OPTIMAL SELECTION OF TECHNICIANS IN FIELD SERVICES OF A WHITE GOODS MANUFACTURER

by

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ABSTRACT

OPTIMAL SELECTION OF TECHNICIANS IN FIELD SERVICES OF A WHITE GOODS MANUFACTURER

Field Service Management is a complex system composed of multiple interacting factors that must be coordinated to make the best use of limited resources. As a result, field service managers often face conflicting objectives, such as maintaining high-quality customer service while ensuring profitability. Thus, the aim of this thesis is to develop a mathematical optimization model that incorporates real-life factors to improve the efficiency and effectiveness of field service management.

A mixed integer linear programming model is developed to assist field service operations based on key principles of field service management, with the goal of maximizing the profit under labor and sale restriction. Moreover, two alternative scenarios are developed to provide field service managers with a clear action plan under varying conditions. These scenarios consider dynamics such as increases in transaction volume and the introduction of new product to customers, and accordingly, the mathematical model presented in the first section is adapted to reflect these changes.

The model determines the optimal number of installation and repair technicians assigned to each skill level to maximize profit, considering factors such as technician costs, complaint rates, and workforce capacity. According to the results, the model allocates the number of technicians at different skill levels for installation and repair separately. The results reveal that installation technicians contribute higher revenues, whereas repair technicians account for the majority of costs for complaint-related activities.

ÖZET

BEYAZ EŞYA ÜRETİCİSİ FİRMANIN YETKİLİ SERVİS TEKNİSYENLERİNİN OPTİMUM SEÇİMİ

Saha hizmetleri yöneticileri, sınırlı kaynakların en iyi şekilde kullanılması için koordine edilmesi gereken, birbiriyle etkileşim halindeki birçok etmenden oluşan karmaşık bir sistemdir. Sonuç olarak, saha servis yöneticileri genellikle kârlılığı korurken yüksek kaliteli müşteri hizmeti sunmak gibi birbiriyle çelişen hedeflerle karşı karşıya kalırlar. Bu nedenle, bu tezin amacı, saha hizmetleri yönetiminin verimliliğini ve etkinliğini artırmak için gerçek yaşam etmenlerini içeren bir matematiksel optimizasyon modeli geliştirmektir.

Saha hizmetleri yönetiminin temel ilkelerine dayalı olarak saha operasyonlarını desteklemek ve kârı işgücü ve satış kısıtlamaları altında enbüyüklemek amacıyla, bir karmaşık tamsayılı doğrusal programlama gösterimi geliştirilmiştir. Ayrıca, saha hizmetleri yöneticilerine değişen koşullar altında uygulanabilir bir eylem planı sunabilmek amacıyla iki alternatif senaryo tasarlanmıştır. Bu senaryolar; işlem hacmindeki artışlar ve müşterilere yeni ürünlerin sunulması gibi değişimleri göz önüne almakta olup, bu doğrultuda ilk bölümde sunulan matematiksel model söz konusu değişken koşulları yansıtacak şekilde yeniden yapılandırılmıştır.

Model, teknisyen maliyetleri, şikayet oranları ve iş gücü kapasitesi gibi etmenleri göz önünde bulundurarak, kârı en üst düzeye çıkarmak için her beceri seviyesine atanacak optimum kurulum ve onarım teknisyeni sayısını belirler. Sonuçlara göre, model farklı beceri seviyelerindeki teknisyen sayısını montaj ve onarım için ayrı ayrı tahsis eder. Sonuçlar, montaj teknisyenlerinin daha yüksek gelir sağladığını, onarım teknisyenlerinin ise şikayet maliyetlerinin çoğunu karşıladığını ortaya koymaktadır.

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LIST OF SYMBOLS

A_s	The minimum number of repair technicians by s skill in period n
a_{sn}	The number of installation jobs that can be completed by skill s in period n
b_{sn}	The number of repair jobs that can be completed by s skill in period n
c_s	Cost of an installation technician with skill type s, per period
c_s^{fail}	The cost of unsuccessful repair job by s skill
c_r^i	Distribution of jobs in region r in work type i
cr_i	The cost of technician repair jobs by s skill in period n
cr_r^i	Distribution of complaints in region r in work type i
$cratio_n$	Complaint ratio for region r in period n
D_i	Manpower coefficient
d_r^i	Distribution of job i in region r
d_s^{save}	The revenue of successful repair job by s skill
e_s^{suc}	The probability of successful repair by s skill in period n
$fcost_n$	Total penalty cost in period n
I^{max}	The maximum number of installation technician in period n
i	Index for technician job type ($i = 1$: installation, $i = 2$: repair)
$k_{sp'n}$	Number of product type p' can be sold by a repair technician with skill level s in period n
M_n	The total number of installation jobs in period n
N	The total number of periods in months
n	Time period index, in months
$Overf_{rn}$	Excess complaint rate for region r in period n
P	The total number of product types for technicians
p'	Index for the product type sold by a technician
$p_{sp'n}$	Number of product type p' can be sold by an installation technician with skill level s in period n

$pcost_n$	Unit complaint cost for excess complaint
Q^{max}	The maximum number of repair technician in period n
q_s	Cost of a repair technician with skill type s, per period
R_n	The total number of repair jobs in period n
R'	Index for the total number of regions
r	Index for type of region
$r_{p'}$	Revenue generated from product type p'
S	Index for the total number of skill types for technicians
s	Index for technician skill type
T_{inst}	Total number of installation jobs over all planning periods
T_{rep}	Total number of repair jobs over all planning periods
Tcc_n	The total technician complaint cost in period n
$Tcost_n$	The total technician salary cost in period n
$Trev_n$	The total revenue in period n
t	Complaint rate threshold
w_n	The total revenue obtained from successful repair in period n
X_s	The minimum number of installation technicians by s skill in period n
y_{sn}	The number repair technician with skill s in month n
z_{sn}	The number installation technician with skill s in period n

LIST OF ACRONYMS/ABBREVIATIONS

ACSI	Average Customer Satisfaction
FSM	Field Service Management
KPI	Key Performance Indicator
LP	Linear Programming
MILP	Mixed-Integer Linear Programming
RHS	Right Hand Side
SLA	Service Level Agreement
TRSP	Technician Routing and Scheduling Problem

1. INTRODUCTION

1.1. Field Service Management

Optimization can be challenging for Field Service Management (FSM) since it involves multiple goals and number of constraints. Some goals and constraints may even be contradictory such as increasing customer satisfaction and minimizing cost. It may be necessary to sacrifice some goal such as cost reduction in order to increase customer satisfaction. These kind of decisions depend on service strategies in real life and strategies can change during different time periods. Therefore, addressing the model with its goal and constraints in a way that is suitable for changes, forms the central motivation underpinning this thesis.

Defining constraints is one of the most important step for optimization. Field services generally involve constraints such as the number of technicians, the service time of different jobs for each technician or traveling time. Another significant subject may be uncertainties of goals, constraints, decision variables and their effects on each other. Most of the time there is a need for reduction of uncertainties since each customer and each technician has different characteristics. The purpose of the present work is to optimize the field service objective, which is maximizing profit with limited resources. For this study, a Mixed Integer Linear Programming (MILP) model is developed.

Many models are built to support and explicitly consider the trade-offs between resource utilization and task fulfillment in the literature. It is needed a better understanding of how field services can ensure that their service goals succeed. Hence, “What Key Performance Indicator (KPI) must a field service has in order to achieve its goals?” becomes the fundamental question to be answered. Various contributions are made in order to understand the purpose and scope of the authorized field service while trying to answer it. The performance measurement methods have been explained in detail, and the objectives have been classified with respect to aspects such as cost, quality, customer satisfaction, and delivery in [1]. Various performance indicators for field services are illustrated in Table 1.1 grouped according to their corresponding performance dimensions.

Table 1.1. Key performance indicators by dimension [2].

Dimension	**Performance Indicators**
Quality	First Time Fix Rate Mean Time Between Failure % of Not Completed Service Requests
Cost - Operational	Total Personnel Cost Inventory Costs
Cost - Investments	Total Infrastructure Investments Cost of a Car Fleet
Delivery - Reliability	% of Services Delayed % of Services Delayed Because of Unavailability of Employees
Delivery - Response Time	Average Time to Arrive On-Site Average Time to Answer a Call
Customer Satisfaction	Average Customer Satisfaction (ACSI) Net Promoter Score
Flexibility	Utilization of Personnel Average Number of Different Products Handled

1.2. Characterization of a Field Service Technician

The qualifications of a field service are typically different than those of a other service business. Rather than focusing on maximizing revenues, a service or a technician usually seeks to improve both operations and being better brand representatives. Even though an objective such as minimizing costs may still be valid for them, they will often balance such concerns against the underlying importance of effectively serving their clients.

An important difference between field service and other service businesses has to do with the skills of the labor force. A technician/service can be seen as a final step of a supply chain. Therefore, a technician has a responsibility to ensure trust to customers in all steps from production to customers. Field services represent whole brand power and capacity when they communicate with the customers. It can be said that communications skills in the challenging situations are as important as their technical abilities about appliances. A technician needs to know various type of abilities rather than basic service business skills. He should know how a product sell effectively by learning marketing abilities, and observe and learn different type of customer expectations since cultural background of a customer can change from one region to another. Additionally, a technician can be considered as a mediator. Customer can have several complaints about product itself, service operations or price of service. During these challenging situations it is a basic expectation for a technician to pacify the customer and convince them to accept logical solution by ensuring satisfaction. For all these reasons, the identity of the field service technician is transition from issue fixers to solution providers.

1.3. Objectives of the Study

Achieving profitability in FSM is essential for maintaining operations and promoting growth. Not only does efficient FSM guarantee that customers' needs are satisfied, but it also has a big financial impact. Businesses can cut expenses and boost income by reducing procedures, improving service delivery, and allocating resources optimally. By concentrating on profitability, companies can increase their market share, enhance customer satisfaction and invests in technology. Additionally, a successful field service business builds customer loyalty and satisfaction, giving it a competitive edge in the market. Since profitability has a direct impact on financial health and business sustainability, it is fundamental to the long-term success and scalability of FSM. Therefore, profit is the main objective as is the real goal of many companies.

A MILP model is developed to maximize profit by analyzing the relationship among three important decisions: the number of technicians, product sales, and customer complaints. The model aims to identify the optimal combination of these variables that yields the highest profit.

Moreover, there can be differences between the planned and the actual processes. For instance, if the workload changes, the established model may require a complete revision. Therefore, Scenario 1 thoroughly examines how all variables and the maximum profit are affected when the workload increases, and the results are compared with the original model.

While technology plays a significant role in all aspects of modern life, it is particularly critical for field services. In [3], the importance of technology is explicitly highlighted, as it offers notable benefits including cost reduction, increased operational efficiency, and stronger customer engagement. Field service organizations need to adopt advanced technological infrastructures in order to achieve their objectives more efficiently and to enable growth and development. For these reasons, a dedicated scenario is developed in the model to observe the role of technology in Section 6.1.

Chapter 1 concludes by presenting the main objectives of the study. The rest of this thesis is organized in 6 chapters. Chapter 2 presents a review of the literature related to FSM and workforce constraints. Chapter 3 introduces the problem and developing a mathematical model that includes the objective, constraints, and underlying assumptions. Then, the model is validated in Chapter 4. Chapter 5 is on the application of the model to real life situations. Two potential scenarios are analyzed by means of the model in Chapter 6. A discussion of the implications and limitations of the research study is provided and different future research directions are proposed in Chapter 7.

2. LITERATURE SURVEY

The proposed model is supported not only by sectoral expertise but also by a comprehensive literature review. In the process of examining the relevant academic and professional literature, models and sources related to FSM, resource allocation and workforce management are examined. The literature survey is organized into two main sections, reflecting the key areas of focus relevant to the topic. Section 2.1 focuses on FSM and includes all types of models developed specifically within this domain, while Section 2.2 encompasses models based on optimization and goal programming techniques developed and applied in different industry sectors.

2.1. Literature About Field Services

Optimization models involving FSM have been extensively studied in the literature. Most of these studies predominantly focus on assignment and routing problems within the context of field services. In particular, a wide range of various characteristics of vehicle routing models have been proposed and summarized in [4], which also identifies key challenges associated with applying traditional vehicle routing frameworks to real-world scheduling. These challenges are classified into three overarching categories:

- Simplified vs. Complex Problems: Simplified models try to reflect complex structure with straightforward variables, limited constraints, balanced-calculated, coherent assumptions and demands.

- Static vs. Dynamic Problems: Most research related to vehicle scheduling problems are based on static data in order to recover from uncertainties. However, the dynamic nature of a process, especially one planned for a long period of time, is inevitable.

- Deterministic vs. Stochastic Problems: Information is often uncertain or incomplete, which limits the realism of deterministic models. Although stochastic models better handle this uncertainty, they are frequently constrained by data scarcity and complexity.

While grounded in the classical Technician Routing and Scheduling Problem (TRSP), author is proposed with workload balance and substitution skills in [5]. The goal of the objective function is to reduce the total cost incurred while assigning and completing tasks. This minimization is carried out under specific constraints, particularly those related to technician skill compatibility and predefined time windows for task completion in [5].

Similar to [5], another routing problem is formulated with comparable constraints; however, unlike other TRSP, the objective is not to minimize total cost but rather to minimize total delay and total service time in [6]. In addition, some constraints are included in [6] to ensure that all demands are fully satisfied. Moreover, the model incorporates a penalty cost for unmet demands that are not fulfilled during the initial service attempt.

Another article about TRSP is presented, in which individualized, experience-based learning is incorporated in [7]. They show that considering learning and workforce heterogeneity leads to significantly improved solutions, driven by specialization pattern.

Besides [7], a multi-criteria FSM model is built in [8]. It consists of job type, due dates, job duration and penalty costs. This model objective focused on minimizing travel cost by allocating resources optimally. They used mixed integer linear programming formulation.

An alternative perspective is provided by [9]. The aim is to visit as many optional customers as possible with the least travel time. The approach has two steps: planning routes for required and optional customers and adjusting these routes in real time to handle uncertainties and keep time schedules [9].

A field service scheduling problem is built with three objectives which are the minimization of the operational costs, the maximization of the service quality and the maximization of the technician–task fit in [10] and some constraints related to technician skill compatibility, job completion time windows, and task sequencing are added to the model. It is evident that the parameters and constraints defined in the model reflect a realistic and practical perspective of the service sector, demonstrating a strong alignment with real-life conditions.

Although limited in number, there are also studies focusing on general FSM operations beyond the scope of TRSP. An example of this can be found in [11]. A field services process flow minimizing repair cost by paying attention to task priority and assigning technicians to jobs is described. They apply task-based resource allocation model algorithm in order to provide more work with less utilized resources.

Different type of jobs can be considered in a FSM model. There are global field service network model simulation with different criteria such as network structure, service locations, districts, organizational forms, role assignments and financial models of collaboration [12]. The author also shares very useful details about the sector for business owners who are interested in service processes.

A simulation model is developed for field service and technician, elevator availability, technician work types are considered in [13].

In certain studies, the emphasis is placed on modeling penalty costs arising from the failure to fulfill specific conditions or demands addressing the balance between operational performance and cost-related results. Unlike previous studies, model in [14] incorporates a variety of penalty cost structures—including constant, linear, staged, asymptotic, and polynomially increasing penalties and offers alternative actions to mitigate these penalties. It is aimed at minimizing the total cost, which consist penalties from five different Service Level Agreement (SLA) violations such as customer loss cost, cost of inability to meet demand in time, order fulfillment time, wrong production delivery in [14].

2.2. Optimization Models In Other Sectors

Studies on goal programming provide a comprehensive review of the literature and detailed information about goal deviation in [15]. Main objective of model is the minimization of the deviation from the goal. This objective function can be applied for field technicians too. However, goals for KPI's change from time to time and goal should consider carefully because if the goal itself is wrongly determined, deviation from the goal also involves the risk of being wrongly determined.

Moreover, an additional contribution is made in [16]. The multiple criteria model is designed with three objectives: profit, client satisfaction, and the labor environment changes. Authors define some constraints related to number of workers, working hours and production capacities, which is differentiated with different types of works and product families.

Unlike other authors, a workforce planning model is built in [16] which is based on important areas such as the quality and efficiency of the work.

There are also studies focusing on assignment problems; one such example focuses on managing the assignment of humanitarian volunteers [17]. In that study, the authors note the importance of characteristics of volunteer workers and their skills by adding different objectives which are minimizing shortage cost and number of undesired assignments to their model. Moreover, their proposed model is based on scarce sources by adding constraints like shortage of volunteers. A further example can be seen in [18], which consider shift and programs of radiology technicians in the hospital.

2.3. Contributions

Two groups of the contributions are realigned. The first ones are related to the development and extensions of a MILP model based on industry experience and real-life evaluations, and the evaluation of the results from this perspective. A review of the existing literature reveals a limited number of models related to field service operations. The available models often revolve around repetitive structures such as TRSP. However, in real world routing activities, technicians generally create their own routes based on their intimate knowledge of the geographic area without relying on mathematical modeling. Therefore, more practical constraints and objectives such as the number of technicians to be employed, monthly profit estimations, and workload analysis—are incorporated into this model. Furthermore, while existing models typically mention KPI's like customer satisfaction or complaint costs, they rarely delve into these aspects in detail. This study thoroughly examines complaint costs and region-based complaint ratios within the service sector and introduces a penalty cost for cases where target KPI's are not met. Such penalty cost assessments, especially for complaints, are scarcely observed in the current literature. In this respect, the model is enriched with a new constraint.

Second group of the contributions consist of the analysis of two scenarios. Key conditions that could fundamentally alter the structure of an authorized service model such as a significant increase in transaction volume in Section 6.1, and process acceleration through system improvements in Section 6.2 have been thoroughly examined. By incorporating these dynamic conditions into the model, the study not only addresses current operational challenges but also provides a framework that can guide and support future studies. Therefore, it can be stated that the model contributes to the literature by offering adaptable and forward-looking perspectives that reflect real-life complexities in the field service domain.

3. PROBLEM DEFINITION AND FORMULATION

The field service optimization model is designed to assist net profit goals under various kind of limitations. This case study is inspired by a real world problem from a white goods manufacturer, which provides both products and on-site services to its customers. To protect confidential information, all parameters have been substituted with fictional data. The model focuses on maximizing net profit for N periods whose structure is represented in Figure 3.1.

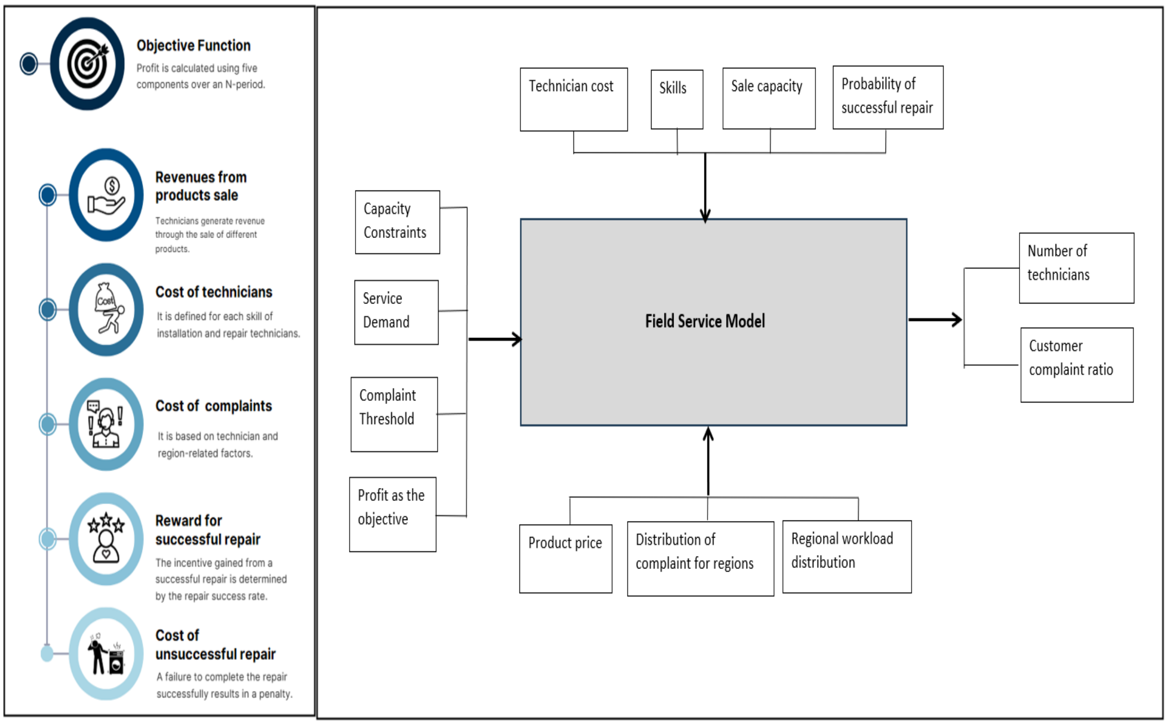

Figure 3.1. The structure of the model.

The objective is the maximization of the net profit over N planning periods which can be expressed as

$$z = \sum_{n=1}^{N} \left(\mathrm{Trev}_n - \mathrm{Tcost}_n - \mathrm{Tcc}_n - \mathrm{fcost}_n + \mathrm{w}_n\right). \tag{3.1}$$

It has five components, which are total revenue, $\sum_{n=1}^{N} Trev_n$, the cost of technicians $\sum_{n=1}^{N} Tcost_n$, the cost of the customer complaint $\sum_{n=1}^{N} Tcc_n$, penalty cost for over complaint in regions $\sum_{n=1}^{N} fcost_n$ and reward for successful repairs $\sum_{n=1}^{N} w_n$ respectively. Product revenue at period n has two terms and it is expressed as

$$\mathrm{Trev}_n = \sum_{p'=1}^{P} \sum_{s=1}^{S} (p_{sp'n} r_{p'} z_{sn} + k_{sp'n} r_{p'} y_{sn}) \qquad n = 1, \ldots, N. \tag{3.2}$$

These two terms are revenues obtained from installation jobs and repair jobs. First part of the equation, $p_{spn} r_{p'} z_{sn}$, is the multiplication of number of product that is sold by a skills installation technician during period n, unit revenue of product p' which is $r_{p'}$ and number of technician for each skill s technician during period n. The second component is formulated in a similar manner to the installation case, using parameter $k_{sp'n}$, which indicates the number of product p' that can be sold by repair technicians in period n. The monthly salary cost of the technicians is represented with the equation as

$$\mathrm{Tcost}_n = \sum_{s=1}^{S} (c_s \, z_{sn} + q_s \, y_{sn}) \quad n = 1, \ldots, N. \tag{3.3}$$

The fixed unit cost denoted by c_s is defined for each technician skill type. The total technician salary cost which is $Tcost_n$ is obtained by multiplying fixed unit cost by the number of installation technicians, denoted by z_{sn}. Similarly, for repair technicians, a unit cost q_s is defined and it is multiplied by the number of repair technicians which is y_{sn}. The sum of these two components represents the total technician cost for installation and repair technicians in period n. Total complaint cost can be expressed as

$$\mathrm{Tcc}_n = \sum_{r=1}^{R'} \left(M_n c_r^1 d_r cr_r^1 + R_n c_r^2 d_r cr_r^2 \right) + \sum_{s=1}^{S} y_{sn} b_{sn} c_s^{\mathrm{fail}} (1 - e_s^{\mathrm{suc}}), \quad n = 1, \ldots, N. \tag{3.4}$$

The first component reflects the complaint-related cost attributable to technicians repair activities driven by the regional distribution of installation. Number of jobs is multiplied by the unit complaint cost, distribution of jobs to regions denoted by d_r and distribution of complaints to regions cr_r^1. This multiplication is complaint costs from regions. Summation of installation and repair complaint cost from regions is obtained in the first component in Constraint (3.4).

The second component captures the cost incurred from failed repair attempts conducted by repair technicians. When y_{sn} number of technicians fails in repair, the costs associated with the subsequent dependent tasks are included as additional expenses. Probability of successful repair is represented with e_s^{suc}. It is assumed that technicians with higher skills have a greater probability of performing successful repairs. Similarly, it is considered that technicians with more skills are linked to a reduced number of complaint units cost. The product of c_s^{fail} and e_s^{suc} represents the cost resulting from each unsuccessful repair task. Then, to account for all repair tasks, the value is multiplied by y_{sn} and b_{sn}.

If the complaint rate in a region is more than the determined constant KPI value, a penalty process should be initiated for that region, so that the services in the relevant region improves this KPI for the next processes. Complaint threshold related constraints are expressed as

$$\text{fcost}_n = \text{pcost} \sum_{r=1}^{R'} \text{Overf}_{rn}(M_n + R_n) \qquad n = 1, \ldots, N \tag{3.5}$$

$$\text{cratio}_{rn} - t \leq \text{Overf}_{rn} \qquad n = 1, \ldots, N \tag{3.6}$$

where t denote complaint ratio as KPI value.

$Overf_{rn}$ represents the proportion of complaints exceeding the target level in a specific region during period n. When multiplied by the sum of M_n and R_n, it yields the total number of complaints that surpass the target threshold. *pcost* refers to the unit penalty cost per complaint. By multiplying the excess number of complaints by *pcost* the total penalty cost for excess complaints, denoted as $fcost$, is obtained in Constraint (3.5). Constraint (3.6) shows that if the complaint rate $cratio_{rn}$ in the region is more than t, there will be a unit penalty payment, *pcost*, for each complaint exceeding value of t. In other words, linear penalty cost is applied in this model, which means penalty cost is increasing the degree of violation. This constraint is shown in Figure 3.2. represents non-negative constraints for values greater than t.

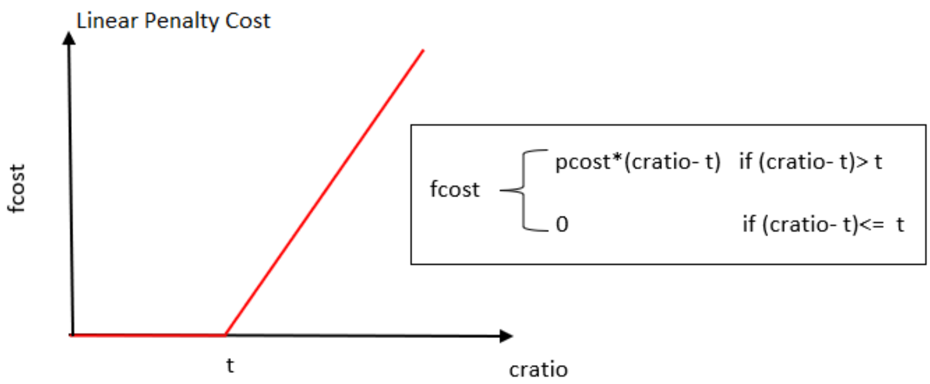

Figure 3.2. Penalty cost for excess complaint.

In addition, the incentive is gained from a successful repair is represented in optimization function. If the repair is successfully done by y_{sn} technician, it generates additional revenue as a reward and it is expressed as

$$\mathrm{w}_n = \sum_{s=1}^{S} (y_{sn} b_{sn} e_s^{\mathrm{suc}} d_s^{\mathrm{save}}) \qquad n = 1, \ldots, N. \tag{3.7}$$

Since e_s^{suc} represents the probability of successful repair and d_s^{save} represents the the revenue of successful repair, multiplication of y_{sn}, b_{sm}, e_s^{suc} and d_s^{save} values in (3.7) refers the total revenue obtained from successful repairs.

The number of technicians plays a crucial role both in this model and in real-world FSM operations. For instance, if technician capacity is insufficient to meet installation and repair demands, customer expectations cannot be satisfied. Conversely, employing an excessive number of technicians may enhance service levels, but it also leads to a significant increase in personnel costs. Due to this trade-off, resource constraints are added into the model to realistically reflect organizational limitations. These constraints are defined as

$$\sum_{s=1}^{S} z_{sn} \leq I^{\max} \qquad n = 1, \ldots, N \tag{3.8}$$

$$\sum_{s=1}^{S} y_{sn} \leq Q^{\max} \qquad n = 1, \ldots, N \tag{3.9}$$

where z_{sn} and y_{sn} denote the number of technicians assigned to installation and repair tasks, respectively, for all s skill types in month n in (3.8) and (3.9). These constraints represent the total number of technicians across all technician skill types through all periods. The first equation refers to the maximum number of technicians for installation, while the second one is for repair. A minimum number of technician per skill constraints are added to guarantee sufficient expertise in each area. They are defined as

$$X_s \leq z_{sn} \qquad n = 1, \ldots, N; s = 1, \ldots, S \tag{3.10}$$

$$A_s \leq y_{sn} \qquad n = 1, \ldots, N; s = 1, \ldots, S. \tag{3.11}$$

While X_s is the minimum number of installation technician for each skill s in period n, A_s is the minimum number of repair technician for each skill s in period n. X_s and A_s are taken as a constant value for each s skill in the model. Other resource constraints are defined for the minimum number of technician for each skill s technician in (3.10) and (3.11). Since certain tasks require specific expertise, additional constraints are introduced into the model.

T_{inst} and T_{rep} represent the expected number of jobs within each predefined period. In order for the model to fully meet the expected job volume in each of the N periods, two equations have been formulated as

$$T_{inst} = \sum_{n=1}^{N} M_n \tag{3.12}$$

$$T_{rep} = \sum_{n=1}^{N} R_n. \tag{3.13}$$

They ensure that the sum of job across all periods is structured to match the total planned job volumes, which are T_{inst} and T_{rep}.

The model determines the monthly distribution of the total number of tasks by internally computing the values of M_n and R_n, while taking into account the monthly technician capacity constraints as

$$M_n = \sum_{s=1}^{S} D_1 \, z_{sn} a_{sn}, \quad n = 1, \ldots, N \tag{3.14}$$

$$R_n = \sum_{s=1}^{S} D_2\, y_{sn} b_{sn}, \quad n = 1, \ldots, N. \tag{3.15}$$

Manpower coefficient D_1 in Constraint (3.14) is set to 1 as a baseline for installation tasks, which are performed individually. However, repair tasks such as device handling, pulling, and transportation are more demanding, so the corresponding D_2 coefficient for repair is set to 2 to reflect the increased difficulty and manpower requirement in (3.15). The total number of jobs completed in period n is calculated by multiplying three values; manpower coefficient, the number of technicians and the number of jobs that a technician can complete per period for installation and repair respectively. Lastly, sign and type constraints are added into model as

$$\text{Overf}_{rn} \geq 0 \qquad r = 1, \ldots, R';\ n = 1, \ldots, N \tag{3.16}$$

$$M_n \geq 0 \qquad n = 1, \ldots, N \tag{3.17}$$

$$R_n \geq 0 \qquad n = 1, \ldots, N \tag{3.18}$$

$$z_{sn} \in \mathbb{Z}_+ \qquad s = 1, \ldots, S;\ n = 1, \ldots, N \tag{3.19}$$

$$y_{sn} \in \mathbb{Z}_+ \qquad s = 1, \ldots, S;\ n = 1, \ldots, N. \tag{3.20}$$

Finally, the objective function and constraints can be put together in order to form the complete MILP model as

$$\begin{aligned}
\max \quad & z = \sum_{n=1}^{N} (\text{Trev}_n - \text{Tcost}_n - \text{Tcc}_n - \text{fcost}_n + w_n) \\
\text{s.t.} \quad & \text{Trev}_n = \sum_{p'=1}^{P} \sum_{s=1}^{S} \left(p_{sp'n} r_{p'} z_{sn} + k_{sp'n} r_{p'} y_{sn}\right), && n = 1, \ldots, N \\
& \text{Tcost}_n = \sum_{s=1}^{S} \left(c_s z_{sn} + q_s y_{sn}\right), && n = 1, \ldots, N \\
& \text{Tcc}_n = \sum_{r=1}^{R'} \left(M_n c_r^{(1)} d_r cr_r^{(1)} + R_n c_r^{(2)} d_r cr_r^{(2)}\right) \\
& \qquad\qquad + \sum_{s=1}^{S} y_{sn} b_{sn} c_s^{\text{fail}} (1 - e_s^{\text{suc}}), && n = 1, \ldots, N \\
& \text{fcost}_n = \text{pcost} \sum_{r=1}^{R'} \text{Overf}_{rn} (M_n + R_n), && n = 1, \ldots, N
\end{aligned}$$

$$w_n = \sum_{s=1}^{S} \left(y_{sn} b_{sn} e_s^{\text{suc}} d_s^{\text{save}} \right), \qquad n = 1, \ldots, N$$

$$\text{cratio}_{rn} - t \leq \text{Overf}_{rn}, \qquad r = 1, \ldots, R';\ n = 1, \ldots, N$$

$$T_{\text{inst}} = \sum_{n=1}^{N} M_n$$

$$T_{\text{rep}} = \sum_{n=1}^{N} R_n$$

$$M_n = \sum_{s=1}^{S} D_1 z_{sn} a_{sn}, \qquad n = 1, \ldots, N$$

$$R_n = \sum_{s=1}^{S} D_2 y_{sn} b_{sn}, \qquad n = 1, \ldots, N$$

$$\sum_{s=1}^{S} z_{sn} \leq I^{\max}, \qquad n = 1, \ldots, N$$

$$\sum_{s=1}^{S} y_{sn} \leq Q^{\max}, \qquad n = 1, \ldots, N$$

$$X_s \leq z_{sn}, \qquad s = 1, \ldots, S;\ n = 1, \ldots, N$$

$$A_s \leq y_{sn}, \qquad s = 1, \ldots, S;\ n = 1, \ldots, N$$

$$\text{Overf}_{rn} \geq 0, \qquad r = 1, \ldots, R';\ n = 1, \ldots, N$$

$$M_n \geq 0, \qquad n = 1, \ldots, N$$

$$R_n \geq 0, \qquad n = 1, \ldots, N$$

$$z_{sn} \in \mathbb{Z}_+, \qquad s = 1, \ldots, S;\ n = 1, \ldots, N$$

$$y_{sn} \in \mathbb{Z}_+, \qquad s = 1, \ldots, S;\ n = 1, \ldots, N.$$

4. MODEL VALIDATION

Numerous validation techniques have been proposed in the literature. For instance, some validation techniques for simulation models are described and categorized in detail such as degenerate tests, event validity, extreme condition tests, face validity, historical data validation, historical methods, parameter variability, sensitivity analysis [19]. The formal process for the validation of Linear Programming (LP) models is explained and illustrated with Figure 4.1 in [20]. We follow these steps as much as possible to validate the LP relaxation of the MILP model introduced in the previous chapter.

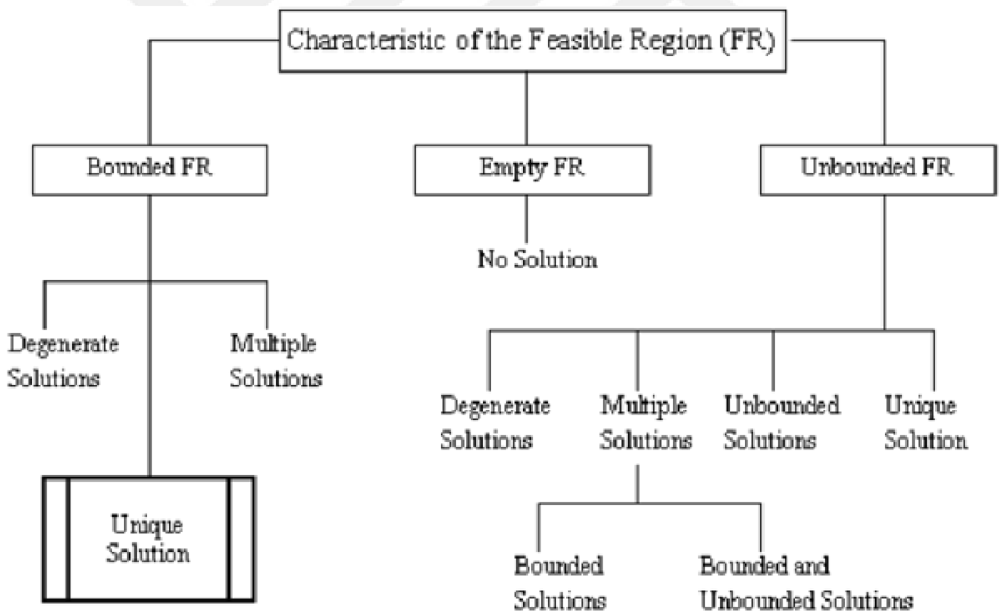

Figure 4.1. Model validation process [20].

To evaluate the structure of the model, some extreme condition tests are performed with parameters such as setting technician costs q_s to zero. Furthermore, some variable for small cases are calculated and made a comparison with the model result. Additionally, face validity method is used in order to ensure model validation. Field expert examine the model and give some feedback the structure of the model and find outs whether the model's input output relationships is reasonable.

4.1. Extreme Condition Tests

To evaluate model's behavior, the contribution of variable q_s is eliminated from the model. While reducing technician costs, an increase in profit is also expected. The objective function can alternatively be defined in terms of profit and is represented as

$$profit_n = Trev_n - Tcost_n - Tcc_n - fcost_n + w_n. \tag{4.1}$$

The q_s parameter in $Tcost_n$ is set to 0 for all three skills, respectively, and the results are shown in the Table 4.1, Table 4.2 and Table 4.3.

Table 4.1. Monthly unit cost for skill 1 repair technician.

Variable	q_1 **= 30,000**	q_1 **= 0**	**Gap**
$q_s y_{sn}$	47,300,000	18,900,000	-28,400,000
$profit_n$	11,341,600	39,741,600	28,400,000

Table 4.2. Monthly unit cost for skill 2 repair technician.

Variable	q_1 **= 0,** q_2 **= 25,000**	q_1**=** q_2**= 0**	**Gap**
$q_s y_{sn}$	18,900,000	5,400,000	- 13,500,000
$profit_n$	11,341,600	53.241.600	13,500,000

Table 4.3. Monthly unit cost for skill 3 repair technician.

Variable	q_1**=**q_2**= 0,** q_3 **=1000**	q_1**=** q_2**=**q_3**= 0**	**Gap**
$q_s y_{sn}$	5,400,000	0	- 5,400,000
$profit_n$	53,241,600	58,641,600	5,400,000

When the repair technician unit labor cost is set to zero for each skill repair technician, a decrease in repair technician cost and therefore an increase in profit at the same amount are clearly seen from the gap values in Table 4.1, Table 4.2 and Table

4.3. This shows that the model reflects the relationship between technician cost and profit in a way that is expected.

4.2. Bounded Feasible Region

For the purpose of understanding how this constraint works and how the change in the constraint affects the model, a number of experiments were conducted. One of these was to reduce the lower bound which is A_{sn} from 45 to 10 and observe the changes in the model. There is a lower bound for repair technician which is

$$A_s \leq y_{sn} \qquad\qquad s = 1, \ldots, S;\ n = 1, \ldots, N. \tag{4.2}$$

Change the number of repair technician for each skill and each month is represented in Figure 4.2. When A is reduced, the model reduces the number skill 3 of technicians and increases the number of skill 1 technicians. Although skill 1 technicians have a higher unit cost than skill 3 technicians, they are technicians who complete more work and bring more product revenues. Since the revenues from product 3 are higher for skill 1 technicians, this change in the model tries to serve the maximization of profit.

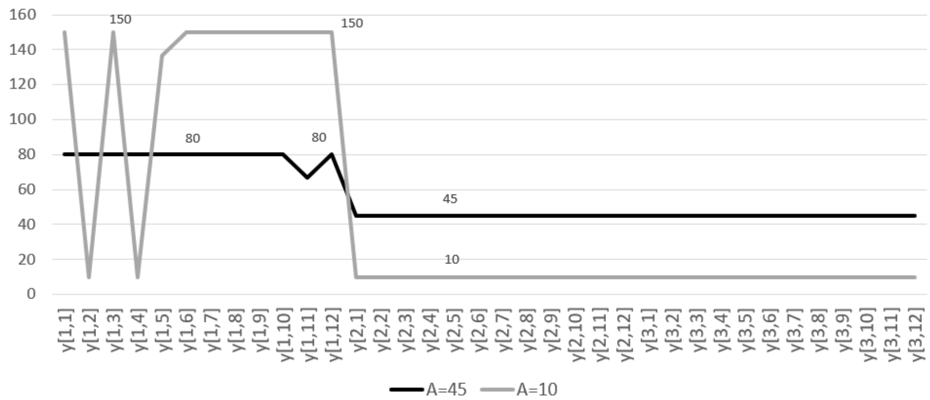

Figure 4.2. The effect of the boundaries.

4.3. General Control

In order to understand variables and parameters in the model, components of objective function, variables are calculated manually and compared with result of the model. For instance, total revenue, $Trev_n$, is one of the important component for the optimal solution, $Trev_n$ value is calculated manually and it is represented as

$$\text{Trev}_n = \sum_{p=1}^{P}\sum_{s=1}^{S}\left(p_{sp'n}r_{p'}z_{sn} + k_{sp'n}r_{p'}y_{sn}\right), \quad n = 1, \ldots, N. \tag{4.3}$$

The model calculates the total revenue for month 12 as 23,000,000 Turkish Lira.

$$\text{Trev}_{12} = 23{,}010{,}000. \tag{4.4}$$

The manual calculation proceeds based on the parameters detailed below. Revenues for installation and repair are calculated in Table 4.5 using the values in Table 4.4.

Table 4.4. Values in the model.

Parameter	**Value**
$z_{1,12}$	210
$z_{2,12}$	100
$z_{3,12}$	100
$y_{1,12}$	80
$y_{2,12}$	45
$y_{3,12}$	45
r_1	5,000
r_2	3,000
r_3	1,000

Table 4.5. Revenue validation.

$p_{sp'12}$	$p_{sp'12}$	$\sum_{s=1}^{S} p_{sp'n} r'_p z_{sn}$	$k_{sp'12}$	$k_{sp'12}$	$\sum_{s=1}^{S} k_{sp'n} r_{p'} y_{sn}$
p_{1112}	9	13,630,000	k_{111}	7	2,800,000
p_{2112}	5	13,630,000	k_{2112}	4	900,000
p_{3112}	0	0	k_{311}	2	450,000
p_{1212}	5	13,630,000	k_{1212}	4	960,000
p_{2212}	2	13,630,000	k_{2212}	2	270,000
p_{3212}	1	13,630,000	k_{3212}	0	0
p_{1312}	4	13,630,000	k_{1312}	4	320,000
p_{2312}	2	13,630,000	k_{2312}	3	135,000
p_{3312}	0	0	k_{3312}	3	135,000
$Totalins.$	-	17,040,000	$Totalrepair$	-	5,970,000

Based on manual calculation, sum of total revenues from installation and repair values is found to be same with the model for time period 12 in total revenue Trev_{12}.

4.4. Sensitivity Analysis

It is frequently impractical and resource-intensive to verify that a model is entirely valid across the entire range of its intended application. Instead, tests and evaluations are carried out until sufficient confidence is achieved about appropriateness of the model.

4.4.1. Shadow Prices

Observing shadow prices is an effective way for model validation. Shadow price quantifies the change in the optimal objective function value resulting from a one-unit increase in the right-hand side (RHS) parameter of a given constraint. If the shadow price value is greater than 0, relaxing the constraint increases the profit, if it is less than 0, relaxing the constraint decreases the profit. To analyze the shadow prices within the model, the constraints are examined and illustrative constraints are

$$cratio_{rn} - t \leq \text{Overf}_{rn} \quad r = 1, \ldots, R; n = 1, \ldots, N \tag{4.5}$$

$$\sum_{s=1}^{S} z_{sn} \leq I^{max} \quad n = 1, \ldots, N \tag{4.6}$$

$$\sum_{s=1}^{S} y_{sn} \leq Q^{max} \quad n = 1, \ldots, N. \tag{4.7}$$

For instance, shadow prices for constraints (4.5), (4.6) and (4.7) are given in Table 4.6. According to Table 4.6, relaxing the Constraint (4.6) increases the profit since it has positive shadow price and it is active in the current solution, indicating that it plays a critical role in limiting the value of z_{sn}. Since an increase in technician capacity would lead to higher sales and, consequently, higher profit, relaxing this constraint could improve the objective function value. Shadow price for Constraint (4.7) is zero. However, regardless of the potential volume of jobs, there should be an upper limit on the number of technicians that can be employed due to operational and managerial constraints. Given that the model aims to reflect realistic operational conditions, this constraint is preserved the same.

Table 4.6. Shadow prices.

n	**Constraint (4.5)**	**Constraint (4.6)**	**Constraint (4.7)**
1	-1	4,480	0
2	-1	4,480	0
3	-1	4,480	0
4	-1	4,480	0
5	-1	4,480	0
6	-1	4,480	0
7	-1	4,480	0
8	-1	4,480	0
9	-1	4,480	0
10	-1	4,480	0
11	-1	4,480	0
12	-1	4,480	0

4.4.2. Slack Values

The slack values of the constraints in the model are examined as part of the validation. For instance, the minimum number of installation technician for each skill is expressed as

$$X_s \leq z_{sn} \quad n = 1, \ldots, N; \; s = 1, \ldots, S. \tag{4.8}$$

Constraint 4.8 is analyzed and most of the variables have zero slack values for z_{sn}. However, some value of z_{sn} has negative slack value such as z_{14}, z_{15} and z_{27}. Results are summarized in Figure 4.3.

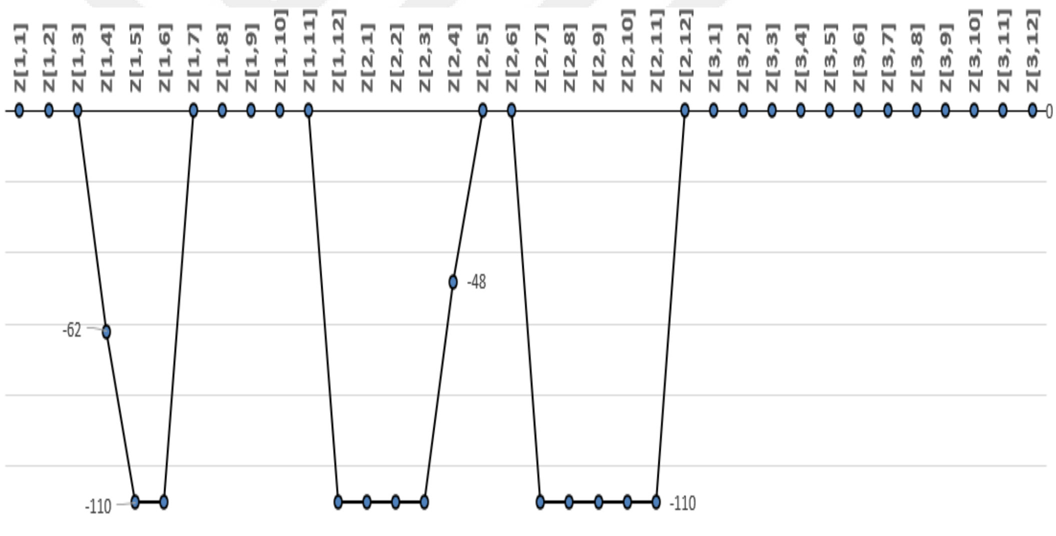

Figure 4.3. Slack values of installation technicians.

Another example can be given for the maximum number of technician constraints which are

$$\sum_{s=1}^{S} z_{sn} \leq I^{\max} \qquad n = 1, \ldots, N \tag{4.9}$$

$$\sum_{s=1}^{S} y_{sn} \leq Q^{\max} \qquad n = 1, \ldots, N \tag{4.10}$$

$$\sum_{s=1}^{S} (z_{sn} + y_{sn}) \leq \mathrm{T}^{\max} \qquad n = 1, \ldots, N. \tag{4.11}$$

The Constraint (4.11) with T^{max} imposes an upper limit on the total number of installation and repair technicians that can be assigned. To evaluate its necessity and relevance, the slack values of this constraint and the related ones is examined. The slack values of these three constraints are given in Table 4.7.

Table 4.7. Slack values.

n	**Constraint (4.9)**	**Constraint (4.10)**	**Constraint (4.11)**
1	0	0	10
2	0	13,333	13,333
3	0	0	10
4	0	0	10
5	0	0	10
6	0	0	10
7	0	0	10
8	0	0	10
9	0	0	10
10	0	0	10
11	0	0	10
12	0	0	10

According to Table 4.7, while slack values of Constraint (4.11) are greater than zero in almost all months, the slack values of Constraint (4.9) and Constraint (4.10) are zero. In this case, Constraint (4.11) is not active. The slack value is checked again by trying different T^{max} values for (4.11), but despite different trials, no decrease in the slack value is observed. Since Constraint (4.11) could not be actively operated, it can be removed from the model.

5. IMPLEMENTATION OF THE MODEL

5.1. Determination of the Parameters

When a service model is considered, the first parameters that come to mind are the number of technicians and the cost, so these parameters are added as a basis. In addition, according to the expert opinions we interview, the technician's field of expertise and skill set are also among the things that must be addressed in an authorized service model, so they are added to the model.

- s_1 represents more experienced and capable technicians. s_3 generally technicians who are in the learning process at the beginning of their career. Costs based on skills are represented in Table 5.1.

- q_s parameter has higher values than c_s values because repair is a more challenging job than installation. Their values are given in Table 5.1.

Table 5.1. Installation and repair technician costs by skill.

s	c_s	q_s
1	30,000	30,000
2	12,000	25,000
3	9,000	10,000

- Similarly, the parameters were selected so that the income from sales would be higher for more skilled technicians. Due to the product's own features, it is a product that consumers prefer during repair rather than installation, therefore for p_3, for example, repair technicians have more sales capacity than installation. Certain products exhibit a higher suitability for being sold in conjunction with repair services rather than the initial installation phase. This distinction often stems from consumer behavior and service context. For instance, in the case of maintenance services, consumers typically do not perceive immediate sale of maintenance service as necessary for a brand-new device that has not yet been used. However, when a product becomes faulty, the perceived need for such additional services increases significantly, making the repair process a more opportune moment for offering this type of product. As an illustrative case, product 3 is one that tends to be more favorably received when offered during repair services rather than installation. To reflect this behavioral tendency within the model, a specific parameter value has been introduced. Taking into account product features and technician skills, sellable quantities for the products have been determined, and the relevant parameters are shown in Table 5.2.

Table 5.2. Sale capacity for products during installation and repair.

p'	s	n	$p_{sp'n}$	$k_{sp'n}$
1	1	1–12	9	7
1	2	1–12	5	4
1	3	1–12	4	4
2	1	1–12	5	4
2	2	1–12	2	2
2	3	1–12	2	3
3	1	1–12	0	2
3	2	1–12	1	0
3	3	1–12	0	3

- Although the main job of service technicians is generally thought of as installation and repair, the ability of technicians to sell services and products that consumers can purchase has an important place in the service sector today. Thus, sales from three different products were included in the model. The first, second and third product represents respectively accessory, additional warranty and the maintenance. Additional warranty and maintenance are less preferred than accessories, so their unit sales are less than accessories. Table 5.3 presents the revenues associated with each one of them.

Table 5.3. Unit revenues per product.

p'	r'_p (TL)
1	5,000
2	3,000
3	1,000

5.2. Results and Their Interpretation

This section examines optimal solutions of the original model and discusses the corresponding results. The proposed optimization model is solved using Python 3.11, with Gurobi employed under an academic license.

Initially, variables such as the number of technicians, number of complaints are modeled as integer variables to better reflect real-world conditions, since fractional technicians are not practical. However, although the model was formulated as a MILP, it is solved using its LP relaxation. This approach is preferred because solving the MILP version is computationally intensive and does not allow for effective sensitivity analysis. LP relaxation, by treating integer variables as continuous, significantly reduced solution time and made the model behavior easier to interpret. While this comes at the cost of potentially losing integrality in decision variables, it provided valuable insights into the structure and performance of the model.

Result of model is summarized in Figure 5.1. In mathematical programming, when a variable has a bound range of [0, 0], it means that the model becomes highly constrained, allowing no flexibility in decision variables. The objective range [1e+00, 1e+00] indicates that the objective function has a constant value of 1.0 across all feasible solutions. After 56 iteration, objective value which is the total profit for all months is found as 17,051,600 Turkish Lira.

```
Gurobi Optimizer version 11.0.0 build v11.0.0rc2 (win64 - Windows 11+.0 (26100.2))

CPU model: 13th Gen Intel(R) Core(TM) i5-13420H, instruction set [SSE2|AVX|AVX2]
Thread count: 8 physical cores, 12 logical processors, using up to 12 threads

Optimize a model with 1742 rows, 1909 columns and 4152 nonzeros
Model fingerprint: 0x682c3fd0
Coefficient statistics:
  Matrix range     [2e-07, 6e+07]
  Objective range  [1e+00, 1e+00]
  Bounds range     [0e+00, 0e+00]
  RHS range        [1e-02, 4e+04]
Warning: Model contains large matrix coefficient range
         Consider reformulating model or setting NumericFocus parameter
         to avoid numerical issues.
Presolve removed 1704 rows and 1825 columns
Presolve time: 0.00s
Presolved: 38 rows, 84 columns, 228 nonzeros

Iteration    Objective       Primal Inf.    Dual Inf.      Time
       0    2.9842613e+07   3.906442e+03   0.000000e+00      0s
      56    1.7051600e+07   0.000000e+00   0.000000e+00      0s
```

Figure 5.1. Application result.

Firstly, the number of technicians are observed in Table A.1 because the number of technicians lead profit and cause complaint costs. In Table A.1, it is observed that the model assigns the minimum possible number of technicians with skill levels 1 and 3 for installation jobs, while for repair jobs, technicians with skill levels 2 and 3 are kept at their minimum levels. The reason why the model makes a difference here is that it changes depending on both revenue and costs; technician cost or just the number of jobs completed does not determine which technician will have more jobs. Therefore, we can understand from this situation that the model is an effective tool in decision making about technician numbers in order to plan the future.

Although the objective function of this study does not explicitly include the number of technicians, the model incorporates several constraints related to installation and repair technicians. Since the number of technicians is a critical parameter that significantly affects the efficiency of operations in the real world, it is examined in detail in this section. The distribution of installation technicians across 12 months for each skill type is analyzed with the number of jobs in order to understand the changes the number of technician for months. Technicians with skill level $s = 1$ is considered more skilled and experienced. Therefore, the higher number of jobs they can complete within a month in the model is taken as a basis when determining the parameters. Additionally, the unit cost associated with them is greater than that of other skill levels. For this trade off, it is analyzed to determine which skill level would have a higher number of technicians.

As shown in Figure 5.2, generally $s = 2$ level technician has higher number than others for most of the year. The model allocates technicians across three skill levels based on the given constraints. Due to these constraints, two skill levels receive the minimum number of technicians, while the third skill level is assigned the maximum possible number of technicians. When the number of installation jobs increases for months $n = 5$ and $n = 6$, the number of technicians with skill level $s = 1$ also increases and the number of technicians with skill levels $s = 2$ and $s = 3$ decreases. This graph suggests that in order to influence the distribution of technician number in levels with unit costs, the unit cost for $s = 1$ technicians may need to be increased further.

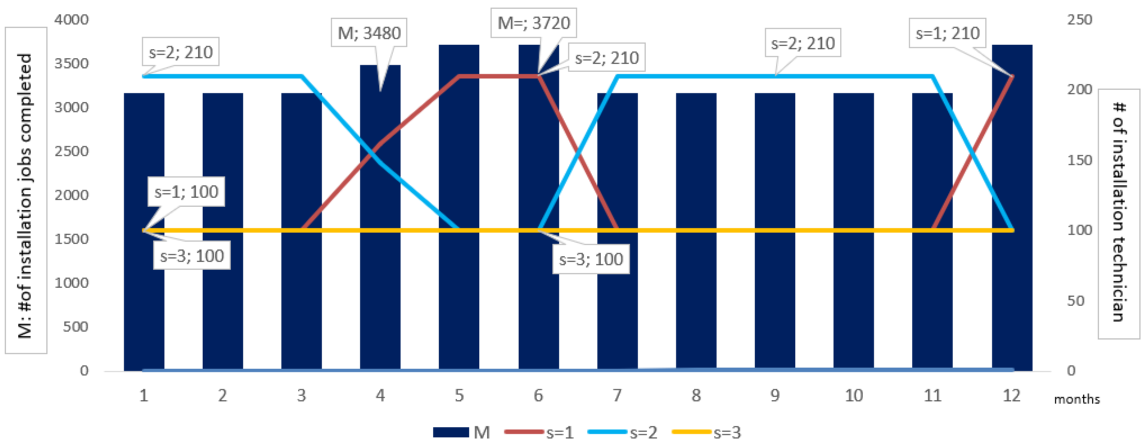

Figure 5.2. Installation technicians and jobs.

Similar graph for repair technicians is given in Figure 5.3. It can be observed that the number of technicians with a skill 2 is significantly higher than those with other skill levels. If skill 1 level technician number decreases, number of repair jobs decreases. This graph creates more question about the relationship between profits and costs in determining the number of technicians. However, the reason behind the observed shift in the 11th month cannot be fully understood from the graph alone. Therefore, a detailed analysis of revenue and costs is necessary in the subsequent sections to better explain this change.

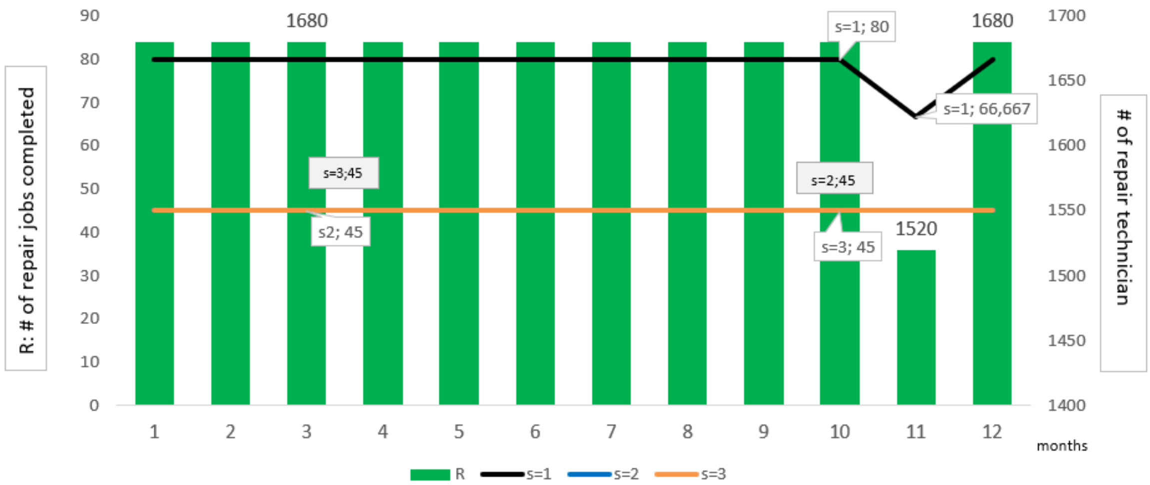

Figure 5.3. Repair technicians and jobs.

Another possible interpretation of this outcome is that the distribution is not solely driven by unit cost but also by other constraints in the model such as revenue. For instance, since $s = 1$ technicians may contribute to higher number of sales than others. The model may prefer to increase their number despite the higher unit cost since the objective is to maximize the profit. The revenue coming from skill becomes less as it goes from 1 to 3. In order to demonstrate this, unit cost for installation technicians is also calculated. The comparison for installation technician's revenue and technician cost regarding this inference is shown in Table 5.4.

Table 5.4. Technician cost and sales revenue comparison.

n	$Trev_n$	$Tcos_n$
1	19,600,000	6.420,000
2	19,600,000	6.420,000
3	19,600,000	6.420,000
4	21,522,000	7.536,000
5	23,010,000	8.400,000
6	23,010,000	8.400,000
7	19,600,000	6.420,000
8	19,600,000	6.420,000
9	19,600,000	6.420,000
10	19,600,000	6.420,000
11	18,920,000	6.420,000
12	23,010,000	8.400,000

Since revenue is one of the key factors affecting the total profit, it is examined in detail on product bases. To understand how the profit is affected, it is observed changes in both the volume and product revenues. We expect to see that these changes have an influence on total profit since net profit is defined by these parameters. For each month, product 1 consistently led in sales revenue, with product 2 and product 3 ranking second and third, respectively. The fact that product 1 has a higher unit selling price r'_p compared to other products, makes it expectedly the largest contributor to total revenue. Additionally, product sale revenue is also influenced by technician skill levels. According to the model parameters, the skill coefficients defined for product 1 are higher than those of the skill levels of other products as can be seen from Table 5.2. As a result, product 1 has a greater impact on total revenue compared to the other products. This fact can be observed from Figure 5.4. Table 5.2 can also be a part of the evaluation process for making changes to products in the future. This analysis is useful for needs such as adding a new product or determining new prices for the existing products.

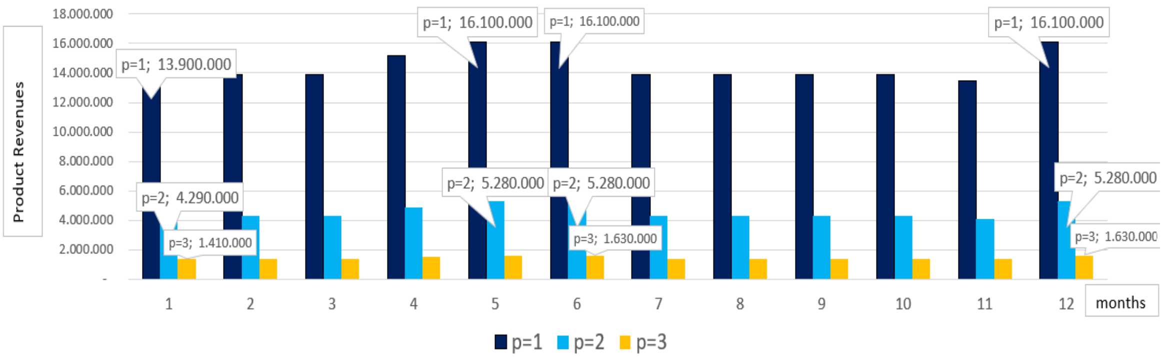

Figure 5.4. Revenues of products.

In order to identify which region(s) exceeded the target complaint rate, the distribution of the overflow complaint costs across regions is calculated in Table A.3. Since the complaint rate in Region 1 is higher than those of the other regions and exceeds the threshold value, it results in a non zero overflow cost.

Table 5.5. Monthly financial breakdown and profit calculation.

n	$Trev_n$	w_n	$Tcost_n$	Tcc_n	$fcost_n$	**Profit**
1	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
2	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
3	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
4	21,522,000	957,000	11,511,000	9,163,600	297,600	1,506,800
5	23,010,000	957,000	12,375,000	9,624,400	345,600	1,622,000
6	23,010,000	957,000	12,375,000	9,624,400	345,600	1,622,000
7	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
8	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
9	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
10	19,600,000	957,000	10,395,000	8,568,400	235,600	1,358,000
11	18,920,000	829,000	9,995,000	8,364,800	216,400	1,172,800
12	23,010,000	957,000	12,375,000	9,624,400	345,600	1,622,000
Total	246,672,000	11,356,000	131,396,000	106,380,400	3,200,000	17,051,600

6. SCENARIO ANALYSIS

Using the model as a reference, an operational planning framework can be developed under current conditions, and the expected revenues and costs can be evaluated accordingly. In this section, two modifications are made by extending the model to address potential alternative scenarios. Given the high level of variability and uncertainty in the service sector particularly due to the dynamic nature of consumer preferences, these scenarios aim to provide insight into possible operational adjustments.

The first scenario considers a potential increase in the volume of operations. An operational expansion of this nature would require enhanced capacity, and therefore, the need for investment in new system infrastructure is examined. The analysis focuses on both the financial implications of this investment and its expected impact on operational efficiency.

The second scenario explores the introduction of a new product to the market. While the model originally includes three different products, the company aims to reach a broader consumer and improve its profit margins through product diversification. Following the introduction of a new product, the profit target to be obtained from field service is added as a constraint. Based on this target, the required number of technicians is calculated under three different unit sales price scenarios. This approach enables a comparative assessment of resource needs depending on the pricing strategy of the new product. Both scenarios serve as strategic tools to support decision-making processes and operational capacity planning in a highly dynamic market environment.

6.1. Scenario 1: Strategic Investment in System Infrastructure Driven by the Growth in Service Demand.

Increased demand for both installation and repair are defined in the model. In certain situations, companies are driven to adopt strategic infrastructure upgrades to meet increasing service demands. With the new system to be purchased, both the additional demand can be met and the technological infrastructure can be made faster, more reliable and digitally. In this sense, although the system infrastructure seems reasonable in the long term, it can often be a more expensive option and take a long time to adapt. For these reasons, this alternative scenario is prepared.In Scenario 1, $v = 0.15$ increase in total demand for both installation and repair operations is assumed. The growth in service demand is represented as

$$(1+v)T_{inst} = \sum_{n=1}^{N} M_n^{new} \tag{6.1}$$

$$(1+v)T_{rep} = \sum_{n=1}^{N} R_n^{new}. \tag{6.2}$$

Since the total demand is updated, the model recalculates the new values for M_n and R_n accordingly, their new values are denoted by M_n^{new} and R_n^{new}. The newly planned system is expected to increase the job completion capacity of technicians by 10%. Therefore, following constraints are updated by multiplying the coefficient h= 0.1. New constraints for job capacities are defined as

$$M_n^{new} = \sum_{s=1}^{S} D_i z_{sn}^{new} a_{sm}(1+h) \quad i=1, n=1,\dots,N \tag{6.3}$$

$$R_n^{new} = \sum_{s=1}^{S} D_i y_{sn}^{new} b_{sn}(1+h) \quad i=2, n=1,\dots,N. \tag{6.4}$$

Based on these changes, the model recalculates the values of z_{sn} and y_{sn}, which are denoted as z_{sn}^{new} and y_{sn}^{new}, respectively. The updated constraints can be expressed as

$$\sum_{s=1}^{S}(1+e)z_{sn}^{new} \leq (1+e)I^{max} \quad n=1,\dots,N \tag{6.5}$$

$$\sum_{s=1}^{S}(1+e)y_{sn}^{new} \leq (1+e)Q^{max} \quad n=1,\dots,N. \tag{6.6}$$

In response to the increased workload, the updated z_{sn}^{new} and y_{sn}^{new} values are unable to exceed maximum number of technician constraint, and thus the model could not fully accommodate the total job volume. increasing only the workload capacity of the technicians led to infeasibility due to the presence of upper bounds. Therefore, the upper bound related constraints which are (6.5) and (6.6) also adjusted by multiplying e value to allow fulfill demand.

The numbers of installation and repair technicians are summarized in Table 6.1 according to these constraints. Upon examining the table, it is observed that there is an increase in these values compared to the ones calculated by the original model.

Table 6.1. Installation and repair technicians in scenario 1.

n	z_{1n}	z_{2n}	z_{3n}	y_{1n}	y_{2n}	y_{3n}
1	100	251	100	97	45	45
2	166.837	184.164	100	45	45	45
3	100	251	100	45	45	45
4	100	251	100	97	45	45
5	100	251	100	97	45	45
6	100	251	100	97	45	45
7	100	251	100	97	45	45
8	100	251	100	97	45	45
9	100	251	100	97	45	45
10	100	251	100	97	45	45
11	100	251	100	97	45	45
12	100	251	100	59.427	45	45

Based on the data presented in the in Figure 6.1, both on a monthly basis and in aggregate, it is observed that the highest revenue is generated from product 1, whereas product 3 consistently yields the lowest revenue. This disparity likely reflects differences in sales volumes and pricing strategies among the products. It can be stated that this trend is consistent with the observations made in the original scenario.

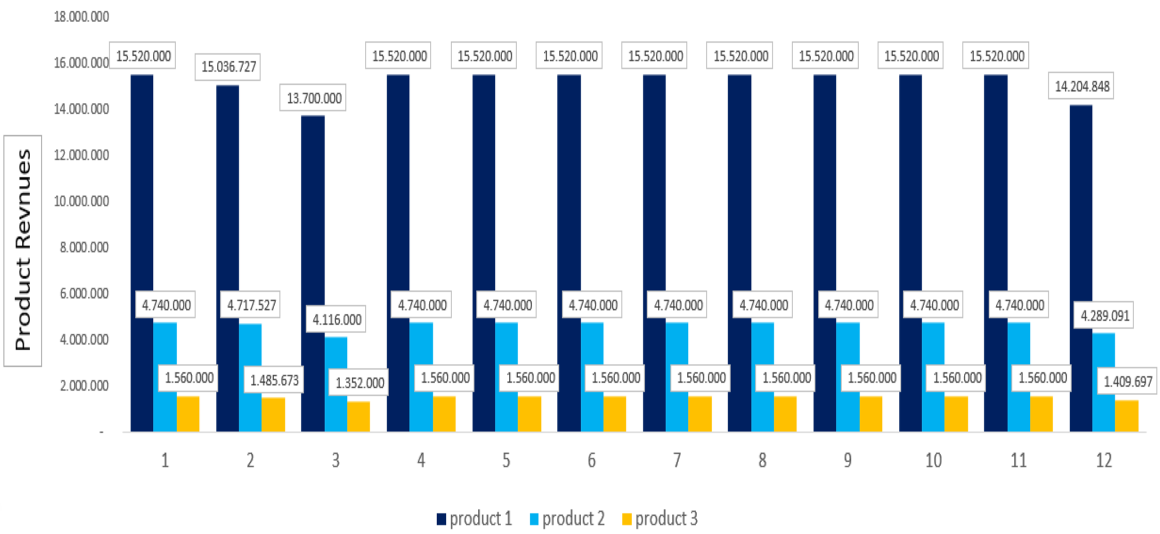

Figure 6.1. Revenues of products for scenario 1.

It can still be concluded that product 1 remains the primary source of revenue in any scenario where changes occur. However, Table 6.2 presents the percentage changes in revenue shares. According to these results, product 3 exhibits a greater increase compared to product 2. In other words, the volume growth has had a more favorable impact on product 3 than on product 2. In future analyses, for instance when investment decisions need to be made at the product level, this table should be taken into consideration, given the evident potential for volume growth in product 3.

Table 6.2. Monthly percentage change by product.

n	$p' = 1$ (%)	$p' = 2$ (%)	$p' = 3$ (%)
1	11.7	10.5	10.6
2	8.2	10.0	5.4
3	-1.4	-4.1	-4.1
4	2.5	-2.2	1.7
5	-3.6	-10.2	-4.3
6	-3.6	-10.2	-4.3
7	11.7	10.5	10.6
8	11.7	10.5	10.6
9	11.7	10.5	10.6
10	11.7	10.5	10.6
11	15.5	14.8	15.0
12	-11.8	-18.8	-13.5
Total	4.9	1.7	3.6

The distribution of revenues and expenses are summarized in Table 6.3. When compared with Table 5.5, it is observed that in Scenario 1, which involves an increase in job volumes, the monthly and total profit decreases. This is an unexpected outcome for this model, given that product revenues are higher and are assumed to have a stronger positive impact. Upon further investigation into the reasons for the reduced profit, it is evident that both revenues and costs are increased. In particular, the increases in complaint cost and over complaint costs of which are higher than those in the original model—have negatively affected profitability.

Table 6.3. Monthly financial summary for scenario 1.

n	$Trev_n$	w_n	$Tcost_n$	Tcc_n	$fcost_n$	Profit
1	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
2	21,239,927	683,100	11,040,055	10,073,513	310,380	499,080
3	19,168,000	683,100	9,837,000	9,367,721	236,860	409,519
4	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
5	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
6	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
7	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
8	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
9	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
10	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
11	21,820,000	1,232,220	11,397,000	10,241,165	319,228	1,094,827
12	19,903,636	835,420	10,269,727	9,610,005	259,708	599,616
Total	256,691,564	13,291,600	133,719,782	121,221,724	3,680,000	11,361,658

6.2. Scenario 2: The Marketing Team Launches a New Product

When a new product comes to the market, it can either take a share from the existing products or generate a new source of income by creating a completely different market. In this model, new product does not effect the existing product's sale. For the new fourth product, a new price and quantity is added to the model. The unit selling price for product 4 is determined based on the average selling price of the three products included in the original model. In scenario 2, it is observed how the addition of a new product to the model affects the number of technicians, sales revenue and net profit. Depending on the net profit, it is decided whether the launch of new product takes place.

It appears that months 3, 4, and 8 correspond to periods with the highest job volume in Figure 6.2. In these months, the model tends to allocate the maximum number of technicians possessing skill level $s = 1$. It is observed that this particular skill group is heavily utilized to meet the demand.

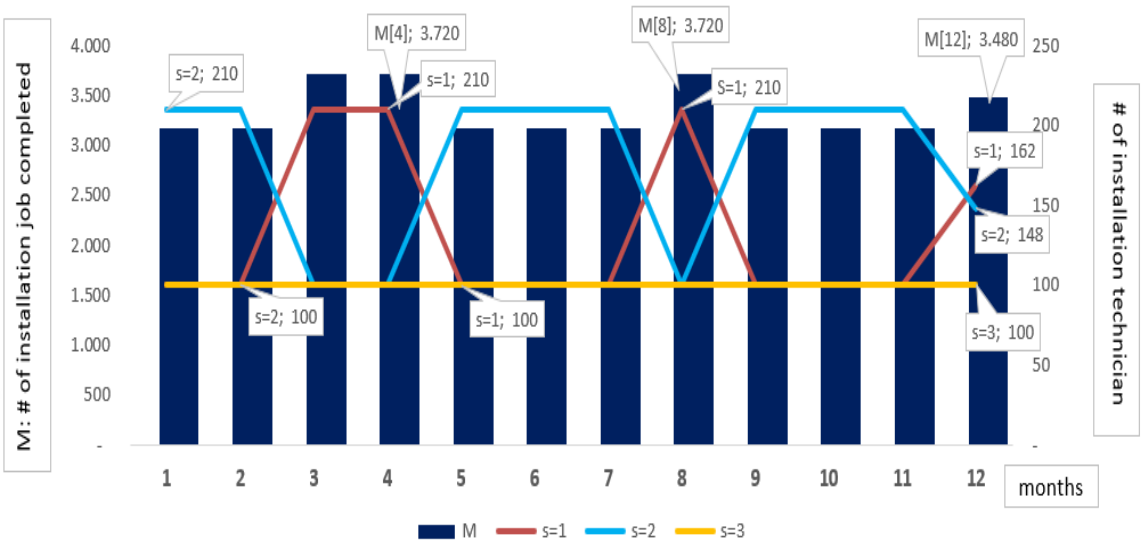

Figure 6.2. Number of installation jobs after new product.

It appears that months 3, 4, and 8 correspond to periods with the highest job volume in Figure 6.2. In these months, the model tends to allocate the maximum number of technicians possessing skill level $s = 1$. It is observed that this particular skill group is heavily utilized to meet the demand.

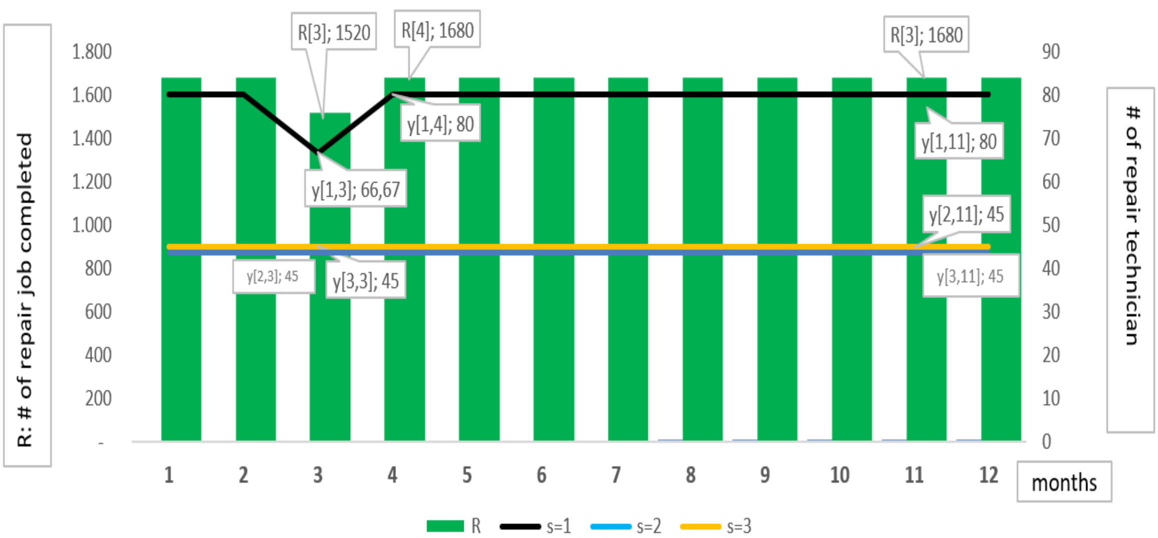

Figure 6.3. Number of installation jobs after new product.

Moreover, when comparing the original model with scenario 2 for the three existing product groups, it is observed that the total annual revenue generated from these products remains unchanged. This outcome aligns with expectations, as the total number of technicians allocated across the year has not been altered. However, due to the monthly redistribution of technician assignments in scenario 2, the revenue contributions from each product vary on a monthly basis. This monthly fluctuation in product level revenues is evident in Table 6.4 and reflects the impact of temporal adjustments in technician allocations.

Table 6.4. Monthly revenue comparison: original model vs.scenario 2.

n	Original Model (3 Products)	Scenario 2 (3 Products)	New Product Revenue	Scenario 2 (4 Products)
1	19,600,000	19,600,000	3,480,000	23,080,000
2	19,600,000	19,600,000	3,480,000	23,080,000
3	19,600,000	22,330,000	3,400,000	25,730,000
4	21,522,000	23,010,000	3,480,000	26,490,000
5	23,010,000	19,600,000	3,480,000	23,080,000
6	23,010,000	19,600,000	3,480,000	23,080,000
7	19,600,000	19,600,000	3,480,000	23,080,000
8	19,600,000	23,010,000	3,480,000	26,490,000
9	19,600,000	19,600,000	3,480,000	23,080,000
10	19,600,000	19,600,000	3,480,000	23,080,000
11	18,920,000	19,600,000	3,480,000	23,080,000
12	23,010,000	21,522,000	3,480,000	25,002,000

In Scenario 2, with the introduction of the new product, it is observed that the sales volumes and complaint rates of the existing products remain unchanged. Detailed tables on product-level quantities and complaint counts for the new model are provided in Tables B.1, B.2 and B.3. When these tables are compared with those from the original model, it is clearly evident that there is no significant change.

All revenues and expenses are presented on a monthly basis in Table 6.5. The new product significantly increases the monthly and total profit compared to the original model. Although no explicit profit target is set in the model, if the calculated profit is to be achieved, it is evident that the new product's unit sales efficiency should be at least equal to the average of the three existing products in other models. Additionally, it is observed that the new product alters the monthly distribution balance. Therefore, if the change in monthly distribution balance is not desired, additional constraints need to be incorporated into the model.

Table 6.5. Monthly financial breakdown and profit calculation for scenario 2.

n	$Trev_n$	w_n	$Tcost_n$	Tcc_n	$fcost_n$	Profit
1	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
2	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
3	25,730,000	829,000	11,975,000	9,420,800	326,400	4,836,800
4	26,490,000	957,000	12,375,000	9,624,400	345,600	5,102,000
5	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
6	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
7	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
8	26,490,000	957,000	12,375,000	9,624,400	345,600	5,102,000
9	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
10	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
11	23,080,000	957,000	10,395,000	8,568,400	235,600	4,838,000
12	25,002,000	957,000	11,511,000	9,163,600	297,600	4,986,800
Total	288,352,000	11,356,000	131,396,000	106,380,400	3,200,000	58,731,600

7. CONCLUSION

This chapter provides a comprehensive summary of the key findings presented in this thesis and discusses their implications within the context of the proposed model. First, the main conclusions are presented based on the analyses and outcomes. Then, possible extensions and future research directions are outlined to guide further development and application of the model.

7.1. Conclusions

In this thesis, an optimization model is developed for FSM using linear programming. The model incorporates multiple variables and constraints, including the number of technicians, product varieties, sales revenues, monthly salaries, and regional complaints. These variables and parameters are commonly encountered in field service operations and represent a realistic reflection of real-world conditions.

Initially, a model is developed, and based on the constraints of this model, region-based, product-based, and technician-based analyses were conducted. According to the results, it is possible to say that revenues from installation technicians are higher, while most of the costs are attributed to repair technicians due to complaints related to repair work. Furthermore, according to the region-based distribution analysis, the highest number of complaints and the associated costs occur in Region 1. The primary reason for this is the greater workload in both installation and repair tasks in Region 1 compared to other regions. Therefore, it is expected that Region 1 would have the highest volume of complaints. However, it is previously unknown whether the complaint rate exceeds the target or which regions surpasses this threshold. This analysis provides valuable insights regarding these questions. Additionally, the model's prioritization criteria for technician and task assignment helps us to understand the conflict resolution principle embedded in the model. This understanding provides a crucial foundation for the development and evaluation of new scenarios.

In Scenario 1, the increase in workload is taken into account and the constraints are accordingly updated. This rise in workload led to a significant change in the model's outcomes. The maximum profit in the new scenario decreases compared to the original model. Detailed analysis reveals that this decline is primarily due to an increase in complaint costs. Additionally, analyses of the quantities sold for each product by region, technician skill level, and product type are conducted and compared with the original model. This scenario can be regarded as a planned model that alerts field service managers in advance and keeps them prepared for the potential outcomes resulting from an increase in workload. Especially during periods when costs rise due to factors such as inflation, an increase in workload might be perceived as positive since it could lead to higher sales revenues. However, results from Scenario 2 indicate that even a 0.15 increase in job volume reduces our profit. This highlights to managers the necessity of developing differentiated classifications and strategies according to varying conditions.

Moreover, Scenario 2 was developed to assess how the introduction of a new product would affect the original model. The fourth product is evaluated based on the average price of the existing three and the resulting outcomes are compared with the original model. The model indicates that the fourth product generates high sales revenue, positively impacting profit.

To reflect real-world conditions, variables such as the number of technicians are initially modeled as integers. Nevertheless, instead of solving the model as a MILP, its LP relaxation is used to improve tractability. This is because MILP models typically involve significantly higher computational complexity compared to LP, which makes it difficult to solve large-scale problems and limits the ability to conduct effective sensitivity analysis. LP helps explore the feasible region and offers bounds for the model, aiding in the evaluation of solution quality. Continuous solutions enable effective sensitivity and parametric analysis, since they respond more smoothly to parameter changes compared to the discrete nature of MILP.

7.2. Potential New Research Directions

The launch of a new product can either reduce the demand for current offerings or open up new revenue opportunities by addressing distinct customer needs. In the context of this model, it is assumed that existing product sales remain stable. In future studies, the model could be further developed by incorporating characteristics such as the potential negative impact of the new product on the sales revenues of existing products, as well as possible increases in complaint rates.

The model proposed in this thesis defines the objective function as profit maximization. For future studies, multi-objective optimization frameworks could be explored by incorporating additional performance indicators such as customer satisfaction and complaint rates, particularly in regions with low service quality. These KPI's can be included alongside profit as concurrent objectives. Alternatively, a weighted multi-objective approach may be employed, assigning different weights to each objective according to their relative importance, thereby enabling a more balanced and comprehensive optimization of service performance.

In the service sector, seasonal changes in job volumes are an important factor that affects the profitability of field service management. Future research could integrate these predictable seasonal demand patterns into modeling frameworks or examine in detail how such seasonal fluctuations alone affect profitability, along with evaluating potential strategic actions that could be taken in response. For instance, it is noted in [21] that shifting customer demand from high-demand to low-demand periods has limited impact on profitability. Alternatively, bundling approaches where off-peak services are packaged with peak-time purchases, prove to be more effective in encouraging demand and improving profit margins.

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APPENDIX A: APPLICATION RESULTS

In order to comprehensively understand the results of the model, detailed analyses are conducted across various categories. Various breakdowns, including workforce allocation by skill and job type, are examined to provide deeper insights. Monthly distribution of technicians according to their job type and skill level, illustrating the overall workforce allocation patterns over n period of time is analyzed in Table A.1.

Table A.1. Monthly distribution of technicians by job type and skill level.

n	z_{1n}	z_{2n}	z_{3n}	y_{1n}	y_{2n}	y_{3n}
1	100	210	100	80	45	45
2	100	210	100	80	45	45
3	100	210	100	80	45	45
4	162	148	100	80	45	45
5	210	100	100	80	45	45
6	210	100	100	80	45	45
7	100	210	100	80	45	45
8	100	210	100	80	45	45
9	100	210	100	80	45	45
10	100	210	100	80	45	45
11	100	210	100	66.677	45	45
12	210	100	100	80	45	45

Table A.2 presents the monthly product quantities categorized by the combination of skill and region. This breakdown provides insights into the distribution of workload across different skill levels and geographic areas, facilitating a detailed analysis of resource allocation patterns.

Table A.2. Monthly product quantities by skill and region combinations.

s	n	$p'=1$				$p'=2$				$p'=3$			
		r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4
1	1	360	180	90	270	200	100	50	150	160	80	40	120
	2	360	180	90	270	200	100	50	150	160	80	40	120
	3	360	180	90	270	200	100	50	150	160	80	40	120
	4	583.2	291.6	145.8	437.4	324	162	81	243	259.2	129.6	64.8	194.4
	5	756	378	189	567	420	210	105	315	336	168	84	252
	6	756	378	189	567	420	210	105	315	336	168	84	252
	7	360	180	90	270	200	100	50	150	160	80	40	120
	8	360	180	90	270	200	100	50	150	160	80	40	120
	9	360	180	90	270	200	100	50	150	160	80	40	120
	10	360	180	90	270	200	100	50	150	160	80	40	120
	11	360	180	90	270	200	100	50	150	160	80	40	120
	12	756	378	189	567	420	210	105	315	336	168	84	252
2	1	420	210	105	315	168	84	42	126	0	0	0	0
	2	420	210	105	315	168	84	42	126	168	84	42	126
	3	420	210	105	315	168	84	42	126	168	84	42	126
	4	296	148	74	222	118.4	59.2	29.6	88.8	168	84	42	126
	5	200	100	50	150	80	40	20	60	118.4	59.2	29.6	88.8
	6	200	100	50	150	80	40	20	60	80	40	20	60
	7	420	210	105	315	168	84	42	126	80	40	20	60
	8	420	210	105	315	168	84	42	126	168	84	42	126
	9	420	210	105	315	168	84	42	126	168	84	42	126
	10	420	210	105	315	168	84	42	126	168	84	42	126
	11	420	210	105	315	168	84	42	126	168	84	42	126
	12	200	100	50	150	80	40	20	60	168	84	42	126
3	1	0	0	0	0	40	20	10	30	0	0	0	0
	2	0	0	0	0	40	20	10	30	0	0	0	0
	3	0	0	0	0	40	20	10	30	0	0	0	0
	4	0	0	0	0	40	20	10	30	0	0	0	0
	5	0	0	0	0	40	20	10	30	0	0	0	0
	6	0	0	0	0	40	20	10	30	0	0	0	0
	7	0	0	0	0	40	20	10	30	0	0	0	0
	8	0	0	0	0	40	20	10	30	0	0	0	0
	9	0	0	0	0	40	20	10	30	0	0	0	0
	10	0	0	0	0	40	20	10	30	0	0	0	0
	11	0	0	0	0	40	20	10	30	0	0	0	0
	12	0	0	0	0	40	20	10	30	0	0	0	0

The current monthly overflow complaint rate across different regions is illustrated in Table A.3. This allows for a detailed assessment of regions and time periods where the overflow rate is above the target level, enabling the identification of potential operational challenges. By examining these variations, insights can be gained into seasonal effects, and areas that may benefit from targeted resource adjustments or process improvements to enhance overall service performance.

Table A.3. Current monthly overflow complaint rate by region.

n	r_1 (%)	r_2 (%)	r_3 (%)	r_4 (%)
1	1.39	0.23	0.24	0.55
2	1.39	0.23	0.24	0.55
3	1.39	0.23	0.24	0.55
4	1.50	0.24	0.25	0.59
5	1.58	0.25	0.25	0.63
6	1.58	0.25	0.25	0.63
7	1.39	0.23	0.24	0.55
8	1.39	0.23	0.24	0.55
9	1.39	0.23	0.24	0.55
10	1.39	0.23	0.24	0.55
11	1.36	0.22	0.22	0.54
12	1.58	0.25	0.25	0.63

APPENDIX B: APPLICATION RESULTS FOR SCENARIOS

This chapter presents the application results for the scenarios. The tables provide detailed insights into the allocation of sales and revenues across different products and periods.

Table B.1. Skill and region assignment across products for scenario 2.

Skill	Month	$p' = 1$				$p' = 2$				$p' = 3$			
s	n	r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4
	1	360	180	90	270	200	100	50	150	160	80	40	120
	2	360	180	90	270	200	100	50	150	160	80	40	120
	3	756	378	189	567	420	210	105	315	336	168	84	252
	4	756	378	189	567	420	210	105	315	336	168	84	252
	5	360	180	90	270	200	100	50	150	160	80	40	120
1	6	360	180	90	270	200	100	50	150	160	80	40	120
	7	360	180	90	270	200	100	50	150	160	80	40	120
	8	756	378	189	567	420	210	105	315	336	168	84	252
	9	360	180	90	270	200	100	50	150	160	80	40	120
	10	360	180	90	270	200	100	50	150	160	80	40	120
	11	360	180	90	270	200	100	50	150	160	80	40	120
	12	583.2	291.6	145.8	437.4	324	162	81	243	259.2	129.6	64.8	194.4
	1	420	210	105	315	168	84	42	126	168	84	42	126
	2	420	210	105	315	168	84	42	126	168	84	42	126
	3	200	100	50	150	80	40	20	60	80	40	20	60
	4	200	100	50	150	80	40	20	60	80	40	20	60
	5	420	210	105	315	168	84	42	126	168	84	42	126
2	6	420	210	105	315	168	84	42	126	168	84	42	126
	7	420	210	105	315	168	84	42	126	168	84	42	126
	8	200	100	50	150	80	40	20	60	80	40	20	60
	9	420	210	105	315	168	84	42	126	168	84	42	126
	10	420	210	105	315	168	84	42	126	168	84	42	126
	11	420	210	105	315	168	84	42	126	168	84	42	126
	12	296	148	74	222	118.4	59.2	29.6	88.8	118.4	59.2	29.6	88.8

Table B.1. Skill and region assignment across products for scenario 2 (cont.).

Skill	Month	$p'=1$				$p'=2$				$p'=3$			
s	n	r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4	r_1	r_2	r_3	r_4
3	1	0	0	0	0	40	20	10	30	0	0	0	0
	2	0	0	0	0	40	20	10	30	0	0	0	0
	3	0	0	0	0	40	20	10	30	0	0	0	0
	4	0	0	0	0	40	20	10	30	0	0	0	0
	5	0	0	0	0	40	20	10	30	0	0	0	0
	6	0	0	0	0	40	20	10	30	0	0	0	0
	7	0	0	0	0	40	20	10	30	0	0	0	0
	8	0	0	0	0	40	20	10	30	0	0	0	0
	9	0	0	0	0	40	20	10	30	0	0	0	0
	10	0	0	0	0	40	20	10	30	0	0	0	0
	11	0	0	0	0	40	20	10	30	0	0	0	0
	12	0	0	0	0	40	20	10	30	0	0	0	0

Table B.2. Monthly revenue comparison by product for scenario 2.

p'	n	Current	Scenario 2	Gap
1	1	13,900,000	13,900,000	-
	2	13,900,000	13,900,000	-
	3	13,900,000	15,633,333	1,733,333
	4	15,140,000	16,100,000	960,000
	5	16,100,000	13,900,000	-2,200,000
	6	16,100,000	13,900,000	-2,200,000
	7	13,900,000	13,900,000	-
	8	13,900,000	16,100,000	2,200,000
	9	13,900,000	13,900,000	-
	10	13,900,000	13,900,000	-
	11	13,433,333	13,900,000	466,667
	12	16,100,000	15,140,000	-960,000

Table B.2. Monthly revenue comparison by product for scenario 2 (cont.).

p'	n	Current	Scenario 2	Gap
2	1	4,290,000	4,290,000	-
	2	4,290,000	4,290,000	-
	3	4,290,000	5,120,000	830,000
	4	4,848,000	5,280,000	432,000
	5	5,280,000	4,290,000	-990,000
	6	5,280,000	4,290,000	-990,000
	7	4,290,000	4,290,000	-
	8	4,290,000	5,280,000	990,000
	9	4,290,000	4,290,000	-
	10	4,290,000	4,290,000	-
	11	4,130,000	4,290,000	160,000
	12	5,280,000	4,848,000	-432,000
3	1	1,410,000	1,410,000	-
	2	1,410,000	1,410,000	-
	3	1,410,000	1,576,667	166,667
	4	1,534,000	1,630,000	96,000
	5	1,630,000	1,410,000	-220,000
	6	1,630,000	1,410,000	-220,000
	7	1,410,000	1,410,000	-
	8	1,410,000	1,630,000	220,000
	9	1,410,000	1,410,000	-
	10	1,410,000	1,410,000	-
	11	1,356,667	1,410,000	53,333
	12	1,630,000	1,534,000	-96,000

Table B.3. Monthly complaint rates by region in scenario 2.

n	r_1 (%)	r_2 (%)	r_3 (%)	r_4 (%)
1	1.39	0.23	0.24	0.55
2	1.39	0.23	0.24	0.55
3	1.54	0.24	0.23	0.62
4	1.58	0.25	0.25	0.63
5	1.39	0.23	0.24	0.55
6	1.39	0.23	0.24	0.55
7	1.39	0.23	0.24	0.55
8	1.58	0.25	0.25	0.63
9	1.39	0.23	0.24	0.55
10	1.39	0.23	0.24	0.55
11	1.39	0.23	0.24	0.55
12	1.50	0.24	0.25	0.59