cost items. On the other hand maintenance activities usually continue without interrupting production except of planned maintenances after shutdown or machine failures in PET resin production plant. Effect of planned or unplanned interruptions are minor relatively to total annual production.

The main objective of this study is to maximize profit. For that purpose an optimal production policy must be followed. Demand must be met on time with minimum inventory and utilized resource must be used on this kind of program.

A comparative study was conducted with the application of these three main factors (energy policy, capacity policy and inventory policy) and it was seen how effective the model was and which points should be examined in order to obtain better results. Some assumptions were made to evaluate the model better.

4.1 Assumptions

- **Problem Type:** Model considered in this thesis is highly based on generally APP area, but it also has MRP properties for its raw material, additive material and utility resource bounds. Labor and overtime costs included in APP model is not used in model due to production system is not directly based on manpower. Even the usage is quite different, model considered in this thesis could be supposed as a MRP model for some parts.

- **Number of products and number of levels:** Multi-item product and single-level production system is defined on model.

- **Time period:** Planning horizon of model is considered as big bucket problem. Planning horizon consists of 12 months of 2017 year.

- **Nature of demand**: Demand pattern is assumed as deterministic in model. Two different approaches are used for demand: Real demand data and forecasted demand data. ARIMA method is used for forecasting.

- **Capacities or resource constraints:** Model of this study is capacitated. The most important constraint of model is production capacity constraint. Resources used in model (raw material, utility and energy resources) are limited by maximum production and processing capacity. Inventory upper limit value of model is maximum end-product storage capacity.

- **Extensions on demand:** Backlogging is used as extension of demand in model. It is not wanted and a high penalty cost is defined to force meeting demand.

- **Extensions on setup:** Extension on setup is not used in model. PET resin production process is basically based on chemical conversion, so setup is different from its classical meaning on most production sites based on assembly of different components. Production changeover is done by adjusting required parameters of related IV and capacity conditions. Setup cost of this production process could be basically written as end product of IV changeover time, because of off-spec grade.

- **Extensions on environmental issues:** Carbon emission is included in model as extension on environmental issues.

- **Modelling approach:** Mixed integer linear modeling is used on model.

- **Solution approach:** Exact method is used on model.

- **Development tool:** GAMS is used as optimization modelling language to solve in model. CPLEX 12.2.0.0 solver is used within GAMS 23.5.1 version.

- **Application:** Optimization of production of PET resin plant is target of this study and it is a real-world application.

- **Limitations:** Some limitations are defined for our model. Safety stock is considered for production system. Backlog is included in model to force meeting the demand. Production quantity is limited by maximum capacity. Maximum production capacity limit means that it is a kind of stationary capacity and production amount cannot exceed this limit. Overtime production capacity is not considered because manpower is not directly related to production quantity. There is not any limitation on solution method, uncertainty, product, application, supply chain and costs.

4.2 Model

Proposed model is given by different parts in this section. Sets, parameters, variables, objective function, equations and constrainsts are explained briefly.

4.2.1 Sets

Main product grade set is represented as ‘J’. Periods are chosen as minimum one month. This set is represented as ‘T’. Sets are given on Table 4.2.

Table 4.2 Sets of model

J	Set of final grades, indexed by j, J = {1, 2, 3} ≡ {0.76, 0.80, 0.84}
T	Time (Month), indexed by t, T = {1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12}

4.2.2 Parameters

Parameters used for model is given on different tables. Parameters for production demand, safety stock quantity and big M value is given on Table 4.3. Unit cost and prices are given on Table 4.4. Unit consumption parameters given on Table 4.5. Monthly and annual upper bound of materials is given on Table 4.6. End product demand is represented as D_{TJ}. It can be real value or forecasted value. Calculated safety stock quantity is represented as SS_{TJ}. Safety stock quantity is given on model according to used safety stock alternative. M represents very large number. It is maximum monthly production amount in model.

Table 4.3 Parameters-1

D_{TJ}	Production demand per period, t ∈ T, j ∈ J
SS_{TJ}	Safety stock per period, t ∈ T, j ∈ J
M	Very large number

Parameters of unit cost and prices are given on Table 4.4. These parameters are assumed as equivalent to 1 t end-product. It means that sales price used in model is for 1 t end-product. In a similar way cost values are constant and these values are calculated to produce 1 t end product.

Table 4.4 Parameters-2 / Unit cost and prices

REV	Sales price
C_F	Fixed setup cost
C_P	Production unit cost
C_{SSPL}	Safety stock overstock deficit unit cost
C_{SSMI}	Safety stock shortage deficit unit cost
C_B	Backlog penalty unit cost
C_{R1}	Raw material-1 unit purchase cost
C_{R2}	Raw material-2 unit purchase cost
C_{ADD1}	Additive material-1 unit purchase cost
C_{ADD2}	Additive material-2 unit purchase cost
C_{ADD3}	Additive material-3 unit purchase cost
C_{ADD4}	Additive material-4 unit purchase cost
C_{U1}	Utility-1 unit cost
C_{U2}	Utility-2 unit cost
C_{U3}	Utility-3 unit cost

Unit consumption parameters given on Table 4.5. These parameters are assumed to produce 1 t end-product such as mentioned on unit costs and price.

Table 4.5 Parameters-3 / Unit consumption rates of required materials

ResR$_1$	Raw material-1 usage per one unit of product j
ResR$_2$	Raw material-2 usage per one unit of product j
ResADD$_1$	Additive material-1 usage per one unit of product j
ResADD$_2$	Additive material-2 usage per one unit of product j
ResADD$_3$	Additive material-3 usage per one unit of product j
ResADD$_4$	Additive material-4 usage per one unit of product j
ResU$_1$	Utility-1 consumption per one unit of product j
ResU$_2$	Utility-2 consumption per one unit of product j
ResU$_3$	Utility-3 consumption per one unit of product j
COE$_P$	Generation of carbon emission as t per one unit of product j

Parameters for monthly and annual upper bound of materials is given on Table 4.6. These parameters are calculated for maximum quantity of related production capacity. According to this study changes are analyzed with increment of capacity. These values are calculated for every capacity value on this thesis.

Table 4.6 Parameters-4 / Upper bounds of quantity of required materials

R$_1$CAP	Monthly upper bound of raw material-1 quantity usage
R$_{11}$CAP	Annual upper bound of raw material-1 quantity usage
R$_2$CAP	Monthly upper bound of raw material-2 quantity usage
R$_{22}$CAP	Annual upper bound of raw material-2 quantity usage
R$_3$CAP	Monthly upper bound of raw material-3 quantity usage
R$_{33}$CAP	Annual upper bound of raw material-3 quantity usage
RADD$_1$CAP	Monthly upper bound of additive material-1 quantity usage
RADD$_{11}$CAP	Annual upper bound of additive material-1 quantity usage
RADD$_2$CAP	Monthly upper bound of additive material-2 quantity usage
RADD$_{22}$CAP	Annual upper bound of additive material-2 quantity usage
RADD$_3$CAP	Monthly upper bound of additive material-3 quantity usage
RADD$_{33}$CAP	Annual upper bound of additive material-3 quantity usage
RADD$_4$CAP	Monthly upper bound of additive material-4 quantity usage
RADD$_{44}$CAP	Annual upper bound of additive material-4 quantity usage
RUTI$_1$CAP	Monthly upper bound of utility-1 consumption
RUTI$_{11}$CAP	Annual upper bound of utility-1 consumption
RUTI$_2$CAP	Monthly upper bound of utility-2 consumption
RUTI$_{22}$CAP	Annual upper bound of utility-2 consumption
RUTI$_3$CAP	Monthly upper bound of utility-3 consumption
RUTI$_{33}$CAP	Annual upper bound of utility-3 consumption
REMICAP	Monthly upper bound of carbon emission generation
RTOTEMICAP	Annual upper bound of carbon emission generation

4.2.3 Variables

Variables used for consumption of required materials (raw materials, additive materials and utility resources) is given on Table 4.7. Total material consumption and total material cost is calculated by the help of these variables.

Table 4.7 Usage of required materials

ResRaw1$_{TJ}$	Raw material-1 usage per period, $t \in T, j \in J$
ResRaw2$_{TJ}$	Raw material-2 usage per period, $t \in T, j \in J$
ResAdd1$_{TJ}$	Additive material-1 usage per period, $t \in T, j \in J$
ResAdd2$_{TJ}$	Additive material-2 usage per period, $t \in T, j \in J$
ResAdd3$_{TJ}$	Additive material-3 usage per period, $t \in T, j \in J$
ResAdd4$_{TJ}$	Additive material-4 usage per period, $t \in T, j \in J$
ResUti1$_{TJ}$	Utility-1 consumption per period, $t \in T, j \in J$
ResUti2$_{TJ}$	Utility-2 consumption per period, $t \in T, j \in J$
ResUti3$_{TJ}$	Utility-3 consumption per period, $t \in T, j \in J$
ByProdEmission$_{TJ}$	Carbon emission generation per period, $t \in T, j \in J$

4.2.4 Decision Variables

Decision variables used in model is given on Table 4.8. In addition to the commonly used variables such as production quantity, inventory quantity and binary variable variables such as backlog quantity, utilization rate and service level is used in model in order to see operation efficiency of plant. Safety stock overstock, safety stock shortage and safety stock variation variables are added to model for modified inventory equation.

Table 4.8 Decision variables

X$_{TJ}$	Production in period t, $t \in T, j \in J$
S$_{TJ}$	Net inventory quantity in period t, $t \in T, j \in J$
SSPL$_{TJ}$	Safety stock overstock quantity in period t, $t \in T, j \in J$
SSMI$_{TJ}$	Safety stock shortage quantity in period t, $t \in T, j \in J$
DSS$_{TJ}$	Safety stock variation in period t, $t \in T, j \in J$
B$_{TJ}$	Backlog in period t, $t \in T, j \in J$
UTIL$_{TJ}$	Utilization rate average value in period t, $t \in T, j \in J$
SL$_{TJ}$	Service level average value in period t, $t \in T, j \in J$
Y$_{TJ}$	Binary variable in period t, $t \in T, j \in J$

4.2.5 Objective Function

$$\max \sum_1^T \sum_1^J \left(Rev * X_{TJ}\right) - (\sum_1^T \sum_1^J \left(SSPL_{TJ} * C_{SSPL} + SSMI_{TJ} * C_{SSMI} + B_{TJ} * C_B + Y_{TJ} * C_F + X_{TJ} * C_P + ResRaw1_{TJ} * C_{R1} + ResRaw2_{TJ} * C_{R2} + ResAdd1_{TJ} * C_{ADD1} + ResAdd2_{TJ} * C_{ADD2} + ResAdd3_{TJ} * C_{ADD3} + ResAdd4_{TJ} * C_{ADD4} + ResUti1_{TJ} * C_{U1} + ResUti2_{TJ} * C_{U2} + ResUti3_{TJ} * C_{U3}\right) \tag{4.1}$$

Main target is maximizing total profit of production. Objective function (4.1) represents this aim as substraction of total cost from total revenue.

4.2.6 Equations and Constraints

$$ResRaw1_{TJ} = resR_1 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \tag{4.2}$$

$$ResRaw2_{TJ} = resR_2 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \tag{4.3}$$

Equation (4.2) and (4.3) shows raw material usage per period. It is equal to multiplying production quantity on related grade on this period and unit raw material consumption.

$$\sum_1^J ResRaw1_{TJ} \leq R_1CAP \qquad \forall j \in J,\ \forall t \in T \tag{4.4}$$

$$\sum_1^T \sum_1^J ResRaw1_{TJ} \leq R_{11}CAP \qquad \forall j \in J,\ \forall t \in T \tag{4.5}$$

$$\sum_1^J ResRaw2_{TJ} \leq R_2CAP \qquad \forall j \in J,\ \forall t \in T \tag{4.6}$$

$$\sum_1^T \sum_1^J ResRaw2_{TJ} \leq R_{22}CAP \qquad \forall j \in J,\ \forall t \in T \tag{4.7}$$

Equation (4.4), (4.5), (4.6) and (4.7) expresses monthly and annual (or sum of related periods) boundaries of raw materials. Equation (4.4) and (4.6) are constraints for monthly raw material usage, (4.5) and (4.7) are for all periods for planning horizon.

$$ResAdd1_{TJ} = resADD_1 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \tag{4.8}$$

$$ResAdd2_{TJ} = resADD_2 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \tag{4.9}$$

$$ResAdd3_{TJ} = resADD_3 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \tag{4.10}$$

$$ResAdd4_{TJ} = resADD_4 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.11)$$

Equation (4.8), (4.9), (4.10) and (4.11) expresses additive materials usage per period. Idea is same with the equation (4.2) and (4.3).

$$\sum_1^J ResAdd1_{TJ} \leq RADD_1CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.12)$$

$$\sum_1^T \sum_1^J ResAdd1_{TJ} \leq RADD_{11}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.13)$$

$$\sum_1^J ResAdd2_{TJ} \leq RADD_2CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.14)$$

$$\sum_1^T \sum_1^J ResAdd2_{TJ} \leq RADD_{22}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.15)$$

$$\sum_1^J ResAdd3_{TJ} \leq RADD_3CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.16)$$

$$\sum_1^T \sum_1^J ResAdd3_{TJ} \leq RADD_{33}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.17)$$

$$\sum_1^J ResAdd4_{TJ} \leq RADD_4CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.18)$$

$$\sum_1^T \sum_1^J ResAdd4_{TJ} \leq RADD_{44}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.19)$$

Equations between (4.12) and (4.19) expresses monthly and annual (or sum of related periods) boundaries of additive materials. Equation (4.12), (4.14), (4.16) and (4.18) are constraints for monthly additive material usage, (4.13), (4.15), (4.17) and (4.19) are for all periods for planning horizon.

$$ResUti1_{TJ} = resUTI_1 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.20)$$

$$ResUti2_{TJ} = resUTI_2 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.21)$$

$$ResUti3_{TJ} = resUTI_3 * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.22)$$

Equation (4.20), (4.21) and (4.22) expresses utilities consumption per period.

$$\sum_1^J ResUti1_{TJ} \leq RUTI_1CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.23)$$

$$\sum_1^T \sum_1^J ResUTI1_{TJ} \leq RUTI_{11}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.24)$$

$$\sum_1^J ResUti2_{TJ} \leq RUTI_2CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.25)$$

$$\sum_1^T \sum_1^J ResUTI2_{TJ} \leq RUTI_{22}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.26)$$

$$\sum_1^J ResUti3_{TJ} \leq RUTI_3CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.27)$$

$$\sum_1^T \sum_1^J ResUTI3_{TJ} \leq RUTI_{33}CAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.28)$$

Equations between (4.23) and (4.28) expresses monthly and annual (or sum of related periods) boundaries of utilities. Equation (4.23), (4.25) and (4.27) are constraints for monthly utilities consumption, (4.24), (4.26) and (4.28) are for all periods for planning horizon.

$$ByProdEmission_{TJ} = COE_P * X_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.29)$$

Equation (4.29) expresses carbon emission generation by production per period.

$$\sum_1^J ByProdEmission_{TJ} \leq REMICAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.30)$$

$$\sum_1^T \sum_1^J ByProdEmission_{TJ} \leq RTOTEMICAP \qquad \forall j \in J,\ \forall t \in T \qquad (4.31)$$

Equation (4.30) and (4.31) expresses monthly and annual (or sum of related periods) boundaries of carbon emission generation by production. Equation (4.30) is constraint for monthly carbon emission generation, (4.31) is for all periods for planning horizon.

$$X_{TJ} \leq M * Y_{TJ} \qquad \forall j \in J,\ \forall t \in T \qquad (4.32)$$

Equation (4.32) shows that production quantity cannot exceed upper boundary as symbolized as 'big M' value. Production depends on production decision as per planned demands, so if there is production binary variable is equal to 1, otherwise it is 0.

$$X_{TJ} \leq M \qquad \forall j \in J,\ \forall t \in T \tag{4.33}$$

$$M = Max\ Monthly\ Production\ Capacity \tag{4.34}$$

Equation (4.33) and (4.34) expresses monthly upper bounds for production. Production quantity cannot surpass maximum bound. M value is equal to maximum bound.

$$\textstyle\sum_1^T X_{TJ} \leq\ Max\ Monthly\ Production\ Capacity \qquad \forall j \in J,\ \forall t \in T \tag{4.35}$$

$$\textstyle\sum_1^T \sum_1^J X_{TJ} \leq Max\ Production\ Capacity\ (\,Total\ Number\ of\ Periods) \qquad \forall j \in J,\ \forall t \in T \tag{4.36}$$

Equation (4.35) and (4.36) expresses monthly and annual (or sum of related periods) boundaries of production quantity. Equation (4.35) is constraint for monthly production quantity, (4.36) is for all periods for planning horizon.

$$S_{TJ} = 0,\ T = 1 \qquad \forall j \in J \tag{4.37}$$

$$R_{TJ} = 0,\ T = 1 \qquad \forall j \in J \tag{4.38}$$

$$\textstyle\sum_1^T \sum_1^J S_{TJ} \leq Max\ Storage\ Capacity \qquad \forall j \in J,\ \forall t \in T \tag{4.39}$$

Equation (4.37) and (4.38) shows that at the start of first period there is not production inventory and backlog. Equation (4.39) expresses annual (or sum of related periods) boundary of inventory quantity. Maximum storage capacity include mostly storage area and small percentage of it is storage silos.

$$SSPL_{T-1,J} - SSMI_{T-1,J} + B_{TJ} + X_{TJ} = D_{TJ} + DSS_{T,J} + SSPL_{T,J} - SSMI_{T,J}$$
$$\forall j \in J, \forall t \in T \qquad (4.40)$$

Equation (4.40) shows inventory balance equation.

$$S_{TJ} = SSPL_{TJ} + SS_{TJ} - SSMI_{T,J} \qquad \forall j \in J, \forall t \in T \qquad (4.41)$$

$$DSS_{TJ} = SS_{T,J} - SS_{T-1,J} \qquad \forall j \in J, \forall t \in T \qquad (4.42)$$

$$D_{T,J} \geq B_{T,J} \qquad \forall j \in J, \forall t \in T \qquad (4.43)$$

$$SS_{T,J} \geq SSMI_{T,J} \qquad \forall j \in J, \forall t \in T \qquad (4.44)$$

Equation (4.41) shows net inventory. Equation (4.42) shows safety stock variation. Constraints (4.43) and (4.44) expresses that demand must be greater than backlog quantity and safety stock must be greater than safety stock shortage quantity.

$$UTIL_{T,J} = \left(\frac{\sum_1^T \sum_1^J X_{T,J}}{Max\ Production\ Capacity\ (\ Total\ Number\ of\ Periods)}\right) * 100 \qquad \forall j \in J,$$
$$\forall t \in T \qquad (4.45)$$

$$SL_{T,J} = 100 - 100 * \left(\frac{B_{T,J}}{D_{T,J}}\right) \qquad \forall j \in J, \forall t \in T \qquad (4.46)$$

$$TOTSETUP_{T,J} = \sum_1^T \sum_1^J Y_{T,J} \qquad \forall j \in J, \forall t \in T \qquad (4.47)$$

$$X_{TJ}, S_{TJ}, SSPL_{T,J}, SSMI_{T,J}, R_{TJ} \geq 0 \qquad \forall j \in J, \forall t \in T \qquad (4.48)$$

$$Y_{TJ} \in \{0,1\} \qquad \forall j \in J, \forall t \in T \qquad (4.49)$$

Equation (4.45) shows total utilization rate. Equation (4.46) shows service level percentage. Service level can be defined as percentage of unmet demand to total demand. Equation (4.47) shows total number of setup times.

Constraint (4.48) shows non-negativity restrictions on the variables. Constraint (4.49) shows binary restriction on binary variable.

CHAPTER V

IMPLEMENTATION OF MODEL

Implementation of model is evaluated on this chapter. At first implementation principles are mentioned briefly and results obtained from model run is explained. This section consists of forecasting accuracy and evaluation of results. Accuracy of forecasting is shown by selected measures. Evaluation of results consists of interactions between obtained results, interactions between improvements and interactions between improvements by different models. Last section of this chapter is interpretation of results. Result of chosen optimal model is analyzed in this section.

5.1 Results and Improvements

A comparative study was conducted with the application of three main factors (energy policy, capacity policy and inventory policy) and it was seen how effective the model was and which points should be examined in order to obtain better results.

According to this classification 168 models are implemented. When models run, all models found feasible and review is done for all models. But because of high backlog penalty costs, 116 models of them without backlog reviewed detailed.

Table 5.1 Implementation of models by different principles

MAIN CRITERIA	**CATEGORIES**
DEMAND DATA	Real Data
	Forecast for Past Data
INVENTORY POLICY	Safety Stock Decision-0
	Safety Stock Decision-1
	Safety Stock Decision-2
	Safety Stock Decision-3
CAPACITY POLICY	Production Capacity: Low to High
ENERGY POLICY	ENERGY: Natural Gas
	ENERGY: Both (Equal Weight)
	ENERGY: Coal

When comparing results objective function (total profit) result is decisive. It must be as much as possible. However, total cost, total product inventory and generated carbon emission quantity must be minimum. Production quantity, production demand and utilization rate must be adjusted as optimum values.

There are four safety stock alternatives. Safety stock decision-0 expresses that there is not defined safety stock in prepared model design. Quantity of other safety stock decisions are calculated as mentioned on Chapter IV.

If planning horizon is considered, it is seen that model implementations are done for 12 month period. It means that planning horizon is suitable for medium range planning (between 3 and 18 months) as well as long range planning (between 1 and 15 years) consistent with master production scheduling logic.

5.1.1 Forecasting Methods and Accuracy

Constant values seen on Table 5.2 and Table 5.3 are used in forecasting methods. These values are chosen according to compatibleness between forecasted demand and real demand data. Forecast results with smallest difference for each calculation are selected. When forecasting future demand data, the most consistent values are chosen.

Constant values used for ARIMA method are seen on Table 5.2.

Table 5.2 Best constant values for ARIMA forecasting method implementation

FORECASTING METHOD: ARIMA					
PRD GRADE	FORECAST REFERENCE	FORECAST PERIOD	AR ORDER / AR^N	MA ORDER / MA^N	DIFFERENCES
0.76	2014_01 - 2016_12	2017_01 - 2017_12	3	1	1
0.80			2	0	2
0.84			2	3	1

Constant values used for Holt-Winter method are seen on Table 5.3. Possible highest values for forecasting accuracy are α, β and γ values. It means that the lower values than these values could be used to calculate demand by HW method.

Table 5.3 Best constant values for HW forecasting method implementation

FORECASTING METHOD: HOLT - WINTER						
PRD GRADE	FORECAST REFERENCE	FORECAST PERIOD	SEASONS / S	ALPHA / α	BETA / β	GAMMA / γ
0.76	2014_01__ 2016_12	2017_01 - 2017_12	2	0.15	0.20	0.00
0.80			4	0.20	0.20	0.00
0.84			4	0.20	0.20	0.00

On Figure 5.1 change of real demand and forecasted demand data by time seen. Fluctuation on demand data forecasted with HW method is much more than demand data forecasted with ARIMA method.

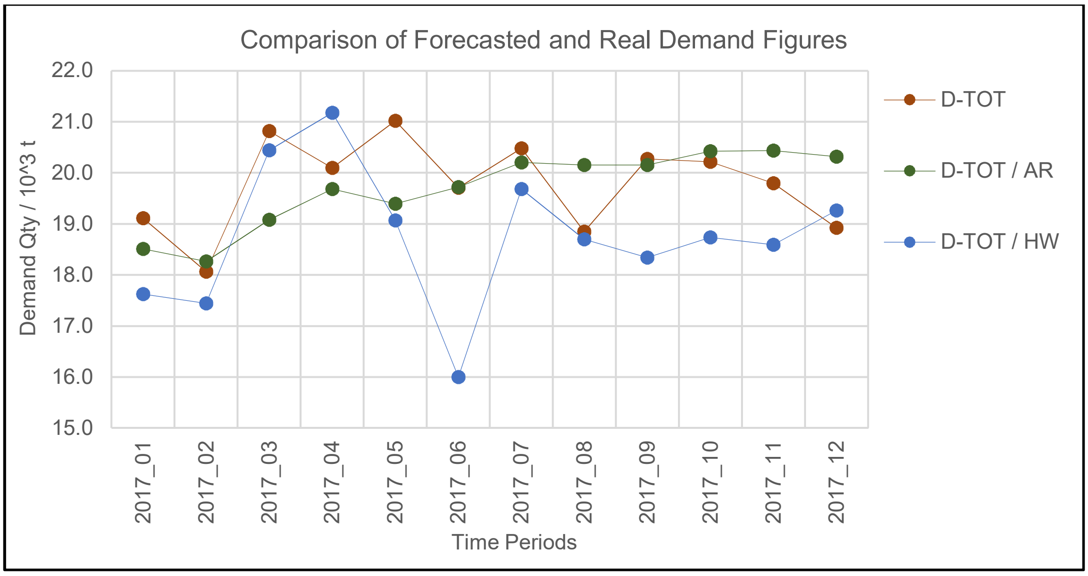


Figure 5.1 Comparison of forecasted and real demand figures

Demand comparison for every product grade are shown respectively in Figure 5.2, 5.3 and 5.4. Demand data estimated by the ARIMA method is more consistent than demand data estimated by the HW method as can be seen from Figures 5.2, 5.3 and 5.4. There are fluctuations on trends of forecasted demand by HW method. These deviations could be seen indicators of forecast inaccuracy.

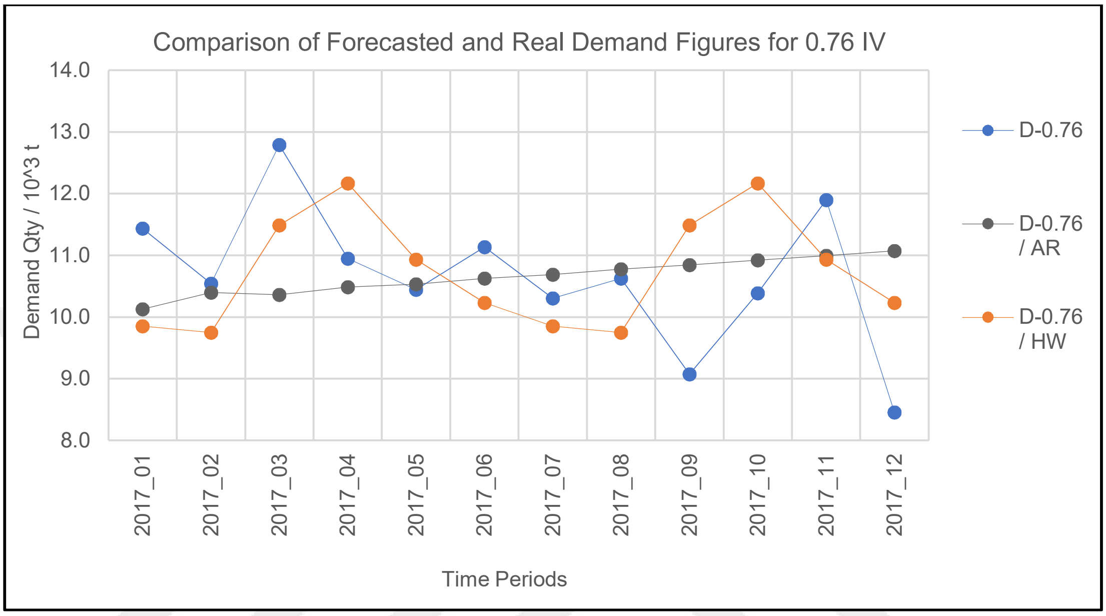


Figure 5.2 Comparison of forecasted and real demand figures for 0.76 IV

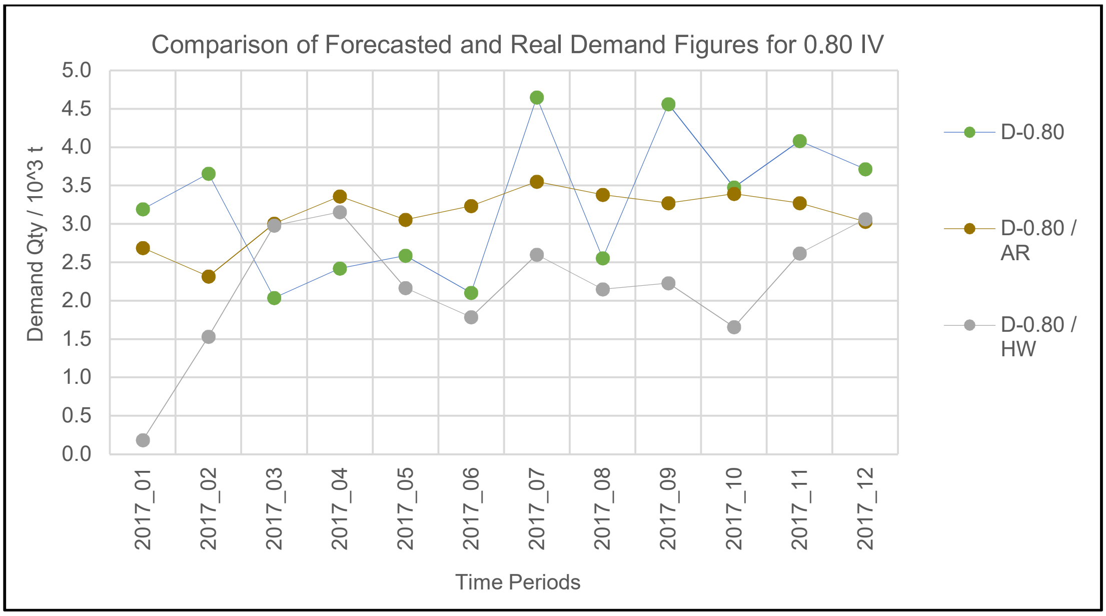


Figure 5.3 Comparison of forecasted and real demand figures for 0.80 IV

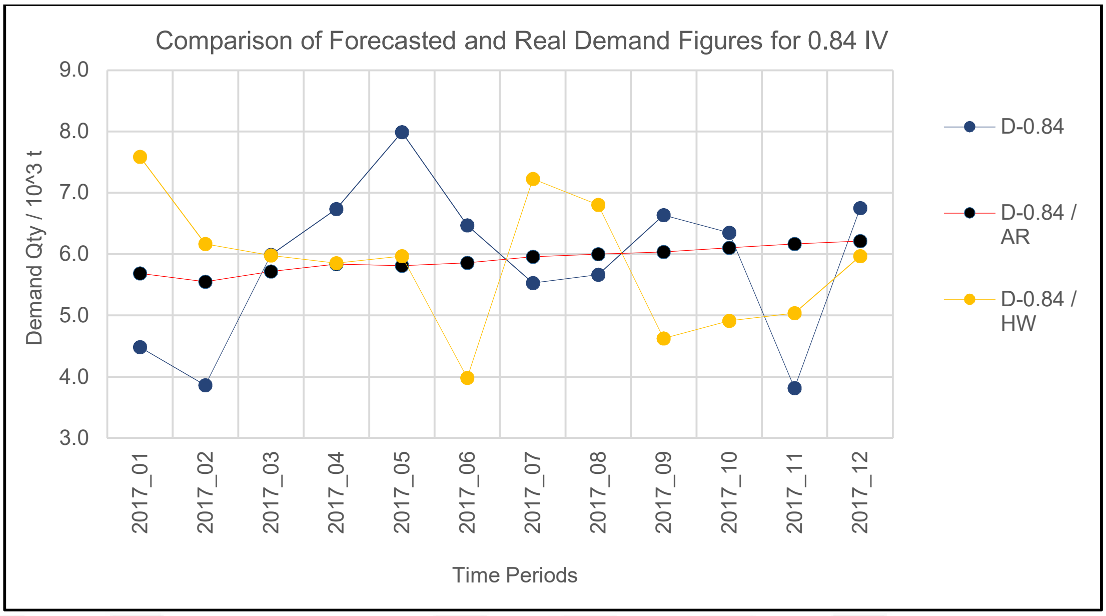


Figure 5.4 Comparison of forecasted and real demand figures for 0.84 IV

Forecasting methods could be compared with these basic data. However, a proper evaluation couldn’t be made with these graphs. RMSE, MAE and MAPE methods are used to see forecast accuracy of these two methods.

RMSE, MAE and MAPE error values for two forecast methods are seen for each product grade on Table 5.4. According to value ranking for every metric and every grade, smallest value must be chosen because smaller values would indicate better performance. According to these results best method for all production grades are chosen and it is given on Table 5.5.

Table 5.4 Comparison of different forecasting errors

FORECAST METHOD	**FORECAST ERROR METRIC**	**PRODUCT GRADE**				**AVERAGE**
		0.76	**0.80**	**0.84**	**TOTAL**	
ARIMA	rmse	1.27	0.92	1.18	0.93	1.08
	mae	0.94	0.85	0.95	0.71	0.86
	mape	0.09	0.28	0.18	0.04	0.15
HW	rmse	1.34	2.90	1.79	1.57	1.90
	mae	1.21	2.59	1.59	1.26	1.66
	mape	0.12	0.92	0.29	0.06	0.35

ARIMA method is best for most product grades and forecast error metrics as seen from Table 5.5 because for all product grades smaller values than HW method are obtained.

ARIMA method is better than HW method according to these results. Though it is not true always. Results may differ according to trend patterns, number of periods etc.

Table 5.5 Best method for every production grade by three forecast error metrics

FORECAST ERROR METRIC	**PRODUCT GRADE**				**AVERAGE**
	0.76	**0.80**	**0.84**	**TOTAL**	
rmse	ARIMA	ARIMA	ARIMA	ARIMA	ARIMA
mae	ARIMA	ARIMA	ARIMA	ARIMA	ARIMA
mape	ARIMA	ARIMA	ARIMA	ARIMA	ARIMA

Forecasted data obtained by two methods are compared on Table 5.6 and Table 5.7. There is not much difference forecasted data by two methods for 0.76 IV and 0.84 IV product grades. However intolerable difference found between forecasted data by ARIMA and HW method for 0.80 IV product grade.

Table 5.6 Comparison of total forecasted and real demand by product grade

DEMAND DATA OBTAINED BY	**DEMAND FOR DIFFERENT PRODUCT GRADES / 10^3 t**			
	0.76	**0.80**	**0.84**	**TOTAL**
REAL DATA	128.0	39.0	70.3	237.4
ARIMA METHOD	127.8	37.6	70.9	236.3
HW METHOD	128.8	26.1	70.1	225.1

Table 5.7 Difference between total forecasted and real demand by product grade

DEMAND DATA OBTAINED BY	**DEMAND FOR DIFFERENT PRODUCT GRADES / 10^3 t**			
	0.76	**0.80**	**0.84**	**TOTAL**
REAL DATA	0.0	0.0	0.0	0.0
ARIMA METHOD	-0.2	-1.5	0.7	-1.0
HW METHOD	0.8	-12.9	-0.2	-12.3

5.1.2 Evaluation of Results

Change of real data on 2017 is seen on Figure 5.5. Optimal results obtained by real demand data and forecasted demand data is seen on Figure 5.6 and Figure 5.7.

Optimal production and inventory quantity can be compared with real data according to Figures 5.5, 5.6 and 5.7. Trends of total production quantity and total net inventory quantity of both optimal results (using demand data by real value and forecasted value) seems constant for most periods except of first and last periods of planning horizon. It seems chase strategy is used for demand generally. On the first period, it is assumed there is not any inventory from previous period. Total net inventory quantity is kept constant for almost all planning horizon because of there is certain quantity of safety stock must be hold. Total production quantity and total net inventory quantity is increased in the last period of planning horizon. This change may be compensation of the first period to balance inventory.

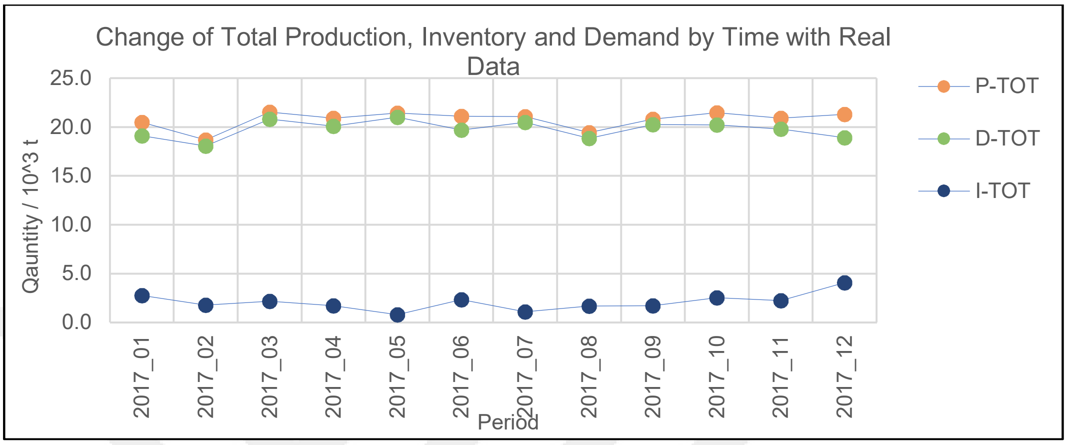


Figure 5.5 Change of main parameters with time

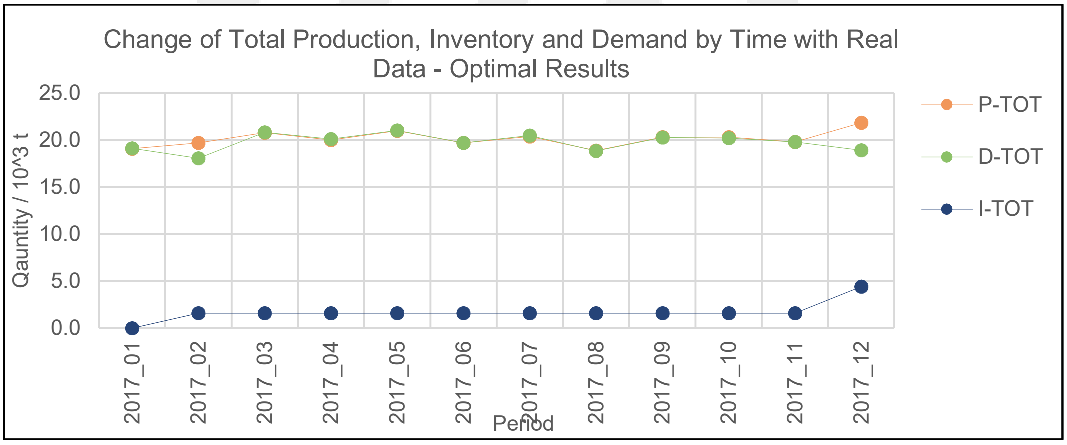


Figure 5.6 Change of main parameters by time with real data – optimal results

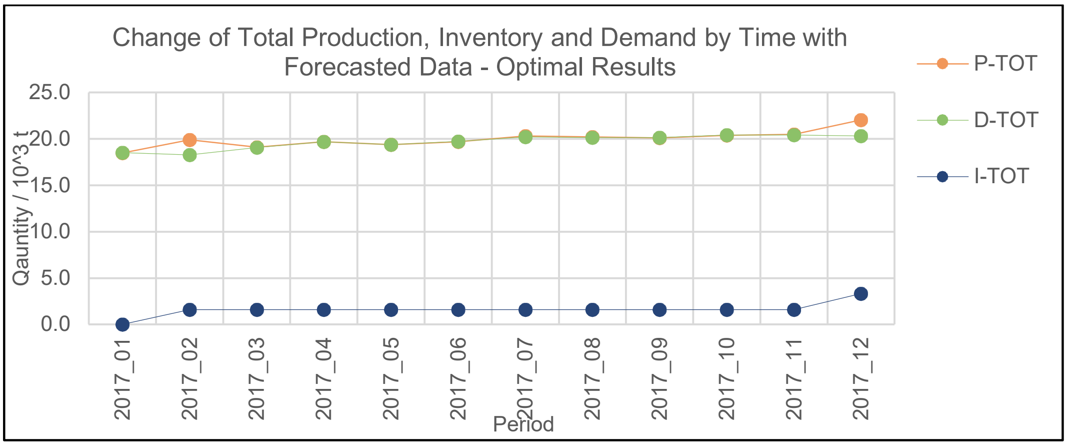


Figure 5.7 Change of main parameters by time with forecast – optimal results

Comparison of total production quantity and total net inventory quantity with real data and optimal results are seen on Figure 5.8 and 5.9. Trends of total production quantity and total inventory quantity of both optimal results found very near to each other as mentioned above. However change of total production quantity and total inventory quantity can be seen more clearly on these figures. There is visible difference between trend of production quantity found by forecasted demand and real demand between February and June 2017. There is more end product by real demand than forecasted demand on March 2017 and May 2017. On the other hand there is more end product by forecasted demand than real demand on August 2017 and November 2017. These differences are due to different demand values. Trend of inventory quantity is almost same due to same safety stock policy.

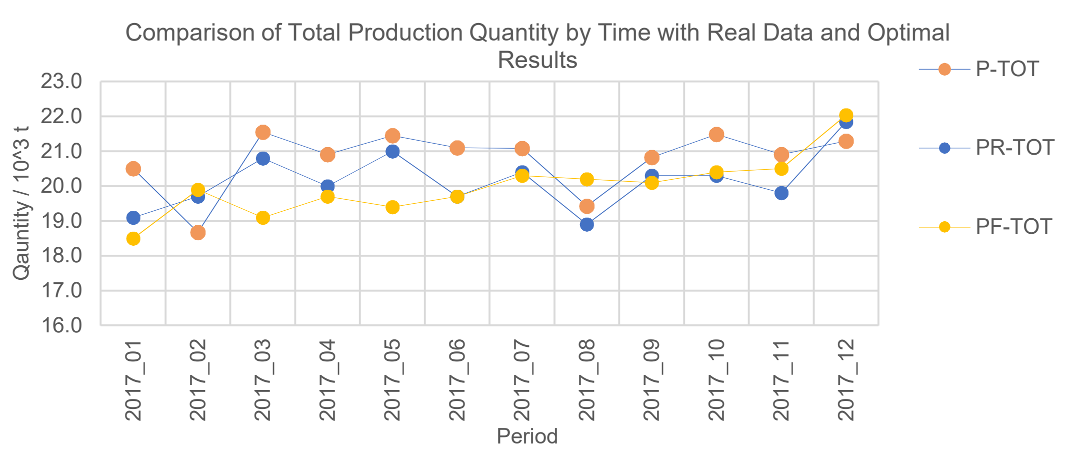


Figure 5.8 Total production quantity by time with real data and optimal results

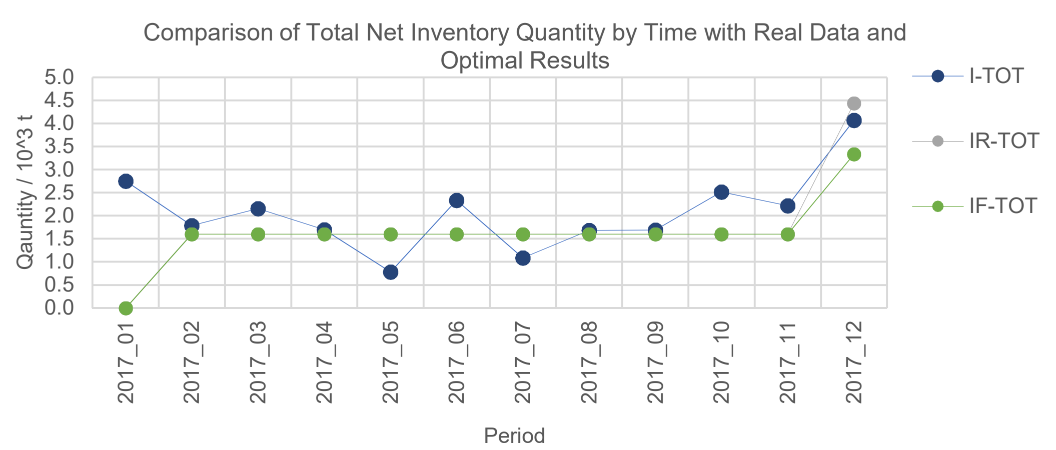


Figure 5.9 Total net inventory quantity by time with real data and optimal results

5.1.2.1 Interactions Between Obtained Results

Optimal results obtained by running model are examined with regular production capacity increase in this section. Demand data of model is forecasted. Both energy resources are used equally as using one resource. Safety stock desicision-3 is chosen for inventory policy.

Average inventory quantity value is found its peak on 655 t/d capacity where backlog is finished as it seen from Figure 5.10. It reached its minimum value on 675 t/d capacity.

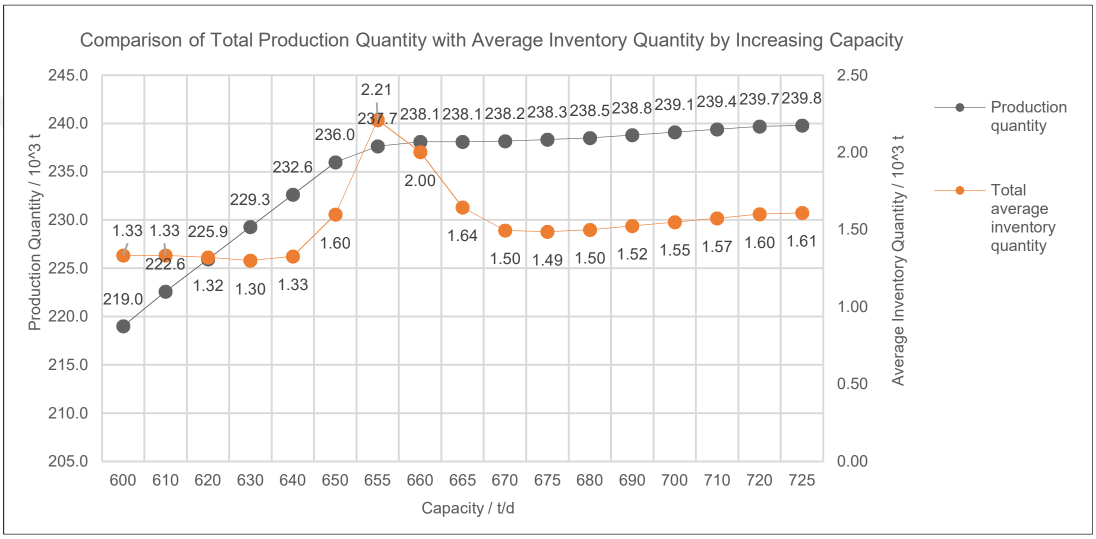


Figure 5.10 Total production with average inventory per capacity

Backlog quantity and utilization rate decrease by increasing capacity as it seen from Figure 5.11. There is not backlog after reaching 655 t/d capacity. Utilization rate decreases and it reaches its minimum value on 725 t/d capacity. In another words production capacity and utilization rate and backlog quantity is inversely proportional.

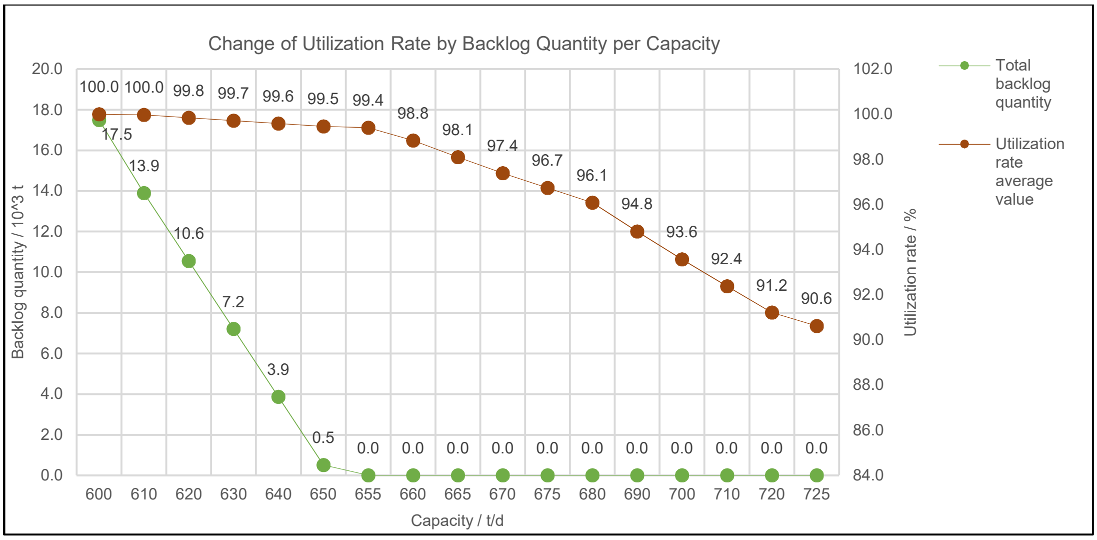


Figure 5.11 Change of utilization rate by backlog quantity per capacity

Service level increases by increasing capacity contrary to utilization rate as it seen from Figure 5.12. Service level increases and it reaches its maximum value on 655 t/d capacity because there is not backlog after reaching 655 t/d capacity. Service level is constant during regular capacity increase after 655 t/d capacity.

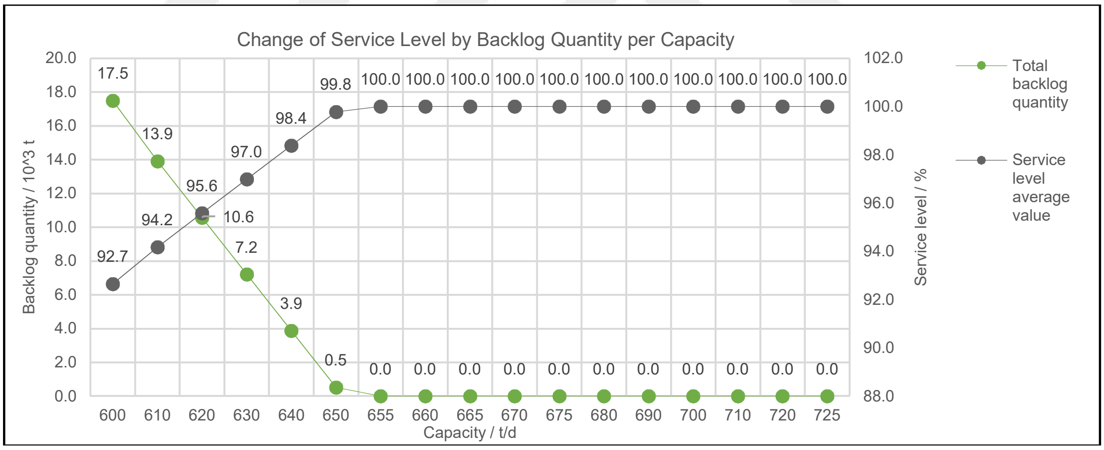


Figure 5.12 Change of service level by backlog quantity per Capacity

Relations of utilization rate and service level with backlog by increasing capacity is mentioned individually on Figure 5.11 and 5.12. Relation between these two parameters is seen on Figure 5.13. Utilization rate decreases and it reaches its minimum value on 725 t/d capacity. Service level increases and it reaches its maximum value on 655 t/d capacity and it is constant during regular capacity increase after this capacity. Before production capacity reaches 655 t/d (when there is backlog) relation between service level and utilization rate is inversely proportional. After production capacity reaches 655 t/d service level doesn't change because there is not backlog anymore. Utilization rate decreases due to meeting demand with higher capacity is easier and it is not required to run plant in its maximum production capacity.

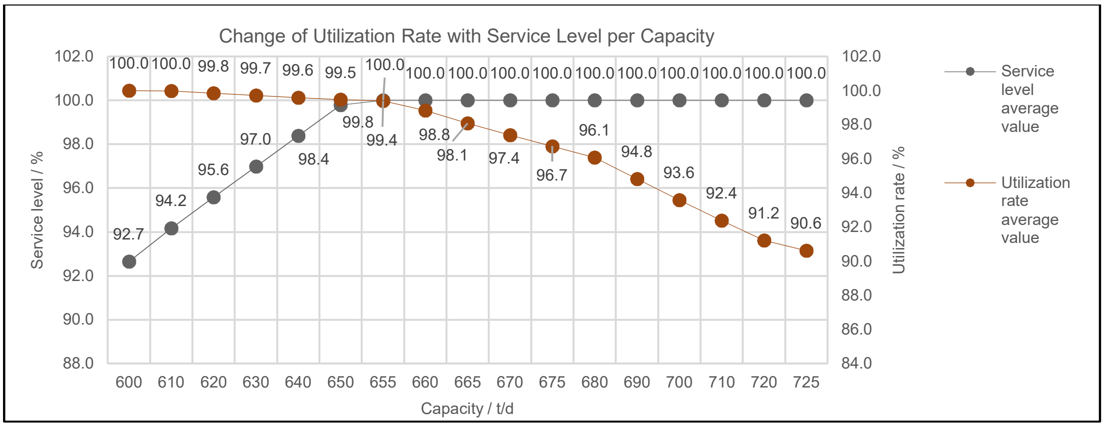


Figure 5.13 Change of utilization rate with service level per capacity

Relation between backlog quantity and average inventory quantity is seen on Figure 5.14. Backlog quantity decreases by increasing capacity. There is not backlog after reaching 655 t/d capacity. Average inventory quantity reaches its peak value when production capacity reaches 655 t/d and reaches its minimum value when production capacity reaches 675 t/d capacity.

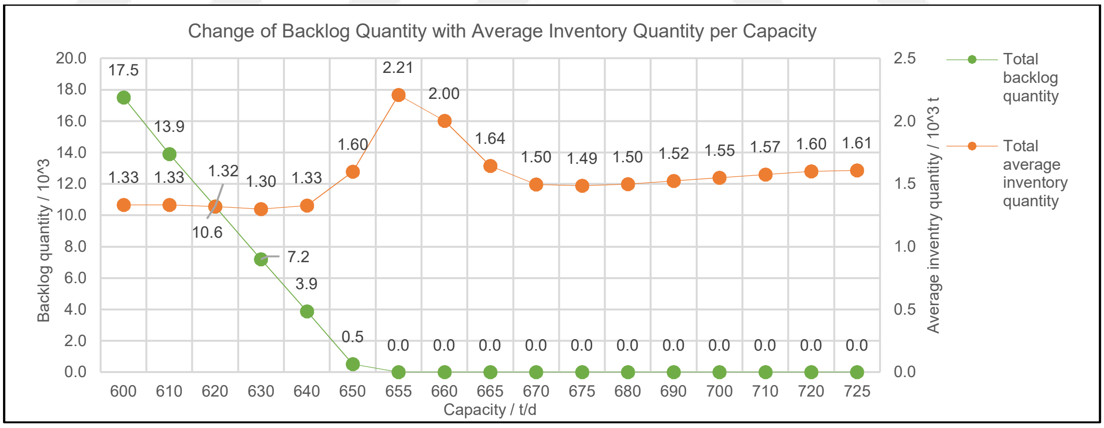


Figure 5.14 Backlog quantity with average inventory quantity per capacity

Relation between generated carbon emission and production quantity is seen on Figure 5.15. When production capacity increases production quantity increases naturally, but the rate of increase slows down after reaching 655 t/d capacity where backlog finishes. Trend of generated carbon emission is very similar to production quantity.

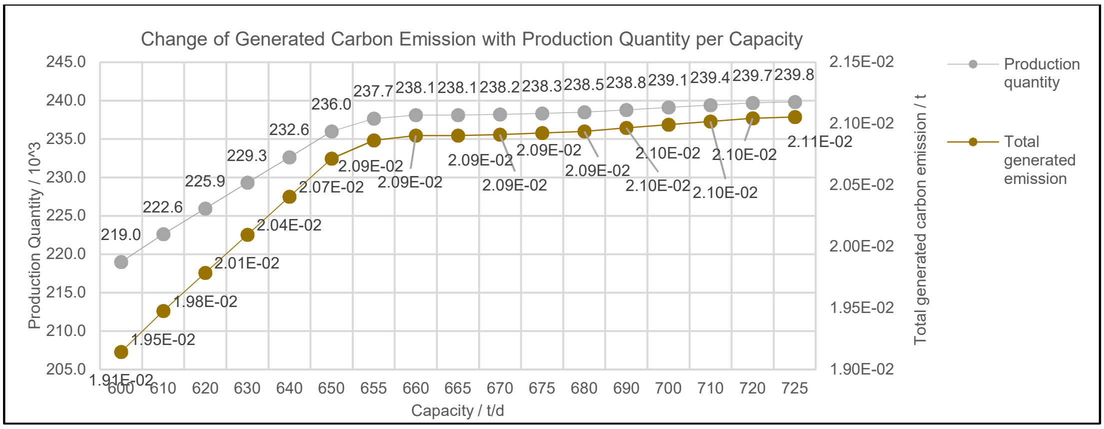


Figure 5.15 Generated carbon emission with production quantity per capacity

Relation between generated carbon emission and utilization rate is seen on Figure 5.16. It is very clear that generated carbon emission and utilization rate is inversely proportional in model.

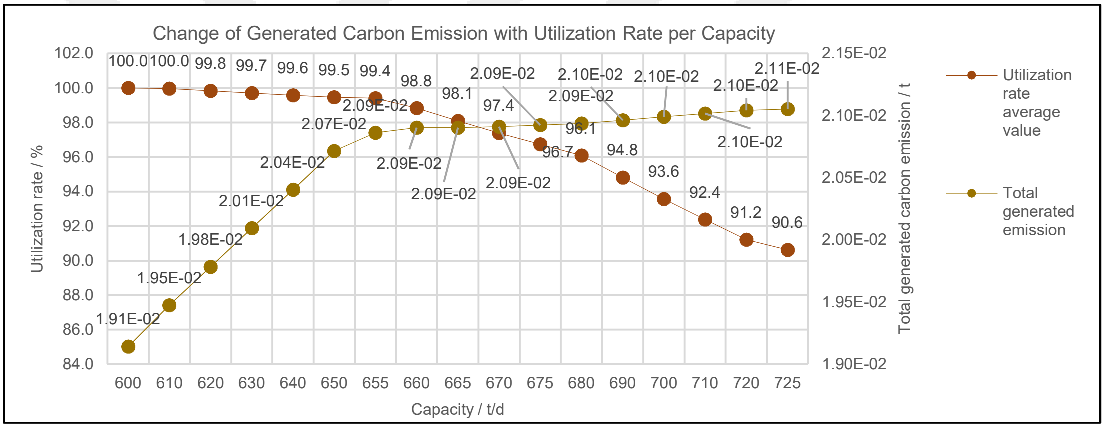


Figure 5.16 Generated carbon emission with utilization rate per capacity

Relation between objective function value (profit) and inventory turnover ratio is seen on Figure 5.17. Trend of inventory turnover ratio is very similar to trend of average inventory quantity on Figure 5.14 but there is a difference on reaching its maximum value. Actually inventory turnover ratio is inversely proportional with inventory quantity. Inventory turnover ratio reaches its minimum value when production capacity reaches 655 t/d capacity (when backlog finishes) and reaches its peak value when production capacity reaches 675 t/d. Inventory turnover ratio increases after production capacity reaches 655 t/d capacity and decreases after production capacity reaches 675 t/d. Profit value increases regularly by increasing capacity. However it becomes almost constant after production capacity reaches 670 t/d. One of the reasons may be demand reaches its saturation point on this value.

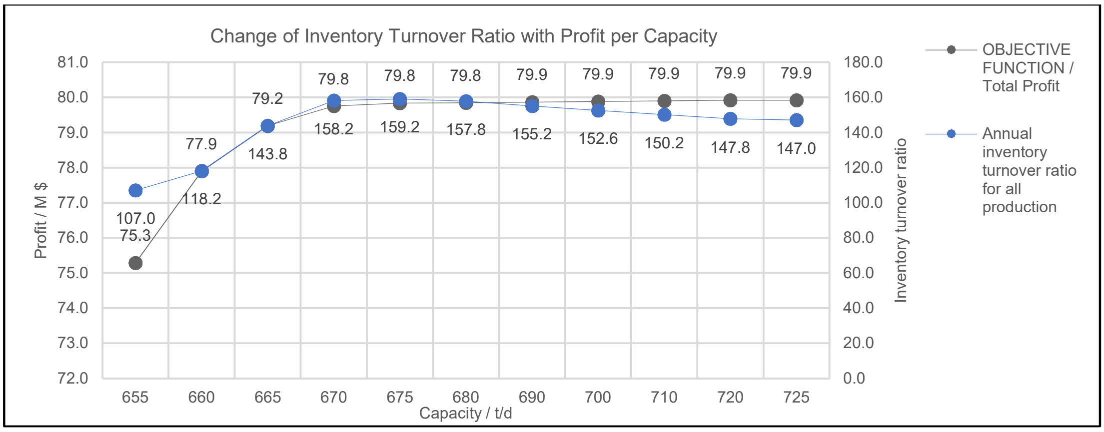


Figure 5.17 Change of inventory turnover ratio with profit per capacity

Relation between objective function value (profit) and inventory turnover ratio for different product grades is seen on Figure 5.18, Figure 5.19 and Figure 5.20. Trend of inventory turnover ratio of product grade j1 is very similar to trend of inventory turnover ratio on Figure 5.17. Inventory turnover ratio reaches its minimum value when production capacity reaches 655 t/d capacity (when backlog finishes) and reaches its peak value when production capacity reaches 675 t/d. Inventory turnover ratio increases after production capacity reaches 655 t/d capacity and decreases after production capacity reaches 675 t/d. However trends of inventory turnover ratio of product grade j2 and j3 are different from trend of inventory turnover ratio of product grade j1. Inventory turnover ratio reaches its peak value when production capacity reaches to a certain point (660 t/d for product grade j2 and 670 t/d for product grade j3) and becomes constant during regular capacity increase.

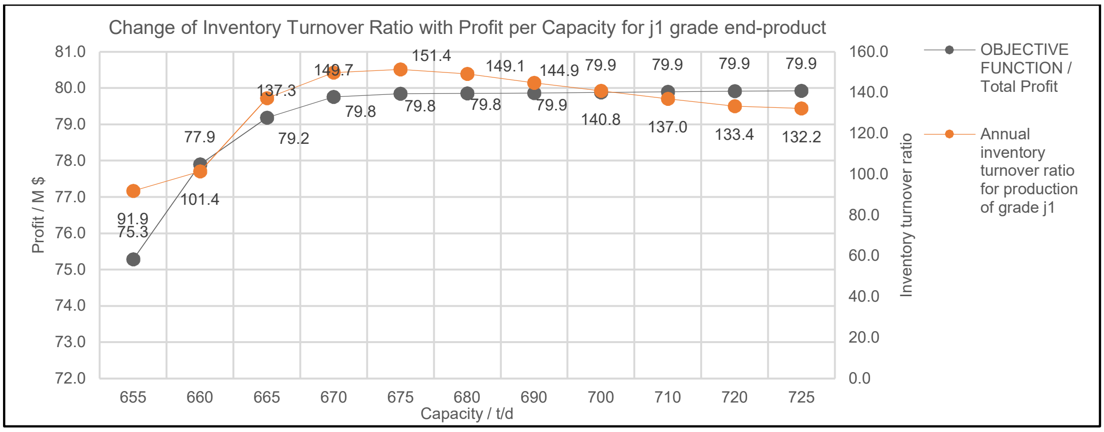


Figure 5.18 Inventory turnover ratio with profit per capacity for j_1 grade

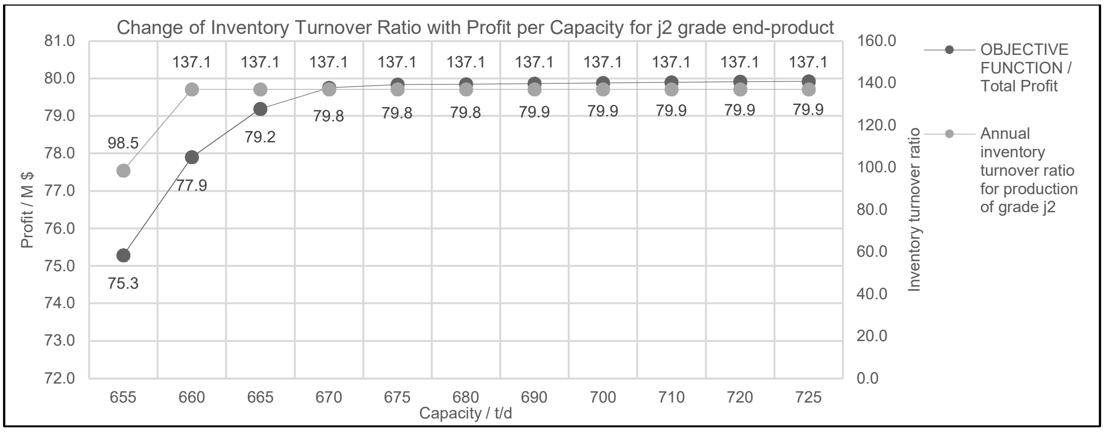


Figure 5.19 Inventory turnover ratio with profit per capacity for j_2 grade

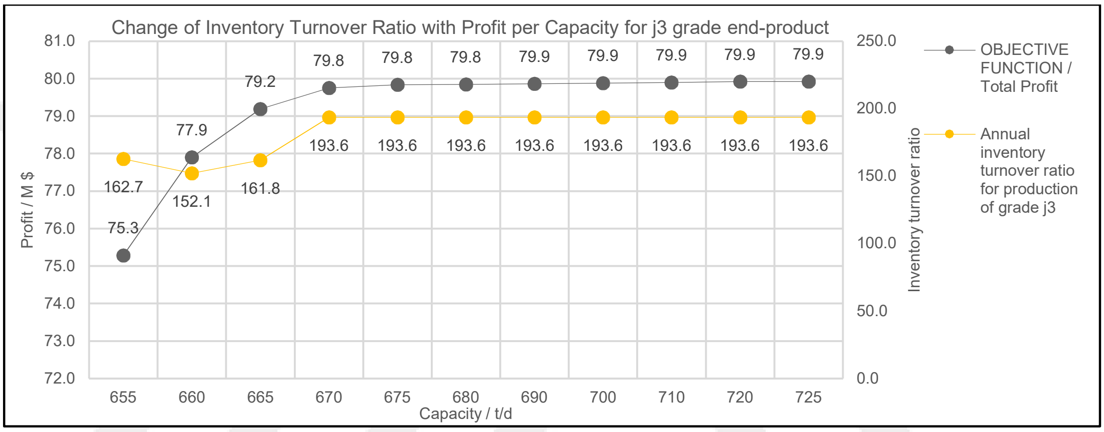


Figure 5.20 Inventory turnover ratio with profit per capacity for j_3 grade

Relation between objective function value (profit) and inventory holding time is seen on Figure 5.21. Interaction between these parameters is same as seen on Figure 5.17. Inventory turnover ratio and inventory holding time is inversely proportional between each other, so when inventory turnover ratio is high, inventory holding time is low.

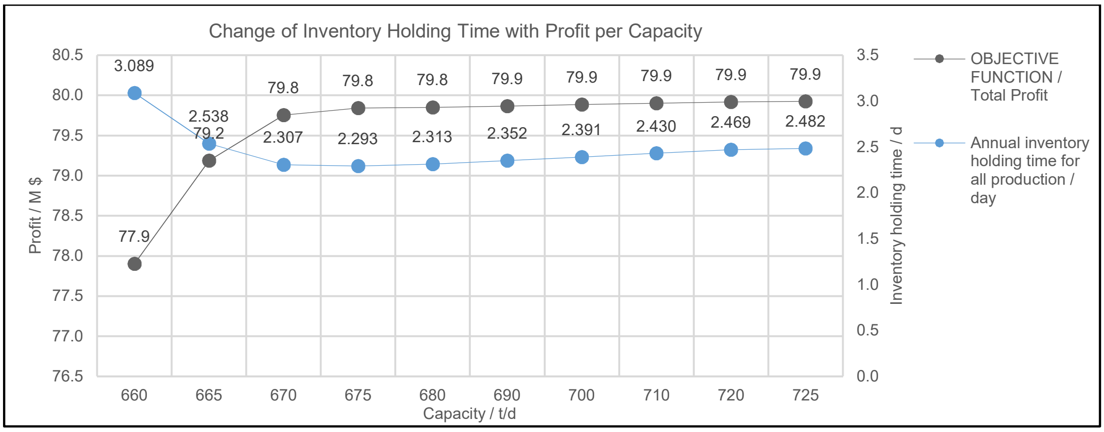


Figure 5.21 Change of inventory holding time with profit per capacity

Relation between objective function value (profit) and inventory holding time for different product grades is seen on Figure 5.22, Figure 5.23 and Figure 5.24. There is a peak value on trend of inventory holding time on different capacity values (665 t/d for j1 and 670 t/d for j2) except of product grade j3. Inventory holding time decreases and almost zero on different capacity values (680 t/d for j2 and 690 t/d for j3) except of product grade j1. Inventory holding time of product grade j1 reaches its peak value on 665 t/d and it reaches its minimum value on 670 t/d. Inventory holding time of product grade j1 increased until it reached a fixed value on 720 t/d capacity. It is constant between 720 t/d capacity and 725 t/d capacity interestingly.

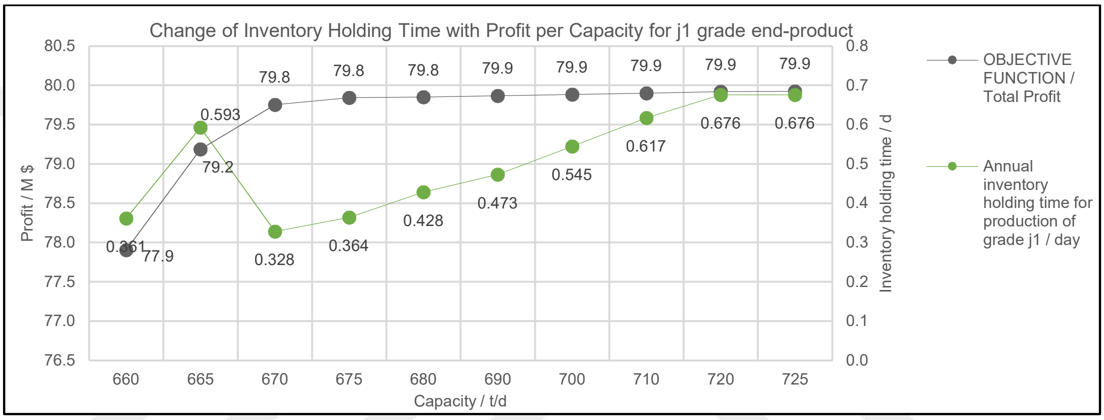


Figure 5.22 Inventory holding time with profit per capacity for j_1 grade

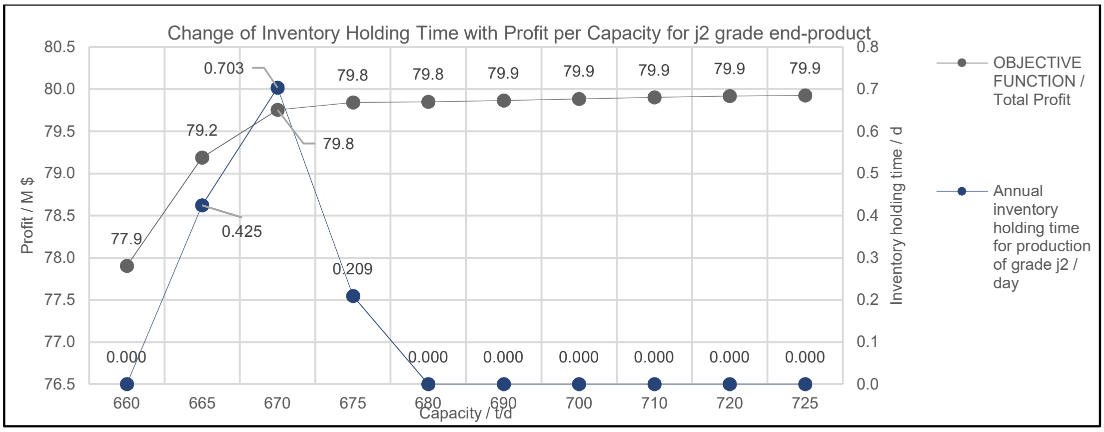


Figure 5.23 Inventory holding time with profit per capacity for j_2 grade

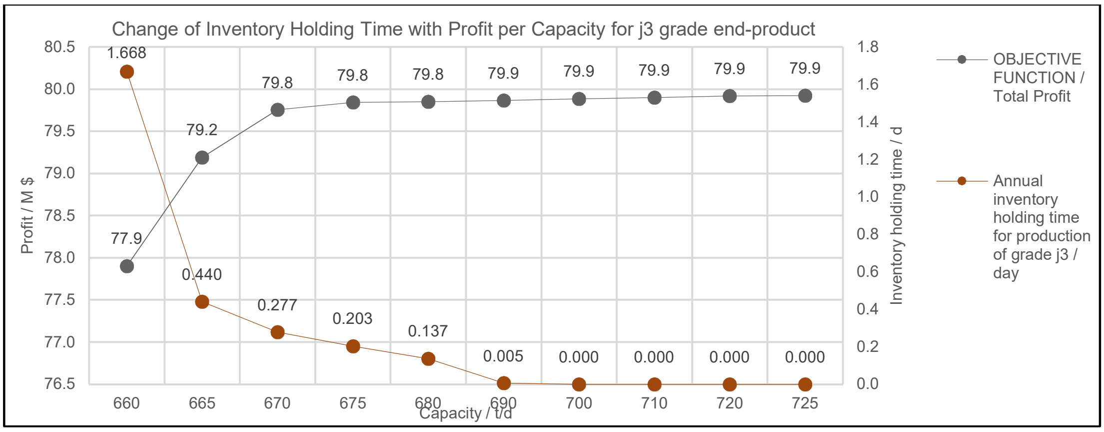


Figure 5.24 Inventory holding time with profit per capacity for j3 grade

Relation between overstock quantity and inventory turnover ratio is seen on Figure 5.25. Trend of overstock quantity is very similar to the trend of average inventory quantity on Figure 5.14 by its peak and bottom values on production capacity. In contradiction of this inventory turnover ratio is its bottom and peak values on same production capacity.

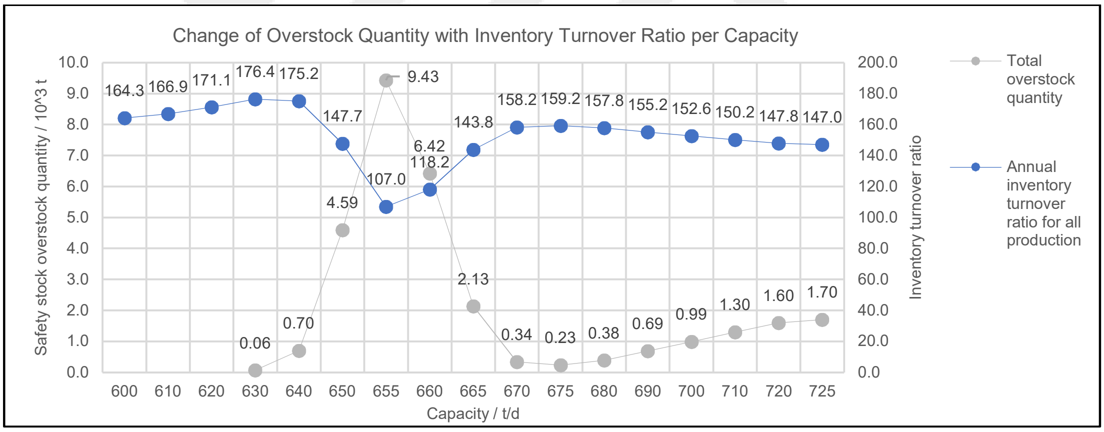


Figure 5.25 Overstock quantity with inventory turnover ratio per capacity

Relation between backlog quantity and inventory turnover ratio is seen on Figure 5.26. Relation between utilization ratio and inventory turnover ratio is seen on Figure 5.27 and relation between service level and inventory turnover ratio is seen on Figure 5.28. There is not backlog after 655 t/d production capacity, so interpretation of trend is done for capacity up to 655 t/d for Figure 5.26. Backlog quantity and inventory turnover ratio is inversely proportional production capacity up to 640 t/d. After that inventory turnover ratio decreases until there is no backlog on 655 t/d capacity. It is highly possible due to model force inventory storage to meet demand and remove backlogs. Service level increases and utilization rate decreases in the same period.

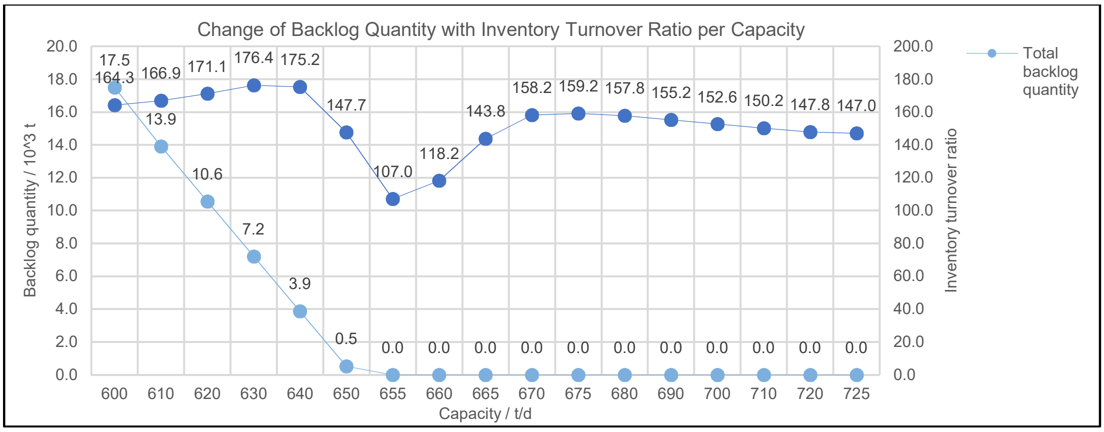


Figure 5.26 Backlog quantity with inventory turnover ratio per capacity

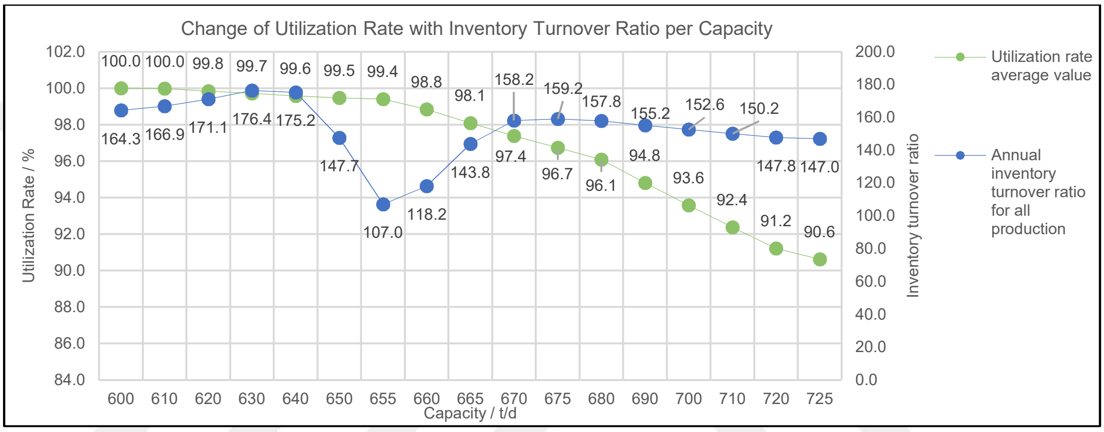


Figure 5.27 Change of utilization rate with inventory turnover ratio per capacity

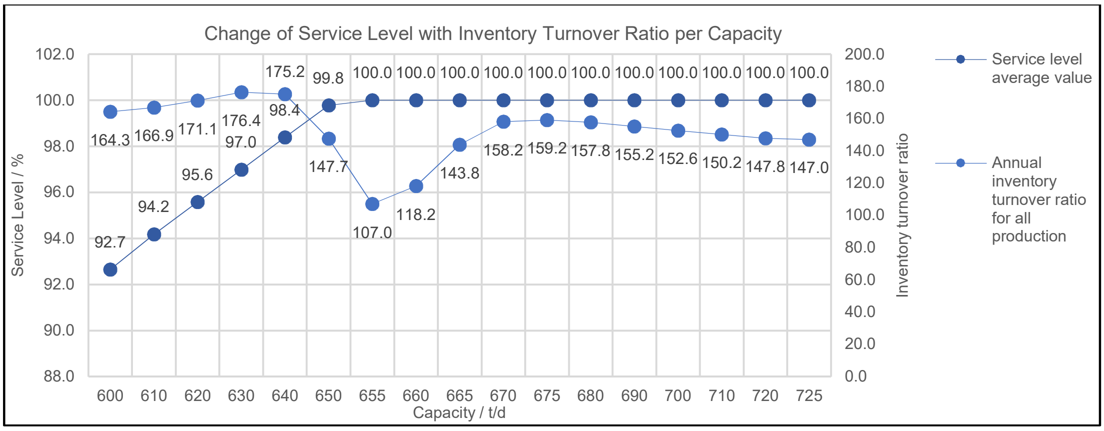


Figure 5.28 Change of service level with inventory turnover ratio per capacity

5.1.2.2 Interactions Between Improvements

Improvements are compared according to model types with regular production capacity increase in this section. Different safety stock decisions are made with proposed model and results obtained according to these decisions. The following graph data are obtained from the estimated demand and model results using two energy sources simultaneously.

At first improvement percentages of objective function value obtained from different implementations are compared. Results obtained from all safety stock decisions are seen on Figure 5.29 and results obtained from all safety stock decisions except of SS-0 (there is not any defined safety stock quantity) are seen on Figure 5.30. There is one common point for all results. Improvement rate of profit increases after 655 t/d capacity to 675 t/d capacity. Rate of increase is almost constant after 670 t/d capacity. Best improvement rate of profit is found by SS-0 decision. However there must be a certain quantity of safety stock to handle various problems. Best improvement rate of profit is found by SS-1 decision for models with safety stock. But as mentioned on Chapter IV, SS-3 is chosen to keep customer service level better. Improvement rate of profit of SS-3 is better than SS-2 but lower than SS-1. Improvement rate of profit is negative for SS-2 and SS-3 decisions on 655 t/d capacity and minimum 660 t/d capacity is favorable for all decisions.

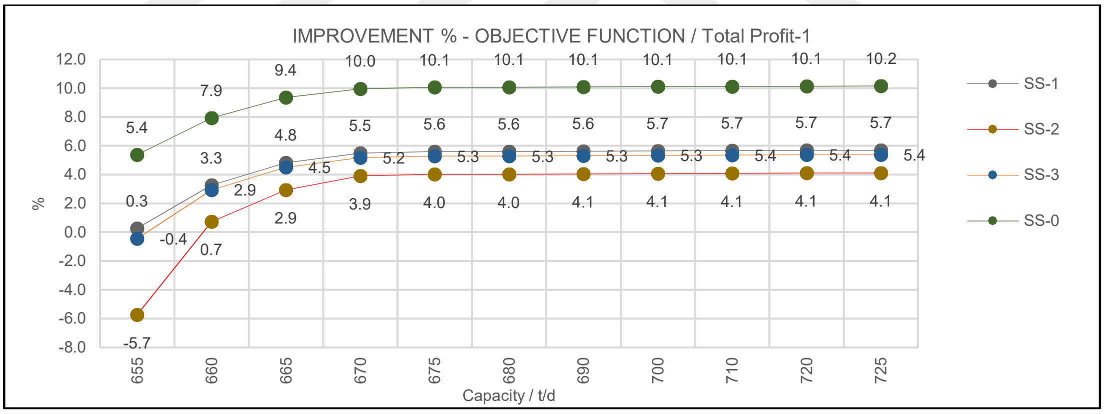


Figure 5.29 Improvement % of objective function / total profit-1

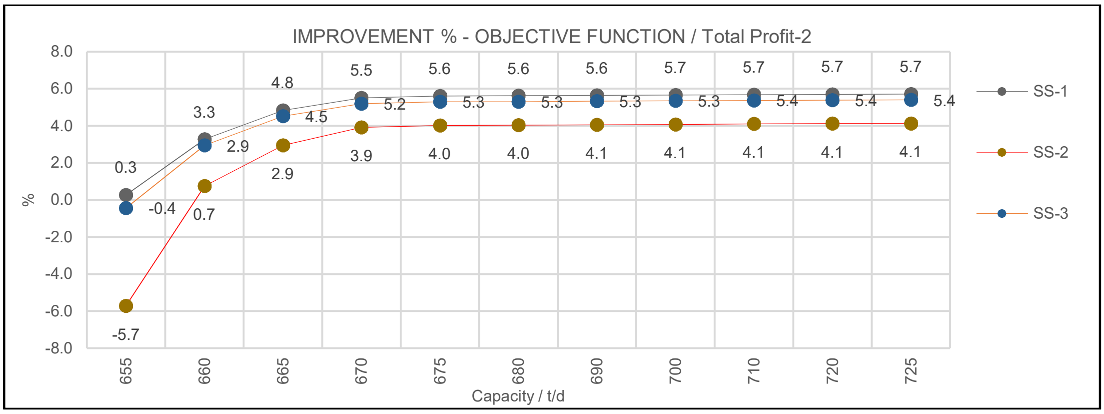


Figure 5.30 Improvement % of objective function / total profit-2

Improvement percentages of total cost and revenue is seen on Figure 5.31 and Figure 5.32. Trend is very similar to profit. Improvement rate of revenue is negative but improvement rate of total cost is also negative and it is lower than revenue. Thus it is possible to make profit with increasing capacity. Improvement rate of revenue is negative because only necessary quantity of production is made according to optimal planning. It is also seen from Figure 5.33.

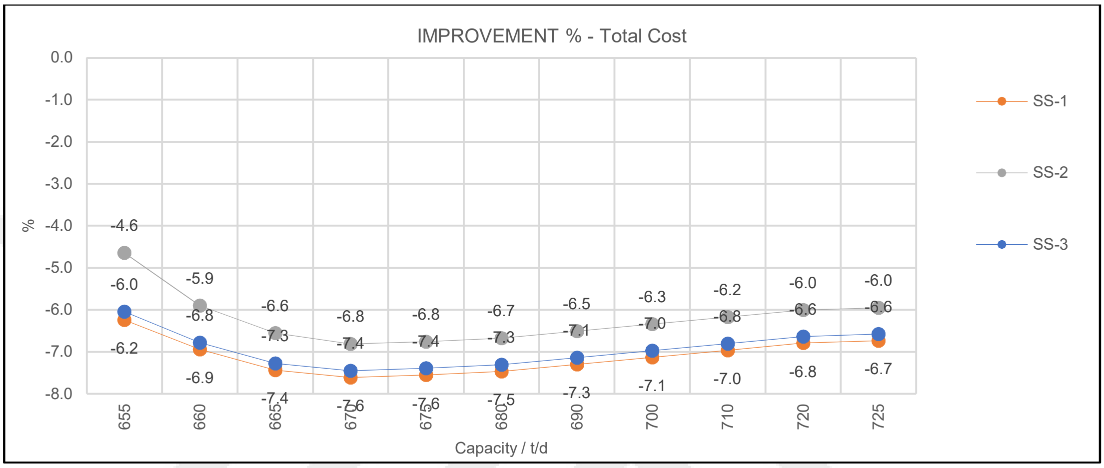


Figure 5.31 Improvement % of total cost

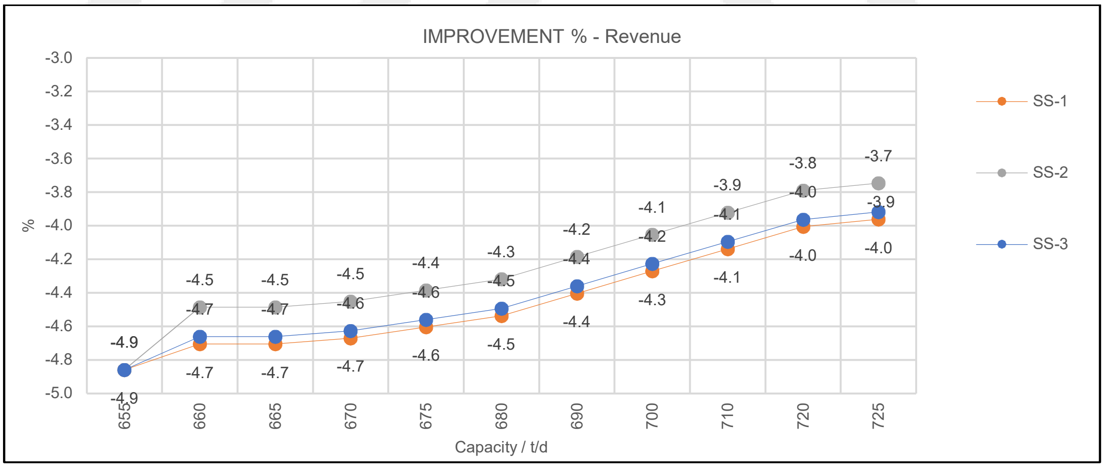


Figure 5.32 Improvement % of revenue

Improvement rate of total inventory quantity and total overstock quantity is seen on Figure 5.34 and Figure 5.35. There are tangible improvements according to these graphs. Best improvement rates are found by SS-1 decision and 675 t/d capacity, but as mentioned before SS-3 decision is made.

Figure 5.33 Improvement % of total production quantity

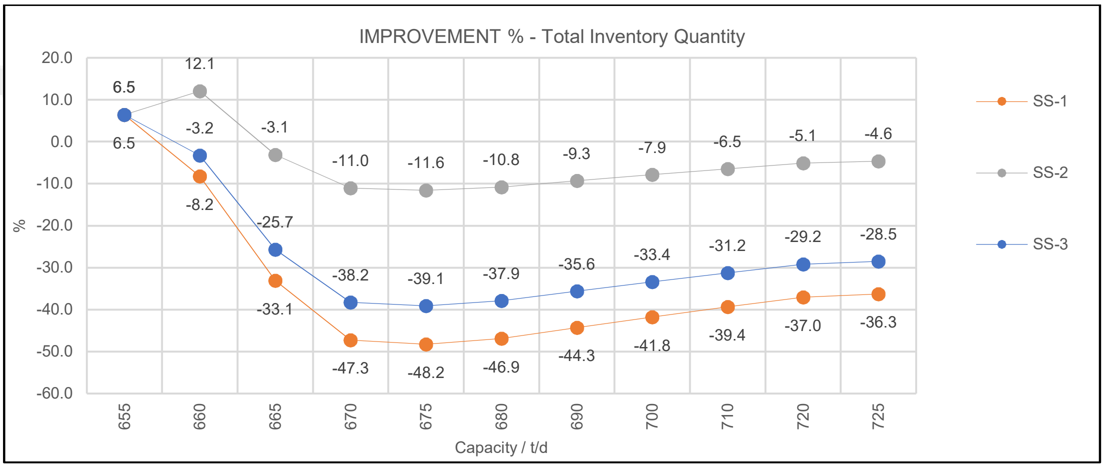


Figure 5.34 Improvement % of total inventory quantity

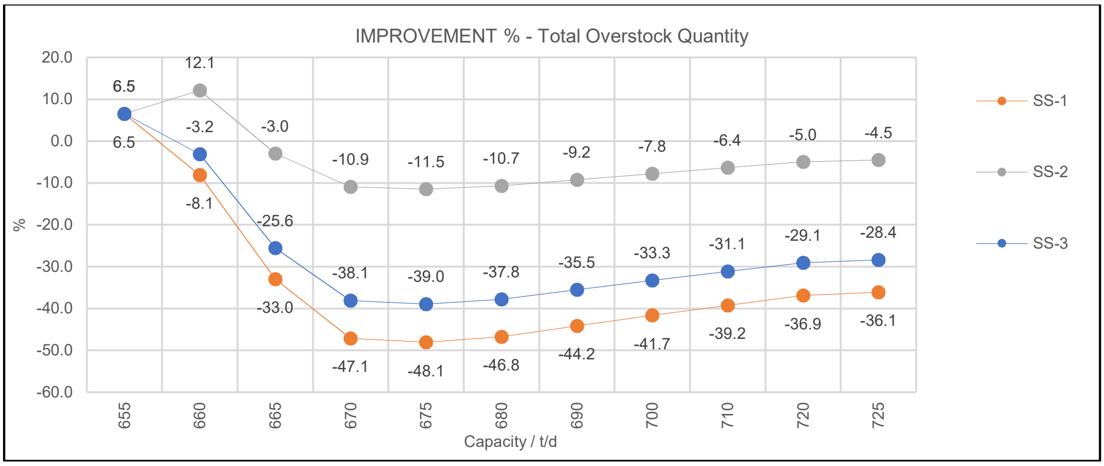


Figure 5.35 Improvement % of total overstock quantity

Improvement percentage of utilization rate is seen on Figure 5.36. Utilization rate decreases by increasing capacity. Almost same results are found by all three decisions.

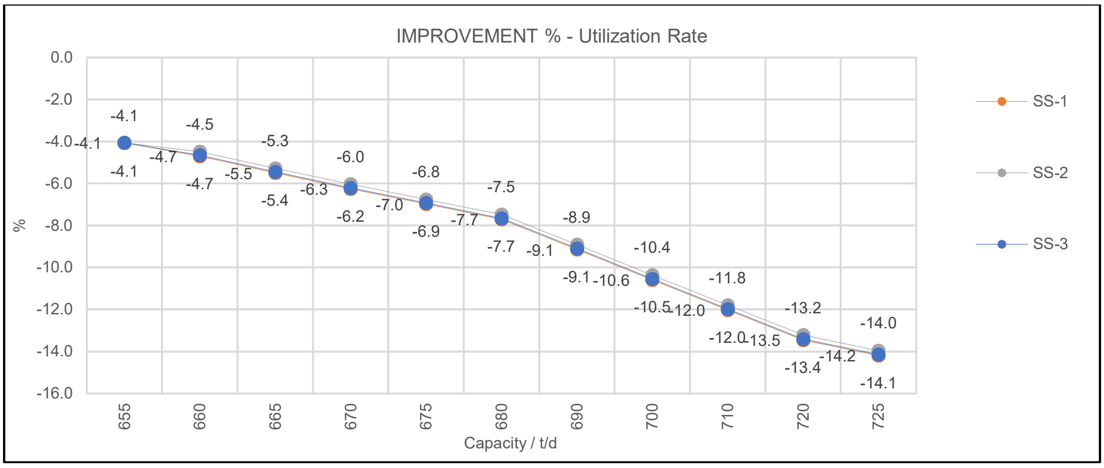


Figure 5.36 Improvement % of utilization rate

Improvement percentage of overstock cost is seen on Figure 5.37. Almost same results are found by all three decisions. Very high level of improvement has been achieved especially from 665 t/d to 700 t/d, even it decreases after 675 t/d.

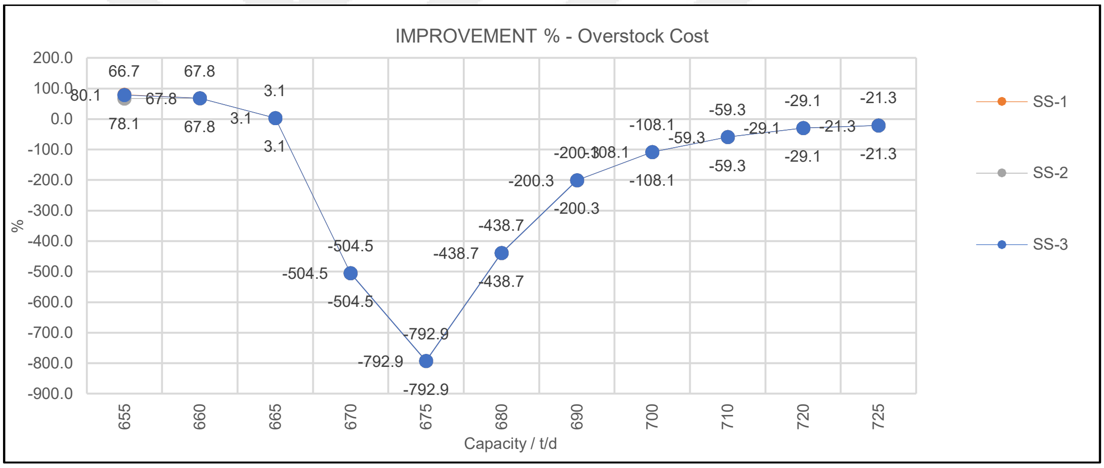


Figure 5.37 Improvement % of overstock cost

Improvement percentages of production cost, total raw material cost and total additive material cost is seen on Figure 5.38, Figure 5.39 and Figure 5.40. Best improvement rates are found by SS-1 decision, but as mentioned before SS-3 decision is made.

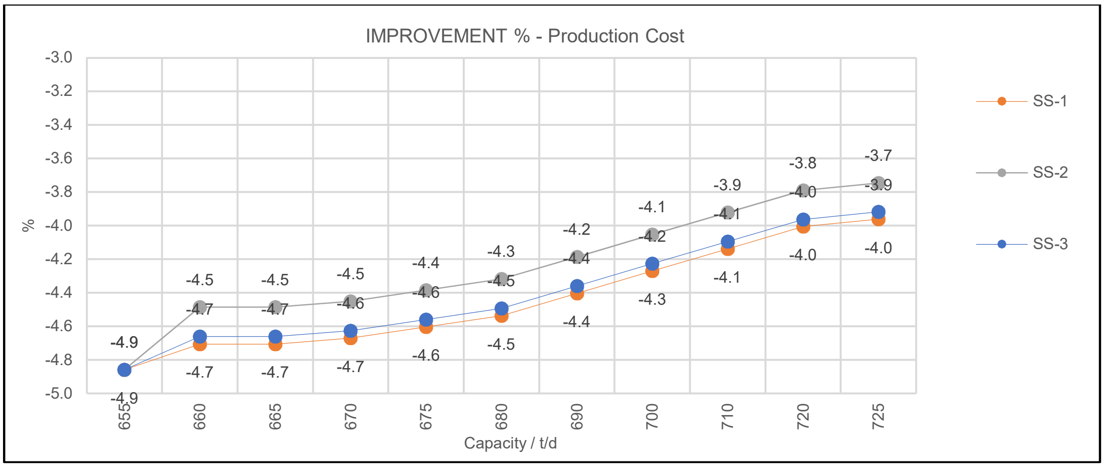


Figure 5.38 Improvement % of production cost

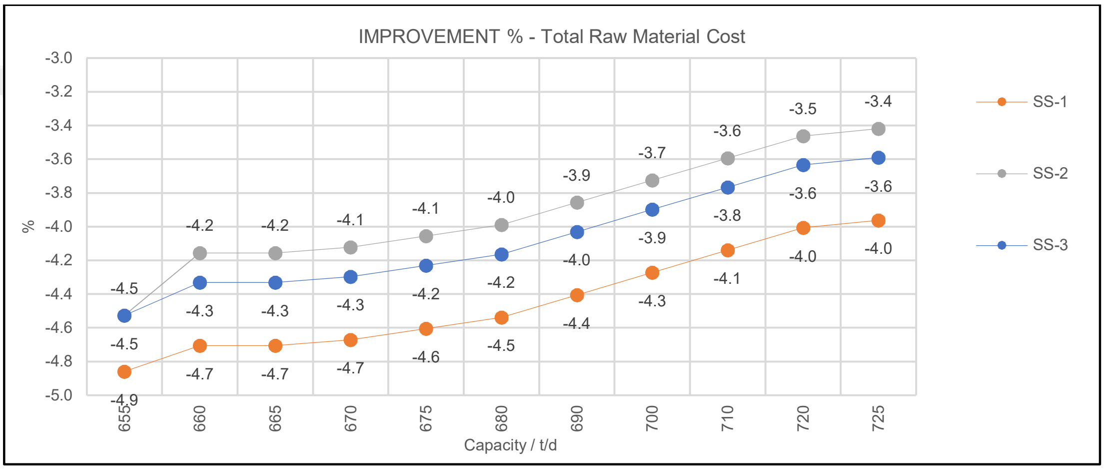


Figure 5.39 Improvement % of total raw material cost

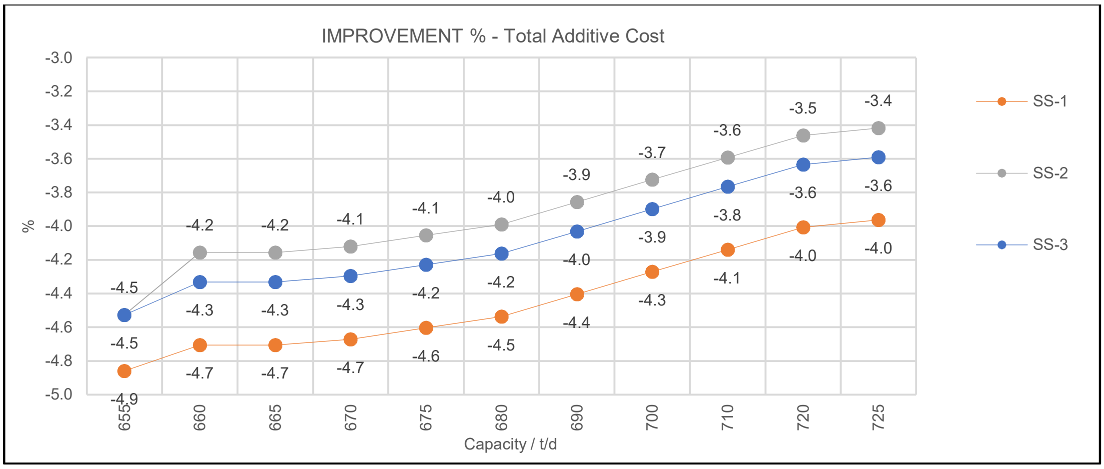


Figure 5.40 Improvement % of total additive cost

Improvement percentages of total utility cost, energy cost and energy consumption is seen on Figure 5.41, Figure 5.42 and Figure 5.43. Very high level of improvement has been achieved. Improvement rate of energy cost and energy consumption is same. Best improvement rates are found by SS-1 decision, but as mentioned before SS-3 decision is made.

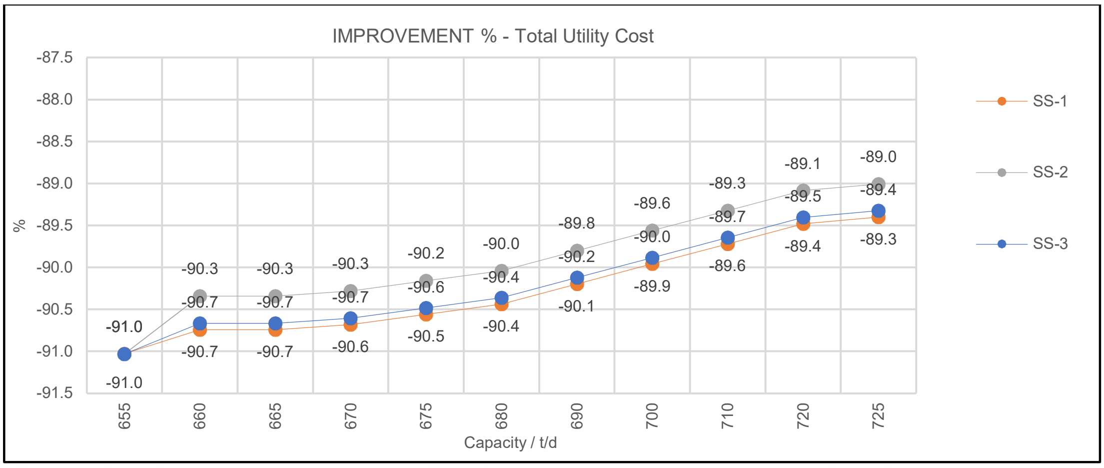


Figure 5.41 Improvement % of total utility cost

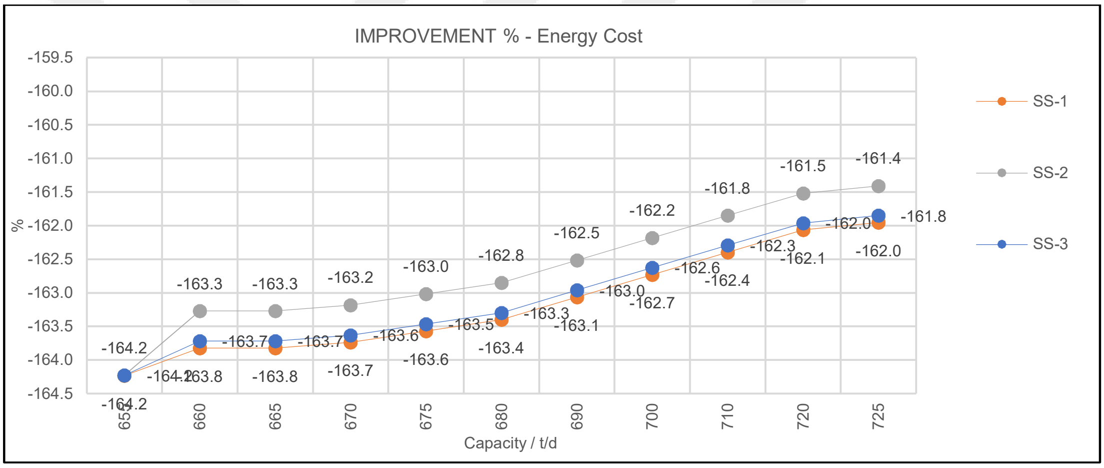


Figure 5.42 Improvement % of energy cost

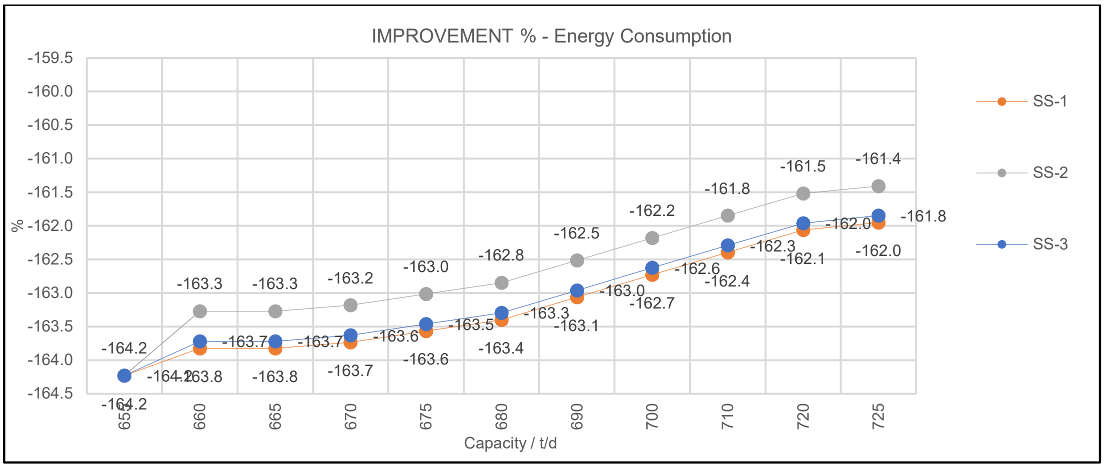


Figure 5.43 Improvement % of energy consumption

Improvement percentages of total generated carbon emission is seen on Figure 5.44. It is very similar to improvement rate of energy cost and energy consumption. Best improvement rates are found by SS-1 decision, but as mentioned before SS-3 decision is made.

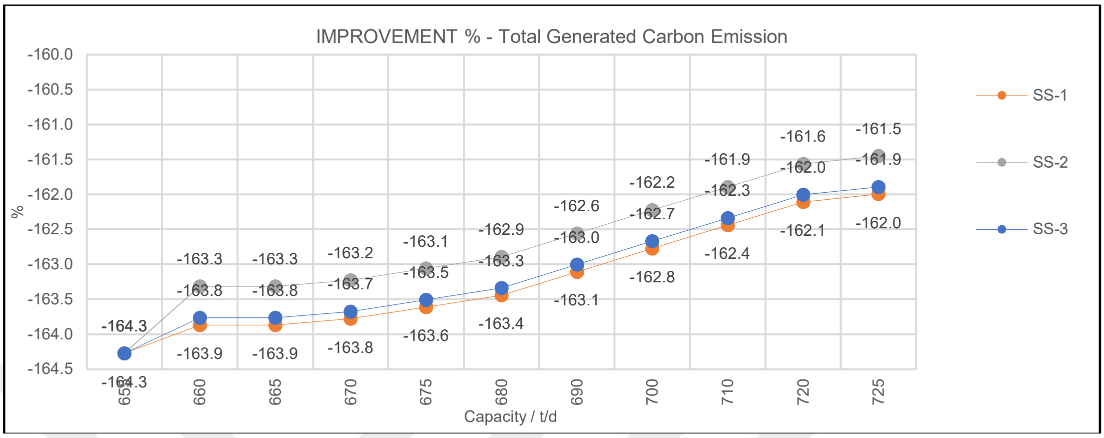


Figure 5.44 Improvement % of total generated carbon emission

Improvement percentages of inventory turnover ratio and inventory holding time is seen on Figure 5.45 and Figure 5.46. Results are very similar to results seen on Figure 5.34 and Figure 5.35. Best improvement rates are found by SS-1 decision and 675 t/d capacity, but as mentioned before SS-3 decision is made.

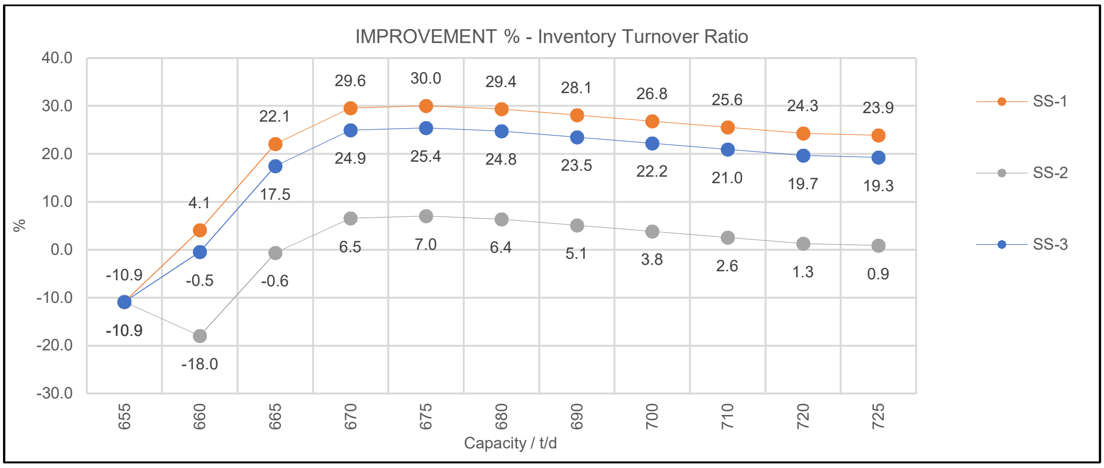


Figure 5.45 Improvement % of inventory turnover ratio

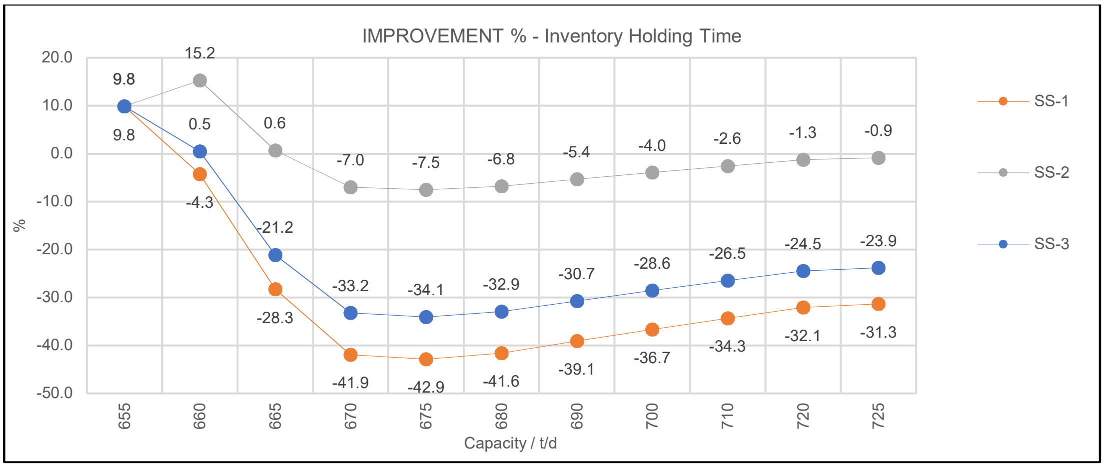


Figure 5.46 Improvement % of inventory holding time

5.1.2.3 Interactions Between Improvements by Different Models

Eight type of models which best results obtained from are evaluated in this section. Forecasted demand data and real demand data used as demand data. Both energy resources together or only natural gas is used as energy resource. Safety stock decision-0 and safety stock decision-3 is used for inventory policy. Different kind of parameters are evaluated.

At first the most important values are analyzed. Improvement rate of objective function (profit) value by different models is seen on Figure 5.47. This value is higher on models without safety stock. But safety stock decision is made as using SS-3 alternative.

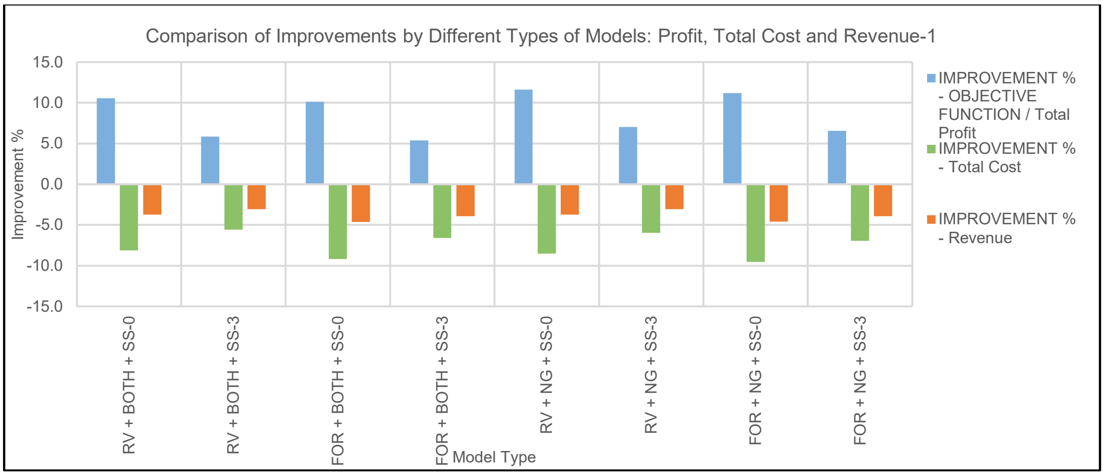


Figure 5.47 Improvements by different models: profit, total cost and revenue-1

Only models using natural gas as energy resource and SS-3 type are examined on Figure 5.48. Improvement rate of profit of real demand value is higher than model using forecasted demand value. Because there is little difference between real demand data and forecasted demand data as can be seen from Figure 5.7. It effects also revenue, it is lower than real model.

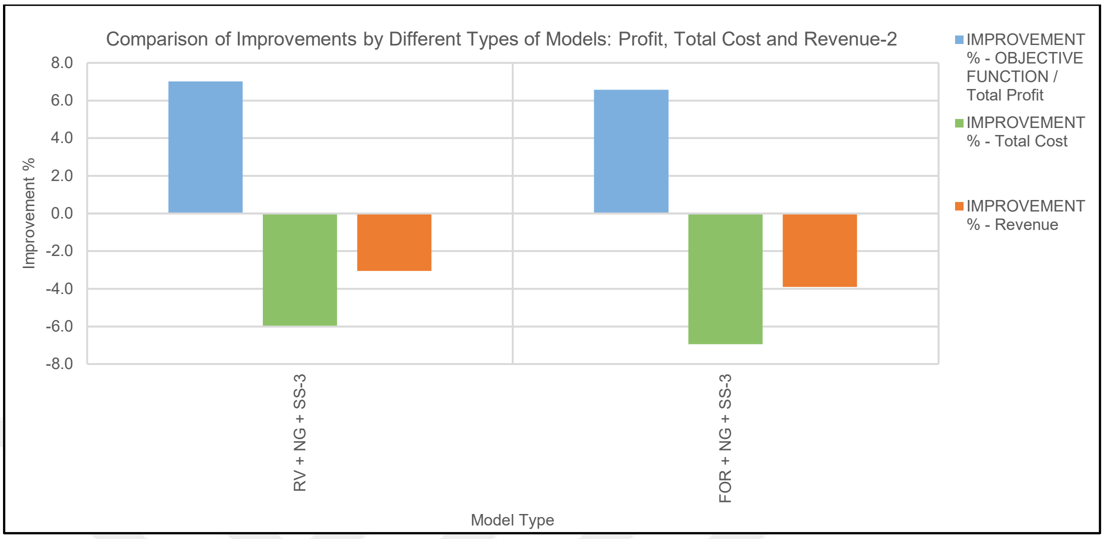


Figure 5.48 Improvements by different models: profit, total cost and revenue-2

Comparison of improvement rates of total production quantity, total number of setups and utilization rate is seen on Figure 5.49. Change of production quantity and utilization rate could be seen from primary axis, but number of setups could be seen from secondary axis. Total number of setups has dropped to a great extent with the help of optimal plan for all model types.

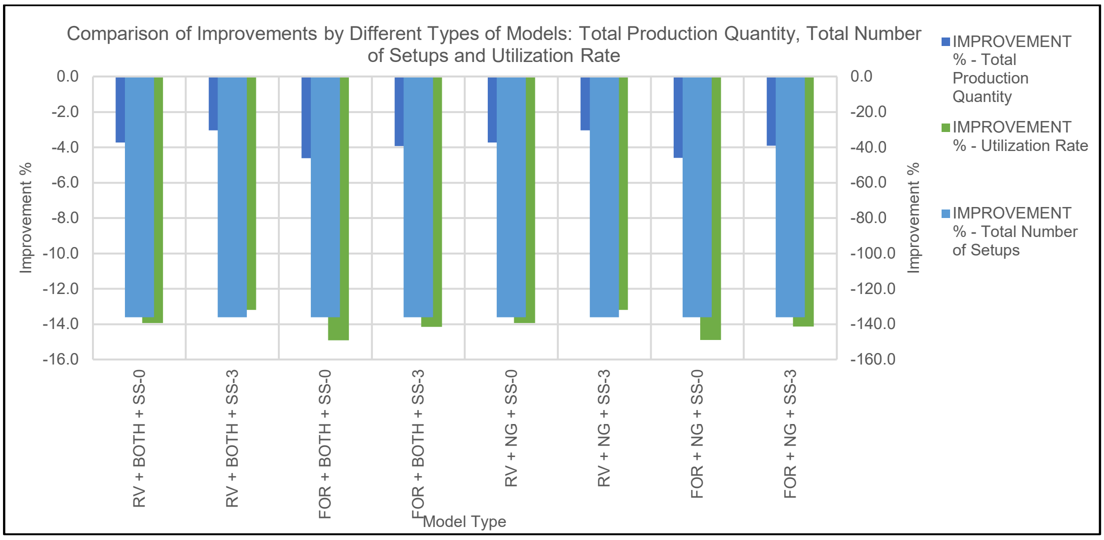


Figure 5.49 Improvements: production, number of setups and utilization rate

Comparison of improvement rates of total production quantity and utilization rate is seen on Figure 5.50. Decrease of utilization rate and production quantity is higher on SS-0 models than SS-3 models.

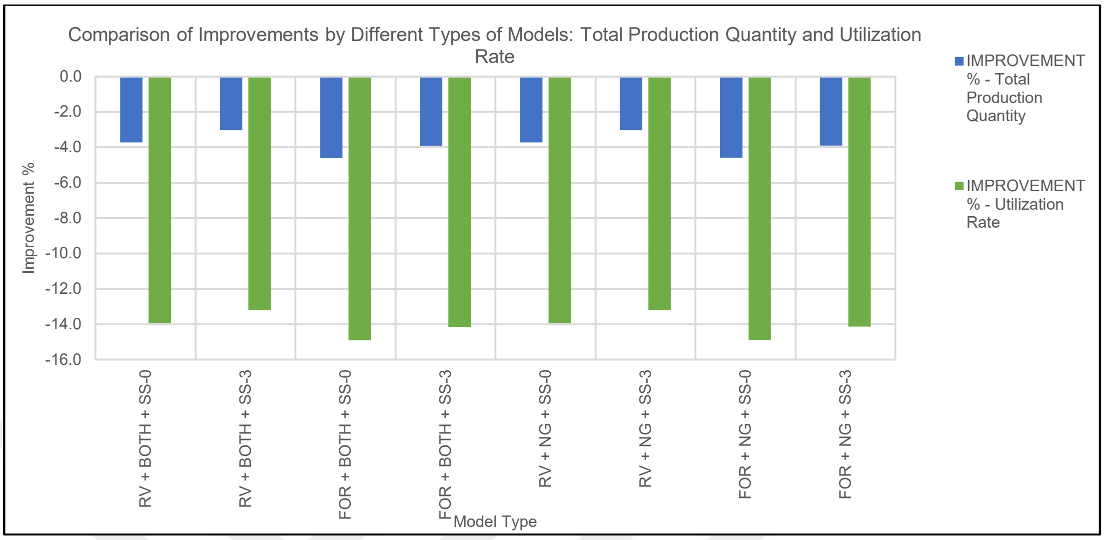


Figure 5.50 Improvements by different models: production and utilization rate

Comparison of improvement rates of total production quantity, total inventory quantity and total overstock quantity is seen on Figure 5.51. Decrease of production quantity, inventory quantity and overstock quantity is higher on SS-0 models than SS-3 models.

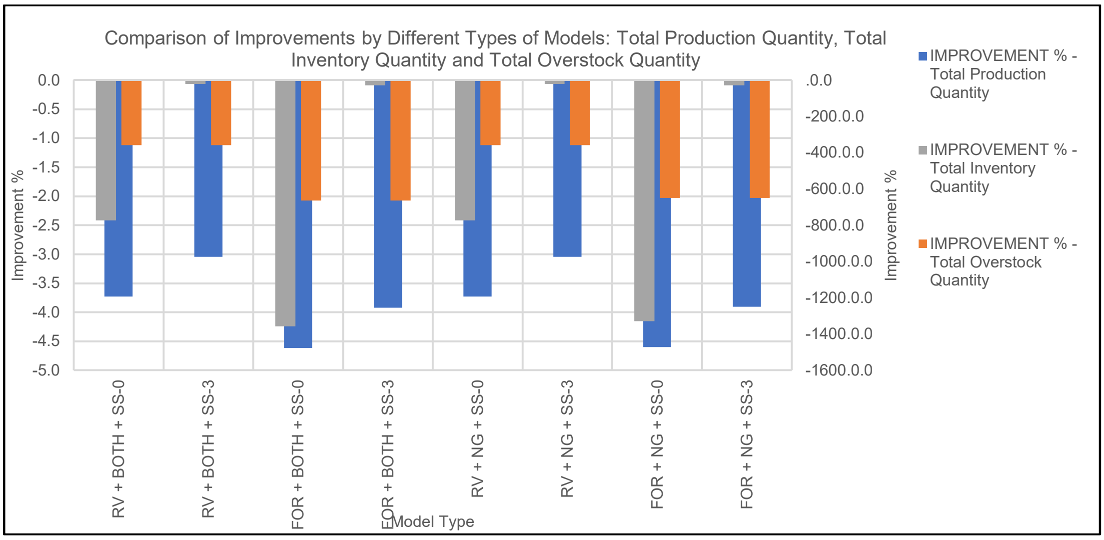


Figure 5.51 Improvements: production, inventory and overstock

Comparison of improvement rates of various cost types is seen on Figure 5.52, Figure 5.53 and Figure 5.54. The most remarkable achievements is seen on setup cost and total utility cost. Improvement rate obtained from results on production and material costs (raw and additive) is more modest than utility and setup cost. All type of costs reduced except of overstock cost. It increases in some cases using SS-0 and SS-3 decisions. Decrease of types of cost is generally higher on SS-0 models than SS-3 models.

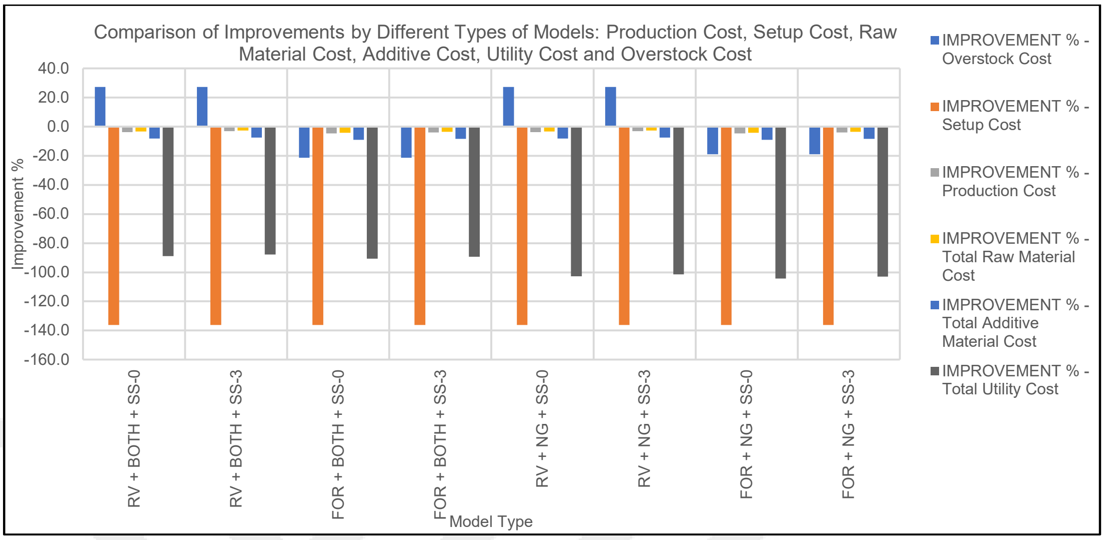


Figure 5.52 Improvements by different models: costs-1

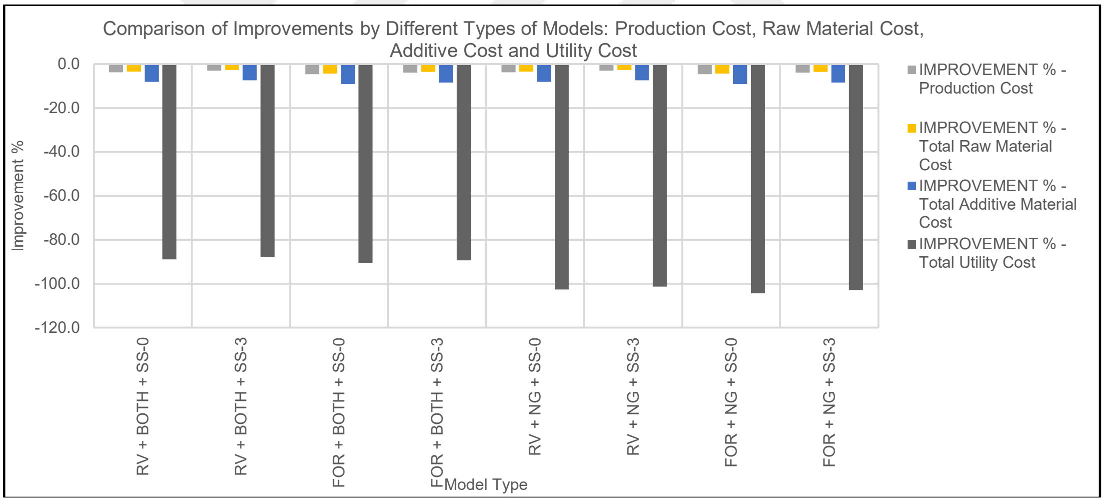


Figure 5.53 Improvements by different models: costs-2

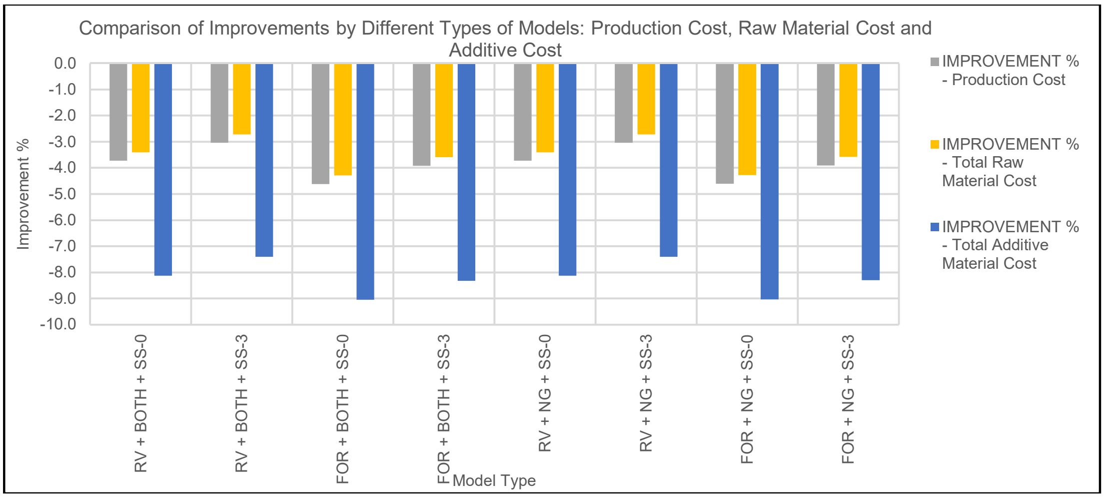


Figure 5.54 Improvements by different models: costs-3

Comparison of improvement rates of total utility cost and energy cost is seen on Figure 5.55. The cost of utility decreases dramatically, but the cost of energy included in the cost of utility falls considerably. Decrease of utility cost and energy cost is higher on models using natural gas as energy resource. Decrease of different types of cost is generally higher on SS-0 models than SS-3 models.

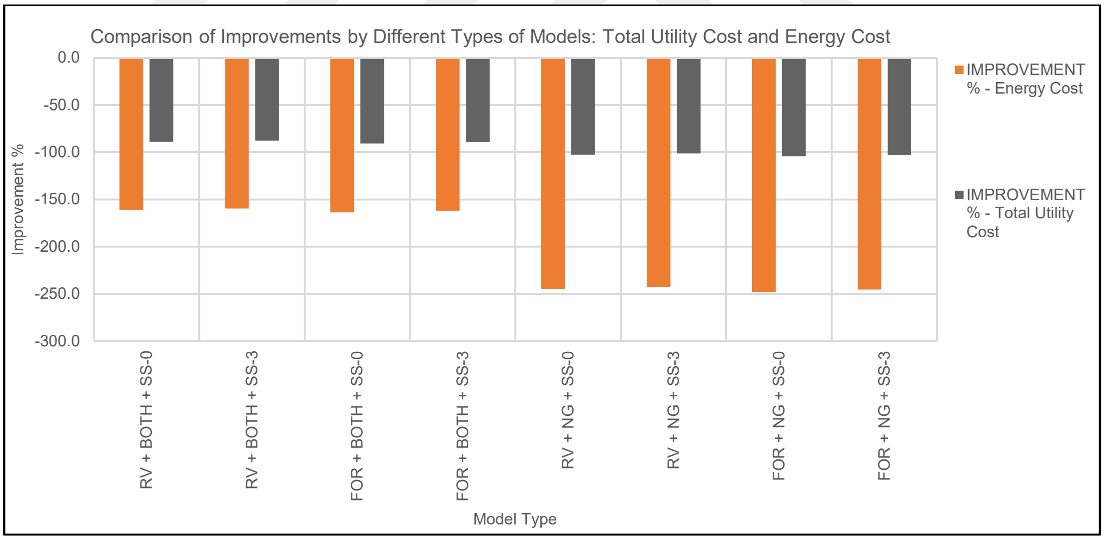


Figure 5.55 Improvements by different models: costs-4

Comparison of improvement rates of energy cost, energy consumption and total generated carbon emission is seen on Figure 5.56. Carbon emission is seen single on Figure 5.57. Models using SS-3 are chosen for evaluation. Decrease of energy cost, energy consumption and total generated carbon emission is almost same and it is higher on models using natural gas as energy resource. The results are striking, decrease of energy cost, energy consumption and total generated carbon emission is very high even both energy resource is used in model.

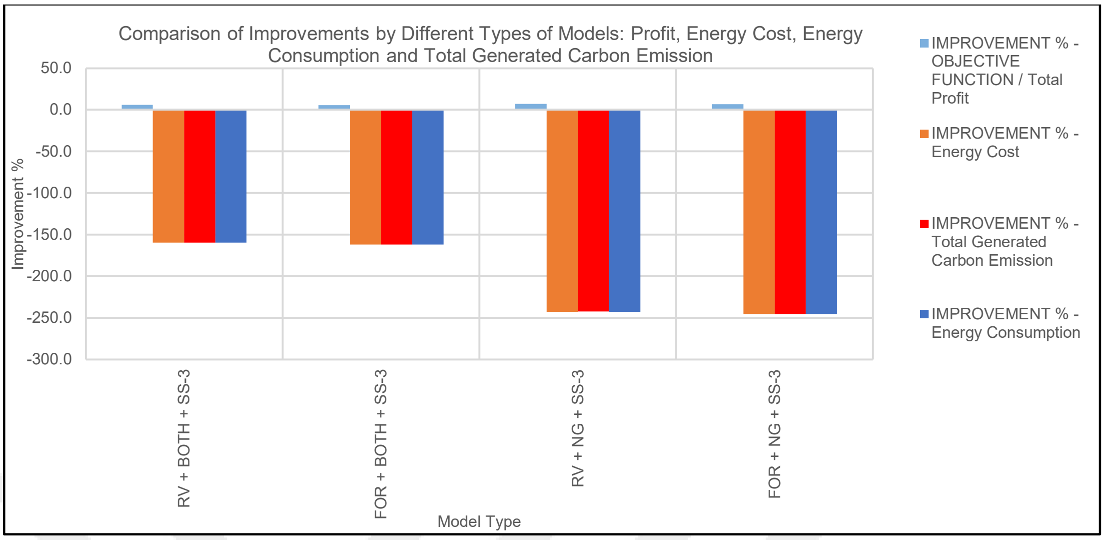


Figure 5.56 Improvements: energy cost, energy consumption and carbon emission

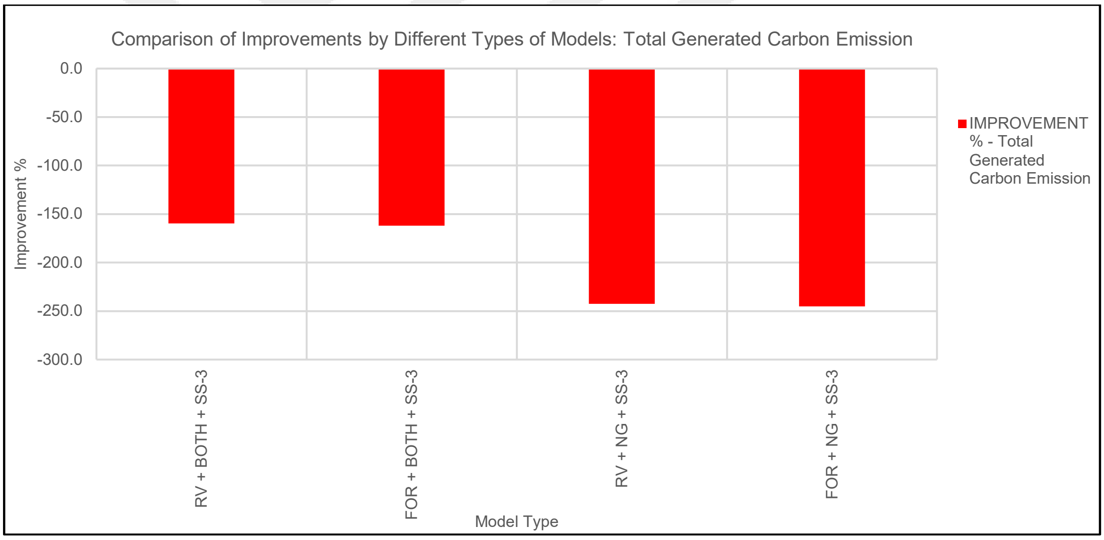


Figure 5.57 Improvements by different models: total generated carbon emission

Comparison of improvement rates of inventory turnover ratio for total production and for product grades separately is seen on Figure 5.58 and Figure 5.59. Results of all models are seen on Figure 5.58 and results for only models with safety stock (SS-3 decision) is seen on Figure 5.59. There is no improvement of inventory turnover ratio of product grade j2 and product grade j3 for models without safety stock (SS-0 decision). However improvement rate of inventory turnover ratio of product grade j1 and total production quantity (as an effect of product grade j1) for models without safety stock is much higher than models with safety stock.

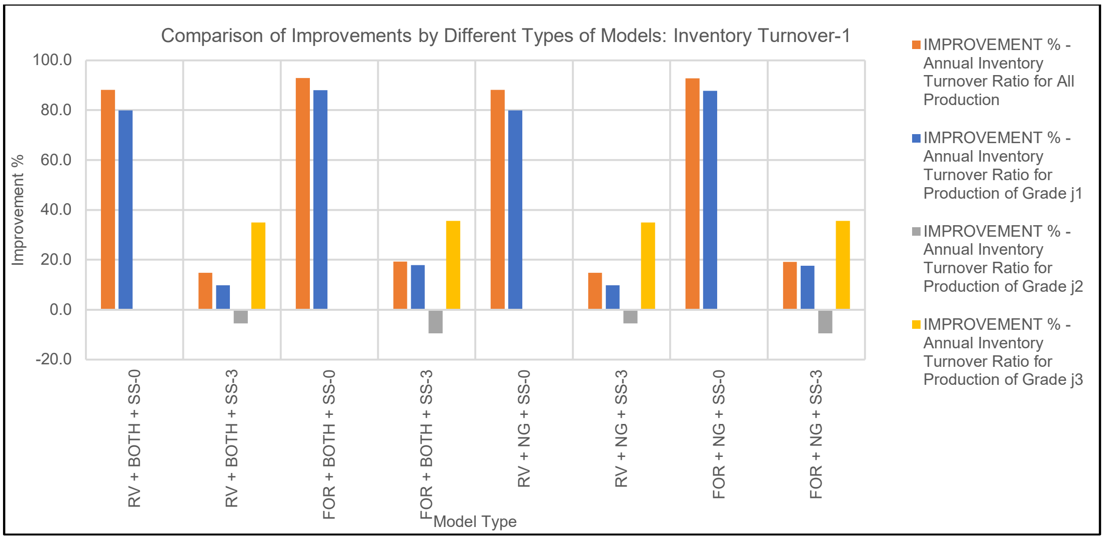


Figure 5.58 Improvements by different models: inventory turnover-1

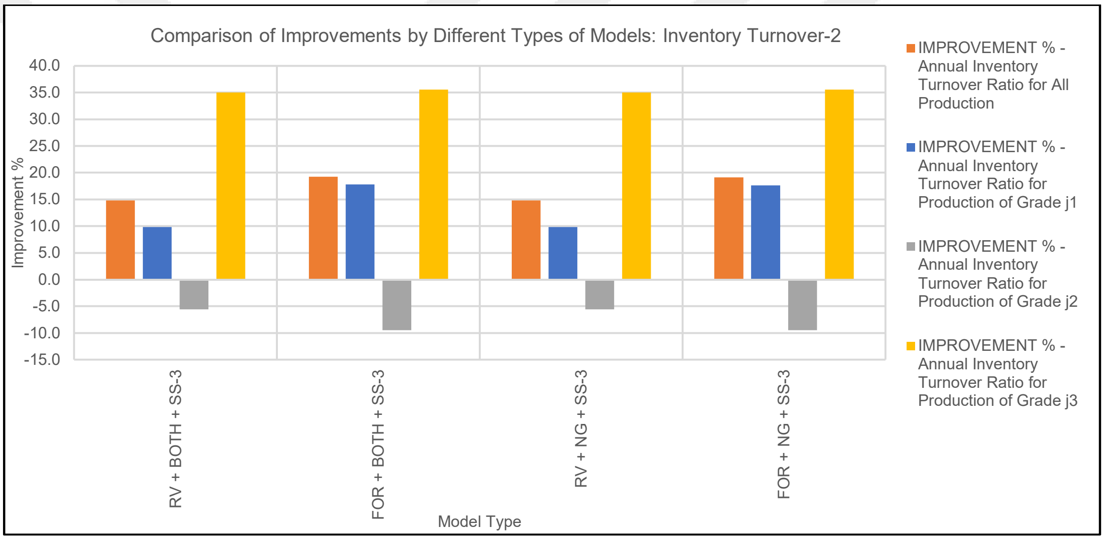


Figure 5.59 Improvements by different models: inventory turnover-2

Comparison of improvement rates of inventory turnover ratio for all product grades is seen on Figure 5.60, Figure 5.61 and Figure 5.62. Inventory turnover ratio of product grades significantly increased except of product grade j2. Rate of rise is higher on models using forecasted demand data. Decrease for product grade j2 is higher on models using forecasted demand data, too.

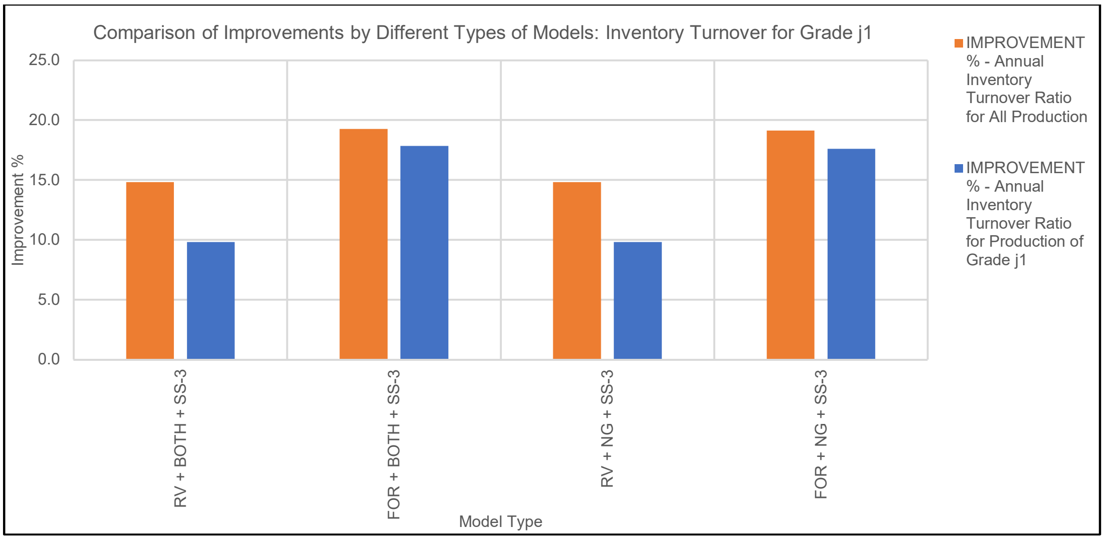


Figure 5.60 Improvements by different models: inventory turnover for j_1 grade

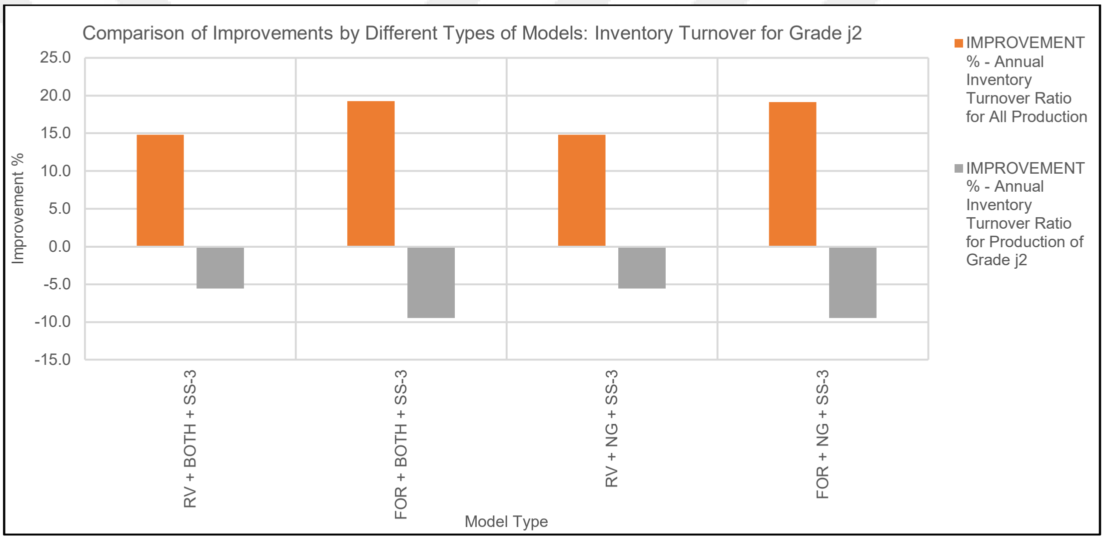


Figure 5.61 Improvements by different models: inventory turnover for j_2 grade

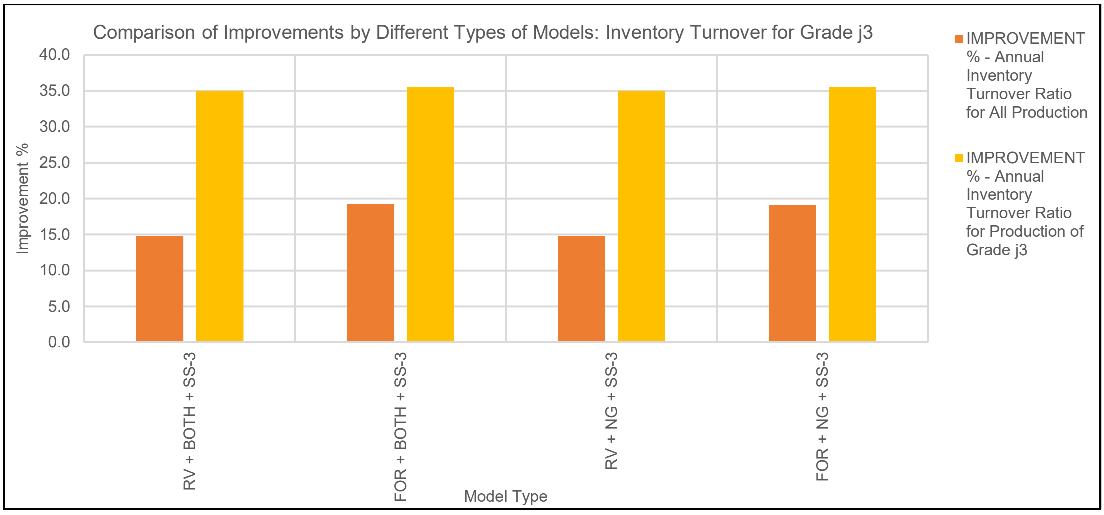


Figure 5.62 Improvements by different models: inventory turnover for j_3 grade

Comparison of improvement rates of inventory holding time for total production and for product grades separately is seen on Figure 5.63 and Figure 5.64. Results of all models are seen on Figure 5.63 and results for only models with safety stock (SS-3 decision) is seen on Figure 5.64. These graphs is very similar to Figure 5.58 and Figure 5.59 inversely, because inventory turnover ratio and inventory holding time is inversely proportional. There is not improvement rate of inventory holding time of product grade j2 and product grade j3 for models without safety stock (SS-0 decision). However improvement rate of inventory holding time of product grade j1 and total production quantity (as an effect of product grade j1) for models without safety stock is much lower than models with safety stock.

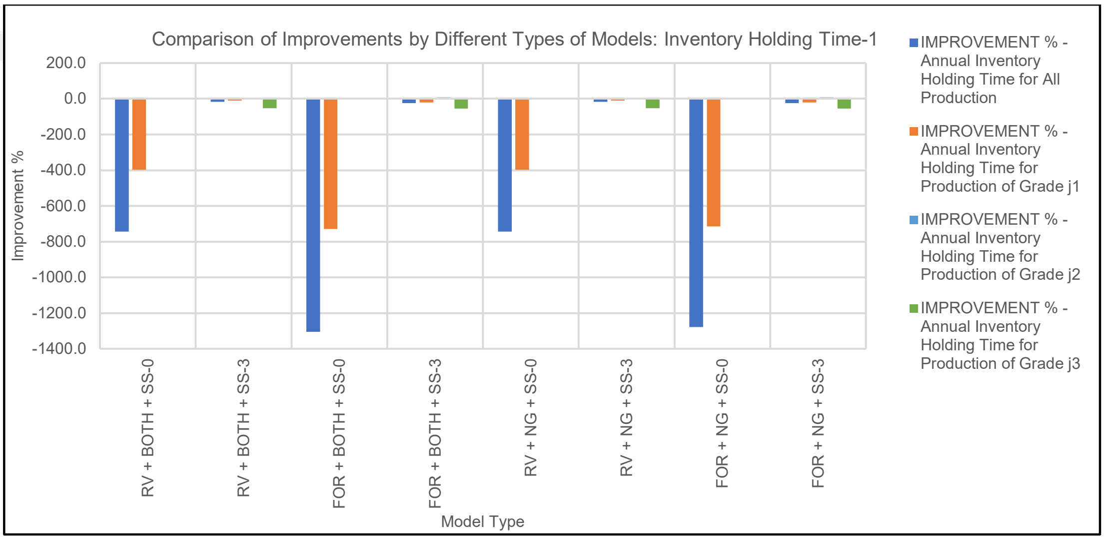


Figure 5.63 Improvements by different models: inventory holding time-1

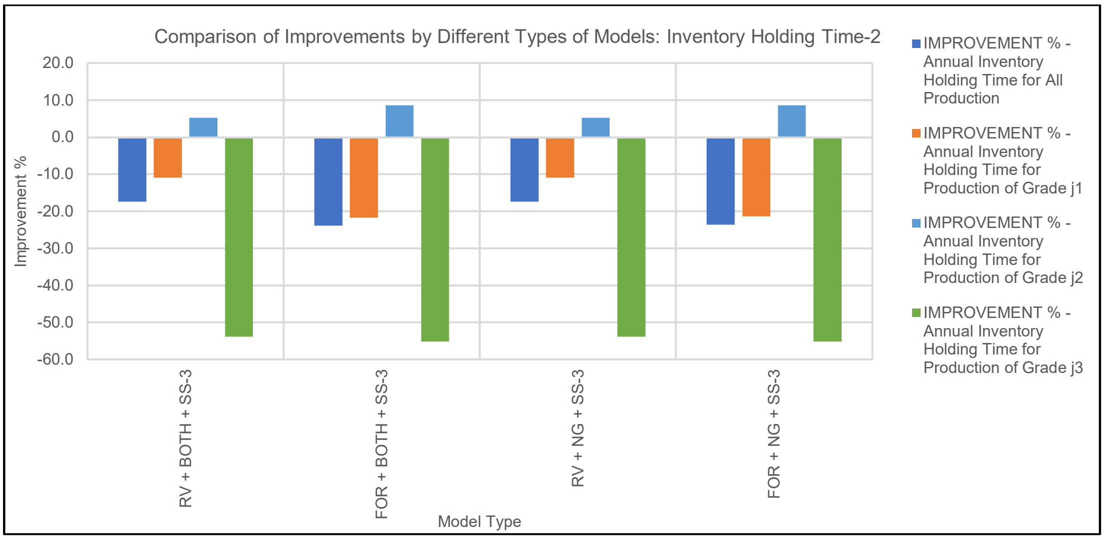


Figure 5.64 Improvements by different models: inventory holding time-2

Comparison of improvement rates of inventory holding time for all product grades is seen on Figure 5.65, Figure 5.66 and Figure 5.67. Inventory holding time of product grades significantly decreased except of product grade j2. Reduction rate is higher on models using forecasted demand data. Rate of rise for product grade j2 is higher on models using forecasted demand data, too.

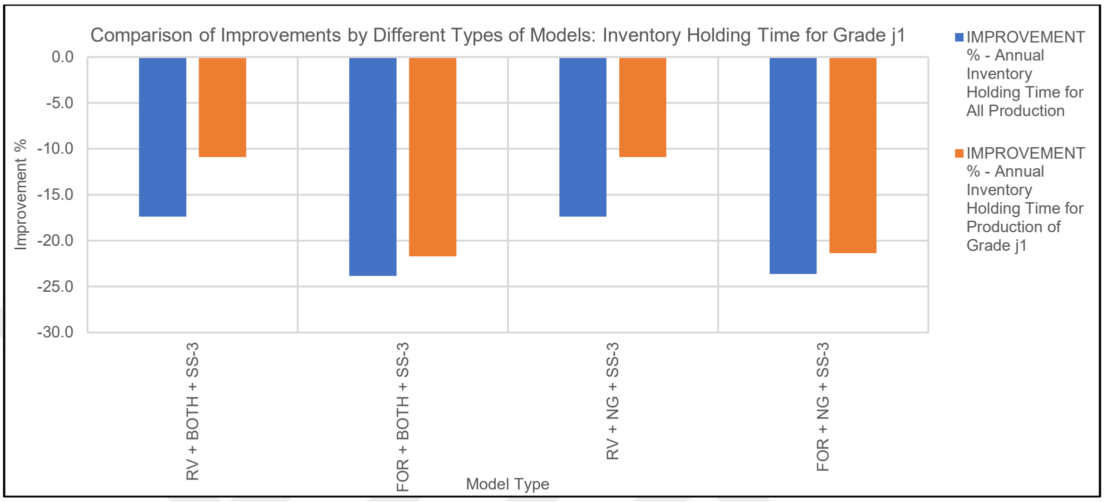


Figure 5.65 Improvements by different models: inventory holding time for j_1

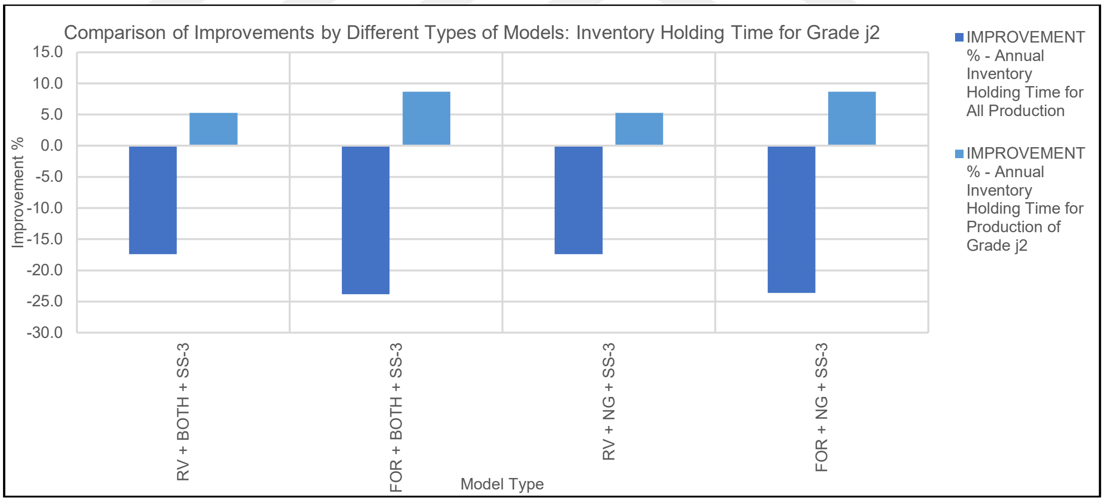


Figure 5.66 Improvements by different models: inventory holding time for j_2

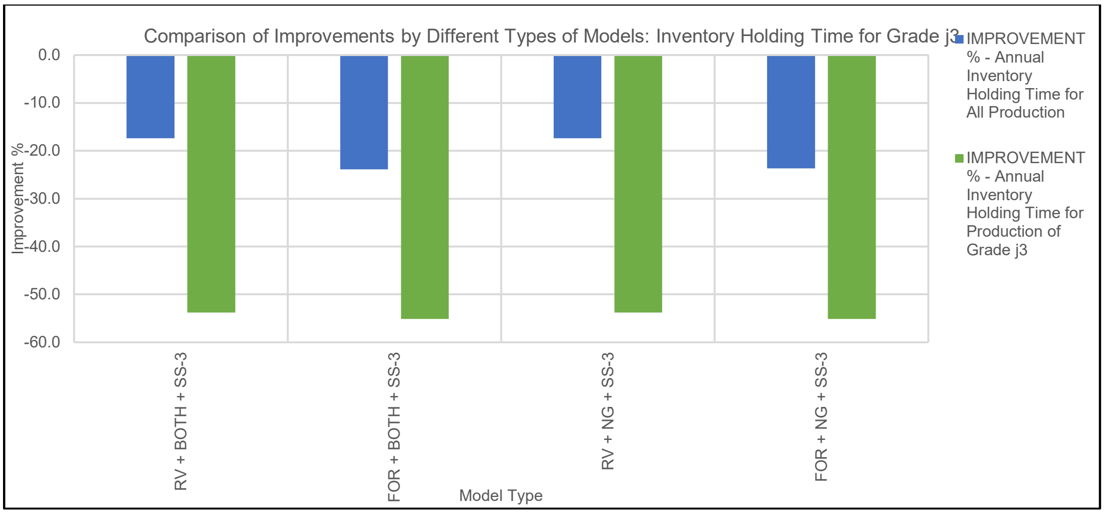


Figure 5.67 Improvements by different models: inventory holding time for j_3

5.1.3 Interpretation of Results

The results of the application of the model and the actual results were compared and significant improvements were achieved. After implementations outcomes seen on Table 5.9 could be mentioned. Model results were interpreted by averaging the two most appropriate results. Demand data is forecasted, 3rd alternative for safety stock is chosen as inventory policy and only natural gas and both natural gas and coal are used as energy resource. According these data profit increased by 6.0% and total cost reduced by 6.8%.

Comparison of real results and best optimal results with forecasted data is given on Table 5.8, 5.9 and 5.10. Total profit, total cost, total number of setups, utilization rate, total production quantity, total inventory quantity and average inventory quantity by all grades are given on Table 5.8. Costs by type and annual inventory turnover ratio by grades are given on Table 5.9. Annual inventory holding time by grade is given on Table 5.10.

Table 5.8 Real results and best optimal results with forecasted data-1

DEMAND DATA	REAL VALUES	FORECASTED VALUES: ARIMA	FORECASTED VALUES: ARIMA
ENERGY SOURCE	NATURAL GAS + COAL	NATURAL GAS	NATURAL GAS + COAL
SAFETY STOCK DECISION	SS-0	SS-3	SS-3
PRODUCTION CAPACITY POLICY / t/d	MIXED	725	725
OBJECTIVE FUNCTION / Total Profit / M $	75.6	80.9	79.9
Total Cost / M $	298.2	278.8	279.8
Revenue / M $	373.8	359.8	359.7
Total production quantity / 10^3 t	249.2	239.8	239.8
Total net inventory quantity / 10^3 t	24.8	19.34	19.30
Total average net inventory quantity / 10^3 t	2.1	1.6	1.6
Total average inventory quantity of grade j1 / 10^3 t	1.2	1.0	1.0
Total average inventory quantity of grade j2 / 10^3 t	0.3	0.3	0.3
Total average inventory quantity of grade j3 / 10^3 t	0.6	0.4	0.4
Total safety stock overstock quantity / 10^3 t	13.0	1.7	1.7
Total safety stock shortage quantity / 10^3 t	0.0	1.6	1.6
Total backlog quantity / 10^3 t	0.0	0.0	0.0
Total number of setups	85	36	36
Utilization rate average value / %	103.4	90.6	90.6
Service level average value / %	100.0	100.0	100.0

Table 5.9 Real results and best optimal results with forecasted data-2

DEMAND DATA	REAL VALUES	FORECASTED VALUES: ARIMA	FORECASTED VALUES: ARIMA
ENERGY SOURCE	NATURAL GAS + COAL	NATURAL GAS	NATURAL GAS + COAL
SAFETY STOCK DECISION	SS-0	SS-3	SS-3
PRODUCTION CAPACITY POLICY / t/d	MIXED	725	725
Safety stock overstock cost / M $	0.62	0.52	0.51
Safety stock shortage cost / M $	0.00	4.80	4.80
Backlog cost / M $	0.00	0.00	0.00
Setup cost / M $	0.01	0.00	0.00
Production cost / M $	1.25	1.20	1.20
Total raw material cost / M $	258.7	249.7	249.7
Total additive cost / M $	9.35	8.64	8.64
Utility-2 (Energy) cost / M $	10.9	3.2	4.2
Total utility cost / M $	28.3	13.9	14.9
Total generated carbon emission / t	0.06	0.02	0.02
Total demand / 10^3 t	237.4	236.5	236.5
Annual inventory turnover ratio for all production	118.7	146.8	147.0
Annual inventory turnover ratio for production of grade j1	108.6	131.8	132.2
Annual inventory turnover ratio for production of grade j2	150.1	137.1	137.1
Annual inventory turnover ratio for production of grade j3	124.8	193.6	193.6
Annual inventory holding time for all production / day	3.1	2.5	2.5

Table 5.10 Real results and best optimal results with forecasted data-3

DEMAND DATA	REAL VALUES	FORECASTED VALUES: ARIMA	FORECASTED VALUES: ARIMA
ENERGY SOURCE	NATURAL GAS + COAL	NATURAL GAS	NATURAL GAS + COAL
SAFETY STOCK DECISION	SS-0	SS-3	SS-3
PRODUCTION CAPACITY POLICY / t/d	MIXED	725	725
Annual inventory holding time for production of grade j1 / day	3.4	2.8	2.8
Annual inventory holding time for production of grade j2 / day	2.4	2.7	2.7
Annual inventory holding time for production of grade j3 / day	2.9	1.9	1.9

According to obtained results best results with forecasted demand data is given on Table 5.11 and 5.12. Some of the developments seen according to the obtained results are summarized below.

- Proposed model run with both forecasted demand data and real demand data. The best results were obtained from real data. Though it is impossible to know future demand, so forecasted demand is used for model run. Profit increased by 6.0% and total cost reduced by 6.8%.

- Best results are found by natural gas for cost and emission quantities in terms of use of energy source. Coal is the worst alternative for both economic and environmental views.

- Best results are found in the case of without safety stock on inventory policy. But as a result of possible demand fluctuation or production problems a certain degree of safety stock must be kept. Total net inventory quantity reduction rate is 28.4%. Inventory overstock (safety stock overstock) quantity reduction rate is 656.6%.

- Capacity is chosen as much as possible (725 t/d) in order to reduce utilization rate. When looking real results for 2017 year, utilization rate is calculated as 103.4% due to low value of maximum capacity (660 t/d) and higher production quantity than expected maximum production. Utilization rate is one of the key factors of production.

When it increases, production efficiency increases. However utilization rate must be lower than %100 to keep better production conditions and handle immediate demands properly. Efficient capacity utilization is one of the expected results of optimal production plan. Total production quantity reduction rate is 3.9%. Utilization reduction rate is 14.1%. Total number of setups reduction rate is 136.1% for both models without safety stock and models with safety stock.

- Service level rate is not changed according to optimal results. Service level is assumed as 100% consistent with real data of 2017, because there is not any backlog situation known.

- Production cost reduction rate is 3.9%. Setup cost reduction rate is 136.1% for both models without safety stock and models with safety stock. Total raw material cost reduction rate is 3.6%. Total additive material cost reduction rate is 8.3%. Total utility resource cost reduction rate is 96.2%. It can be said that the implementation of the model is beneficial in terms of cost reduction especially for setup cost and utility cost.

- In environmental view of aspect, carbon emission generation is compared between real data and optimal data. Emission generation reduction rate is 203.6%.

- There are many metrics used in industry, but most important ones for PET resin production process are chosen and evaluated. Inventory turnover ratio, inventory holding time, utilization rate and service level rate are used in model. These metrics are calculated after optimal run.

Annual inventory turnover ratio increment rate is 19.2%. Annual inventory holding time reduction rate is 23.7%. Annual inventory turnover ratio for grade j_1 production increment rate is 17.7%. Annual inventory turnover ratio for grade j_2 production reduction rate is 9.5%. Annual inventory turnover ratio for grade j_3 production increment rate is 35.5%. Annual inventory turnover ratio is decreased for grade j_2. It means that optimal model is not successful on inventory turnover ratio of grade j_2. Annual inventory holding time for grade j_1 production reduction rate is 21.5%. Annual inventory holding time for grade j_2 production increment rate is 8.7%. Annual inventory holding time for grade j_3 production reduction rate is 55.1%. According to these results better outcomes were obtained with the help of inventory policy except of production grade j_2.

Table 5.11 Best results with forecasted demand data-1

ENERGY RESOURCE	NATURAL GAS	NATURAL GAS + COAL
SAFETY STOCK DECISION	SS-3	SS-3
PRODUCTION CAPACITY POLICY / t/d	725	725
OBJECTIVE FUNCTION / Total Profit	6.6	5.4
Total Cost	-6.9	-6.6
Revenue	-3.9	-3.9
Total production quantity	-3.9	-3.9
Total net inventory quantity	-28.3	-28.5
Total average inventory quantity	-28.2	-28.4
Total safety stock overstock quantity	-649.4	-663.9
Total number of setups	-136.1	-136.1
Utilization rate average value	-14.1	-14.1
Safety stock overstock cost	-19.0	-21.3
Setup cost	-136.1	-136.1
Production cost	-3.9	-3.9
Total raw material cost	-3.6	-3.6
Total additive cost	-8.3	-8.3
Utility-2 (Energy) cost	-245.4	-161.8

Table 5.12 Best results with forecasted demand data-2

ENERGY RESOURCE	NATURAL GAS	NATURAL GAS + COAL
SAFETY STOCK DECISION	SS-3	SS-3
PRODUCTION CAPACITY POLICY / t/d	725	725
Total utility cost	-103.0	-89.3
Total generated carbon emission	-245.2	-161.9
Annual inventory turnover ratio for all production	19.1	19.3
Annual inventory holding time for all production	-23.6	-23.9

CHAPTER VI

CONCLUSIONS, SUGGESTIONS AND FURTHER STUDIES

6.1 Conclusions

This study could be defined as an implementation of a basic production planning model to one of the bottle grade PET manufacturers in Turkey considering sustainability and lean principles. During this process, model was revised many times to approach real values closer. Then it is designed for different cases to see which condition is better for long term planning. Furthermore improvements are evaluated to get trustworthy point of view for correcting weak points in current and optimized horizon.

Some improvements obtained could be summarized as below:

- The objective of model is to maximize profit. Profit increased by 6.0% and total cost reduced by 6.8% according to results obtained.

- Cost types of model consists of production cost, setup cost, overstock cost, shortage cost, backlog cost, raw material cost (raw material and additive material) and utility cost. These are could be separated to three parts basically: production cost (production cost and setup cost), inventory cost (overstock cost, shortage cost, backlog cost) and material cost (raw material, additive material and utility cost). According to the data of 2017 of production facility where the study is made material cost has biggest share followed by production cost. Share of inventory cost is smallest. Cost share of material cost is 99.4%, cost share of production cost is 0.4% and cost share of inventory cost is 0.2%. Even if contribution to total cost is very less production cost (especially setup cost) is reduced with a great pace. Energy cost which cost share of total cost by 3.7% according to 2017 data is following setup cost on cost reduction.

- Production cost reduction rate is 3.9%. Setup cost reduction rate is 136.1% for both models without safety stock and models with safety stock. Total raw material cost reduction rate is 3.6%. Total additive material cost reduction rate is 8.3%. Total utility resource cost reduction rate is 96.2%. It can be said that the implementation of the model is beneficial in terms of cost reduction especially for setup cost and utility cost.

- Results obtained from model prove that optimal production plans is useful for not only economic objectives but also environmental approaches. It could be possible when production plan is integrated with lean principles and sustainability. That kind of integration is on basic level in model. However visible improvements obtained from model owing to optimal planning. Energy consumption, quantity of generated carbon emission and energy cost decreased significantly and it was the direct effect of plan. Total production quantity is reduced consequently excess production is minimized and these are the indirect effects of the plan. The importance of the energy source is also very great to carry out that kind of production plan. There are three alternatives for energy source. Best option is natural gas owing to least emission generation and cheapest price in terms of use of energy source. Coal is the worst alternative for both economic and environmental views. Energy consumption, energy cost and quantity of generated carbon emission reduction rate is 203.6%.

- Operation with high capacity is more advantageous than low capacity. Because demand fluctuations can be handled better and inventory storage is reduced with that strategy. Additionally utilization rate could be decreased to have a margin for controlling immediate production orders. Capacity is chosen as much as possible (725 t/d) in order to reduce utilization rate. Efficient capacity utilization is one of the expected results of optimal production plan. Total production quantity reduction rate is 3.9%. Utilization reduction rate is 14.1%. It reduces from 103.4% to 90.6%. Reduction rate of total number of setups is 136.1% for both models without safety stock and models with safety stock.

- Forecasting demand is not easy but it is very essential to keep proper planning policy, so forecasts must be done regularly and forecast accuracy must be controlled to verify the method. During modeling, ARIMA method was used because this method produced more accurate results.

- There is a tradeoff between expected service level by safety stocks and inventory holding cost. An optimal inventory policy was modeled to balance lean production principles and market requirements. Third alternative for safety stock is chosen for inventory policy because expected consumer service level is obtained with more flexible way. According to the results obtained, even if there is a certain quantity of stock in every period, inventory turnover ratio increased and inventory holding time reduced. It can be said that inventory policy used for model is successful except of product grade j_2. Annual inventory turnover ratio increment rate is 19.2% and annual inventory holding time reduction rate is 23.7%. Total net inventory quantity reduction rate is 28.4% and inventory overstock quantity reduction rate is 656.6%.

With the help of this study, the production plan for a PET resin plant is optimized along with forecasted demand. To the best of our knowledge, there is not sufficient research about this area, so it could be helpful for other PET resin production plants.

6.2 Suggestions and Further Studies

- Visible improvements obtained from model by optimal plan on important points like carbon emission and energy consumption. However integration of production plan to lean principles and sustainability is on basic level. As mentioned before concept of triple bottom line sets out the objectives of sustainable production and it consists of economic, environmental and social dimensions. These principles must be considered for production planning models for future works.

- Model focuses on basic relations between resources and products on a plant basis. Integrated supply chain mechanism could be added, so problem scope could be more realistic. This kind of model could include different production sites. Besides this, effect of logistic opearations could be considered.

- Interactions between obtained results is examined on Chapter V. Some interesting results are found. One of these findings is about profit rate. According to Figure 5.17 profit value increases regularly by increasing capacity. However, it becomes almost constant after production capacity reaches 670 t/d. One of the reasons may be demand reaches its saturation point on this value. Other interesting finding is about inventory turnover ratio. It is also related with inventory holding time, net inventory quantity and inventory shortage quantity. According to Figure 5.17

inventory turnover ratio increases after production capacity reaches 655 t/d capacity and decreases after production capacity reaches 675 t/d. According to Figures 5.19 and 5.20 (inventory turnover ratio of product grade j_2 and j_3) inventory turnover ratio reaches its peak value when production capacity reaches to a certain point (660 t/d for product grade j_2 and 670 t/d for product grade j_3) and becomes constant during regular capacity increase. Such interesting results can be examined in later studies.

- Environmental issues and new industrial development (as known as generally ‘Industry 4.0’) is main emerging topics for recent years. Emission is assessed in model principally, but additionally some other aspects of environment can be mentioned. Recycling is one of these aspects. There is not recycling line on most of PET production plants in the world for now, but especially in developed countries (EU countries, USA, Japan etc.) recycling is becoming a necessity for PET production. New planning models must include recycling facilities consistent with their production processes.

- Automation systems are densely used currently in plant, as a result of this production process is mostly based on these systems and manpower is not directly used. Owing to automation systems, philosophy of plant production is very near to ‘Industry 4.0’ idea. Nonetheless new designs could be done along with developing technology in chemical industry, so new and more complex models must be set to handle actual needs.

- Model is designed as an extension of CLSP problem type. Because there is limited quantity of resource and production horizon is long, one period is equivalent to one month. In some parts other kind of lot sizing problems (for example discrete lot sizing problem etc.) could be modeled. Nonetheless it is a hard decision, because time scope could be changed (one period is equivalent to days or hours). Additionally some other aspects could be modified.

- In recent years some general frameworks and algorithms (genetic algorithm, tabu search etc.) became more popular. This is not only about their practicality, but also for their performance on most optimization problems. These kind of logic ways could be used for more complex problems.

- Production demand is main determinant on inventory equation. In model it is assumed as fixed. On the other hand in actuality, stochastic demand is more realistic and more reliable. New planning models could include demand (and if suitable some other parameters like costs etc.) as stochastic parameter.

- Unit material costs and production prices assumed as fixed, and there is not any dynamic effect (inflation, rate fluctuation etc.) when calculating them. New planning model could comprise such economic considerations.

- Model is designed as 'single level' lot sizing problem. It means that there is not any intermediate section to continue production: Production is done by one section. It is valid for that bottle grade PET production plant obviously, but model must be developed for more complicated production processes.

- Different optimization methods could be used for future studies. Multiobjective optimization or goal programming is one of these ways. In traditional structure, objectives of optimization is usually consists of minimizing total cost or maximize to profit. On the other hand as time goes on, indicators (called key performance indicators) or key success factors need to be evaluated by enterprises. For all these reasons multiobjective optimization or goal programming can be used.

- Extension on multiple and parallel machines is not used in model. PET resin production process consists of more than one equipment in main production line normally. Moreover capacity expansion plans could include increment of number of equipment and number of production lines, so in future that kind of extensions can be done.

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