ENERGY-EFFICIENT LOADING AND SCHEDULING OF AUTOCLAVES IN AEROSPACE COMPOSITE MANUFACTURING

ZEYNEP ÖRDEN

FEBRUARY 2023

ÇANKAYA UNIVERSITY

GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

DEPARTMENT OF INDUSTRIAL ENGINEERING

M.Sc. Thesis in

INDUSTRIAL ENGINEERING

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ABSTRACT

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ÖRDEN, ZEYNEP
M.Sc. in Industrial Engineering

Supervisor: Prof. Dr. Mustafa Alp ERTEM
February 2023, 72 Pages

Energy is a critical factor for the economic development of countries. With the decrease in the resources that meet energy needs, energy costs have started to increase. For this reason, reducing energy consumption and using energy efficiently is vital.

The curing processes of composite materials, which are increasingly used in the aerospace industry, are carried out in autoclaves where energy consumption is intense. In this thesis, energy-efficient loading and scheduling in autoclaves are discussed. Considering the increasing energy costs, it is also aimed to save costs in the study to be carried out. In the study, Industry 4.0 applications were also used to determine the energy consumption of autoclaves. Although there are similar studies in the literature, no study has been found in which energy costs are included in the model.

Two models are proposed to solve the problem. Model 1 minimizes the curing completion time by considering the due dates of parts and material consumption dates of the materials to be cured. Model 2, on the other hand, uses the outputs of the first model as input and reschedules the curing hours of the jobs to minimize energy costs without changing the recipes and parts assigned to the autoclaves.

In the experiments carried out with the created data sets, it has been determined that the energy costs can be reduced by 12.38% on average with the proposed models. As a result of re-planning the real-life sample curing plans with the recommended models, a maximum of 62% energy cost savings were saved.

When the standard deviation increases in the energy cost during the day, the savings from the energy cost for that day also increase.

Keywords: Autoclave loading, Batch scheduling, Energy efficiency, Market clearing price, Electricity cost

ÖZET

ENERGY-EFFICIENT LOADING AND SCHEDULING OF AUTOCLAVES IN AEROSPACE COMPOSITE MANUFACTURING

ÖRDEN, ZEYNEP
Endüstri Mühendisliği Yüksek Lisans

Danışman: Prof. Dr. Mustafa Alp ERTEM
Şubat 2023, 72 Sayfa

Enerji, ülkelerin ekonomik kalkınması için kritik bir faktördür. Enerji ihtiyacını karşılayan kaynakların azalmasıyla birlikte enerji maliyetleri artmaya başlamıştır. Bu nedenle enerji tüketimini azaltmak ve enerjiyi verimli kullanmak hayati önem taşımaktadır.

Havacılık ve uzay endüstrisinde kullanımı giderek artan kompozit malzemelerin kürlenme işlemleri, enerji tüketiminin yoğun olduğu otoklavlarda yapılmaktadır. Bu tezde, otoklavlarda enerji tasarruflu yükleme ve çizelgeleme ele alınmıştır. Artan enerji maliyetleri göz önünde bulundurularak yapılacak çalışmada maliyet tasarrufu sağlanması da amaçlanmaktadır. Çalışmada, otoklavların enerji tüketimlerinin belirlenmesi için Endüstri 4.0 uygulamaları da kullanılmıştır. Literatürde benzer çalışmalar olmasına rağmen enerji maliyetlerinin modele dahil edildiği bir çalışmaya rastlanmamıştır.

Problemi çözmek için iki model önerilmiştir. Model 1, kürlenecek malzemelerin parça teslim tarihlerini ve malzeme tüketim tarihlerini dikkate alarak kürlenmeyi tamamlama süresini en aza indirir. Model 2 ise, ilk modelin çıktılarını girdi olarak kullanır ve otoklavlara atanan reçetelerde ve parçalarda değişiklik yapmadan enerji maliyetlerini en aza indirmek için işlerin kürlenme saatlerini yeniden planlar.

Oluşturulan veri setleri ile yapılan deneylerde, önerilen modeller ile enerji maliyetlerinin ortalama %12,38 oranında azaltılabileceği tespit edilmiştir. Önerilen modellerle gerçek hayattaki örnek kürleme planlarının yeniden planlanması sonucunda maksimum %62 oranında enerji tasarrufu sağlanmıştır.

Gün içerisinde enerji maliyetinde standart sapma arttığında, o gün için enerji maliyetinden elde edilen tasarruf da artmaktadır.

Anahtar Kelimeler: Otoklav yükleme, Yük çizelgeleme, Enerji verimliliği, Piyasa takas fiyatı, Elektrik maliyeti

ACKNOWLEDGEMENT

I want to express my deep gratitude to Prof. Dr. Mustafa Alp ERTEM for his supervision, guidance, feedback, and encouragement. I am very grateful to him for his invaluable patience and support that keeps me motivated and confident.

I owe special thanks to my colleague Sedat ERDOĞAN. This thesis would not have been possible without his experience.

My endless thanks go to my mother, Refiye ÖRDEN. I have achieved everything so far with her love and appreciation. Finally, I greatly appreciate my precious friend Deniz Buğra OĞUZ for his tremendous support and hope he has given to me.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

SYMBOLS

M	: Meter
M^2	: Square Meter
$^{\circ}C$	: Centigrade Degree
kW	: Kilowatt
kWh	: Kilowatt Hour
€	: Euro

ABBREVIATIONS

IoT	: Internet of Things
MCP	: Market Clearing Price
MIP	: Mixed Integer Programming
CP	: Constraint Programming
ILP	: Integer Linear Programming
OSP	: Oven Scheduling Problem
SCADA	: Supervisory Control and Data Acquisition

CHAPTER I
INTRODUCTION

Industry 4.0, the spreading solution components such as Big Data, Artificial Intelligence, Robotics, Internet of Things (IoT), Digital Twins, and Cloud Computing, represents the fourth industrial revolution, involving a new level of networking in manufacturing [1]. Productivity increases, downtime is reduced, and energy is saved using Industry 4.0 technologies. The primary purpose of these technologies is to collect and make sense of data for decision-making. Artificial Intelligence models use Big Data to automate processes, control robots, and facilitate complex decisions. IoT focuses on the remote control of manufacturing devices and has begun to be utilized for energy efficiency. Real-time monitoring via IoT provides efficient process control and automation. Digital Twin applications are used for preventive maintenance and repair operations by analyzing the data fed by sensors monitoring the manufacturing environment. The definitions in the literature and practice seem intertwined; hence, there are no well-agreed-upon boundaries among these Industry 4.0 technologies. While designing a process that includes Industry 4.0 technologies, all technologies and the benefits that can be obtained from them should be considered.

Industry 4.0 applications facilitate automation in processes. For the correct implementation of Industry 4.0, it is necessary to use the technologies that bring value to the right place in the right way. Robots, sensors, analyzers, and three-dimensional printers are central to Industry 4.0. Robots have become the driving force of automation, where it has never been before [2]. Robots evaluate the data collected by sensors and analyzers and then automate decisions. Sensor technologies are essential for collecting and using the data for effective performance [3]. Sensors help machines to capture data by communicating with each other. Sensors ensure better control of processes. While applying Industry 4.0 technologies, energy monitoring and measuring equipment are indisputable. Analyzers are also used for collecting data from processes. Energy analyzers are monitoring devices that enable continuous monitoring of electrical energy with up-to-date technologies, continuous recording of measurement data, and transmission of records by communicating with remote devices and software when necessary. Using Industry 4.0 technologies in energy monitoring and measurement processes saves the data collection process from being manual. After integrating energy monitoring and measuring equipment with Industry 4.0 technologies, the frequency and number of data collected are much higher than the energy data collected manually. This situation increases the accuracy of energy consumption data collected from the field with Industry 4.0 technologies.

Figure 1: Picture of Autoclave

Autoclaves are used in the aerospace industry for the curing of composites. Because composite materials are lightweight, they are the right tools to achieve energy efficiency [4]. Sensors are used for temperature and pressure control in autoclaves. Light composite materials have high fatigue strength and fire resistance and can be produced in large pieces suitable for this industry. The parts placed in the autoclave are first processed in the clean room. Here, pre-prepared composite materials are attached to the molds, and the parts on the tools are bagged and placed in the autoclave. The autoclave curing process consists of heating, waiting (curing), and cooling processes under the desired pressure to transform the pre-prepared material in layers into composite parts. The autoclave is first brought to the desired pressure and then heated with electricity or natural gas. When the desired temperature is reached, the material is kept at this temperature for a predetermined time. As a result of high temperature and pressure, the part is hardened. Finally, the material is cooled with fluid. Nitrogen is generally used to prevent combustion in the pressurization process. In addition, nitrogen in the autoclave is continuously circulated at high speeds during the heating, waiting, and cooling processes to obtain a homogeneous temperature distribution on the material. The detailed stages of the curing process are given in [5].

Autoclave ovens are large pressure vessels with adjustable internal pressure and temperature. Each composite part has its unique temperature and pressure values required for curing. These values are called recipes. Parts with the same recipe can be cured together. The wrapping process of the kits, which consists of layers of material that make up a single piece, is performed on a molding tool. These tools move with the part during the entire curing process. When enough parts are prepared to fill the autoclave, they are loaded and cured with the same recipe. After leaving the autoclave, the cured composite parts are separated from the molding tools. The tools are cleaned and made ready to lay the next piece. Ovens are highly energy-intensive, but because we can group multiple jobs with the same recipes in the same batch, ovens provide a potential advantage [6]. Unfortunately, this potential is sometimes wasted since unplanned (i.e., urgent) parts that must be delivered shortly to the customer can be cured without waiting for the autoclave to be filled in full. Since the cost of heating the autoclave is primarily independent of the number of parts loaded into the autoclave, such unplanned loads will get in the way of energy efficiency. Reducing the number of batches and increasing the capacity in each cycle will reduce the total cost. Therefore, scheduling is essential in autoclaves. While scheduling, the expiry date of the material to be prepared in the clean room, the delivery date of the part to be cured, the autoclave's capacity, the parts' recipes, and energy efficiency constraints should be considered.

The idea that energy demands should also be considered a planning factor in production planning is presented in [7]. The electrical energy consumed in the autoclaves is measured by energy analyzers connected to the autoclaves and with an energy monitoring system and a communication infrastructure. Autoclave curing recipes include pressure increase, heating, waiting, cooling, and pressure reduction stages [5]. When the energy consumption of these phases is examined, it is seen that the heating phase has the largest share. According to the data collected for this thesis, it was seen in the recipes examined that approximately 66% of the consumed electrical energy belongs to the heating phase, 25% belongs to the waiting phase, 5% belongs to the cooling, 4% belongs to the pressure increase and decrease phases.

While scheduling studies are carried out in autoclaves that consume electricity intensively, it should not be ignored that electricity prices change every hour. Examining energy price tariffs while creating scheduling models in autoclaves is suggested in [5]. The market clearing price (MCP) is the price that exists when a market is clear of shortage and surplus or is in equilibrium [8]. Day-ahead trading is offered by some electric power exchanges operating in Türkiye, Austria, Belgium, France, Germany, Luxembourg, the Netherlands, Switzerland, and Great Britain [9]. The electricity MCP keeps the market's fairness and avoids manipulation [10]. To correctly respond to the real-time electricity demand, it is necessary to foresee the demand at any time and plan the power plants that will meet the need at that hour. If electricity is produced more than the consumption demand, resources will be wasted, and costs will increase. Likewise, insufficient production causes interruptions in the electricity supply. In such a system, the amount of energy production and consumption must be kept in balance. The MCP is the electrical energy price of the most expensive power plant in the system at that time, which matches the point where the production and consumption balance is achieved. The schedules created by considering the market clearing price provide significant savings in energy costs with minor changes. In Türkiye, MCP is announced at 14:00 each day for the next day.

In this thesis, the issue of energy-efficient loading and scheduling of autoclaves is discussed. Although there are articles on autoclave scheduling in the literature, no study has been found to minimize energy costs. The research question we focus on in this study is as follows:

Is it possible to load and schedule autoclaves considering energy efficiency?

The remainder of this study is organized as follows. In the second part, a literature review on Industry 4.0 studies, production planning, energy efficiency, and autoclaves have been made. Chapter 3 explains the problem definition examined in the thesis studies and our solution methodology. The proposed mathematical model is solved with a small data set, and a sample result output is given. The fourth chapter explains the proposed models for the energy-efficient autoclave loading and scheduling problem. In Chapter 5, real-life data is given, and the model is applied to the firm's problem. The conclusion and suggestions for future work are given in the last section.

CHAPTER II
LITERATURE REVIEW

The literature review is accomplished in three sub-topics. First, articles about Industry 4.0 technologies are given. Secondly, energy efficiency in production planning is investigated to provide a broader view. Thirdly, previous studies on autoclave loading and scheduling are summarized, and the contribution of this thesis is highlighted.

2.1 INDUSTRY 4.0

With Industry 4.0 applications, the nature of the manufacturing processes has changed. In addition to its benefits, collecting more process data has become possible. It is vital to examine the data collected from the field. After collecting data from the field, it is essential to filter it, normalize it, and format it to be organized into critical process correlations that can be applied in scientific experiments. The biggest challenge is finding the right and adequate technology to process big datasets to extract value from them.

The applications of Big Data that can be realized within the scope of Industry 4.0 are mentioned in [11]. The primary purpose of these technologies is to collect accurate data. Data collected by sensors and other automated sources are structured, the data collected from manuals and books are semi-structured, and the data collected from images and diagrams are unstructured.

A study of layer height control with a sensor using a SINUMERIK™ controller shows that sensors transform machines into cyber-physical systems [12]. Sensors are crucial for Industry 4.0 technologies, digitalization, and preventative maintenance. Sensors and CNC controllers such as SINUMERIK™ can be used together for accurate and controlled processes. Digital Twin will become a reality thanks to these controllers [12]. With the upcoming developments, it is foreseen that sensors and self-adjusting welding robots will monitor the pre-process, in-process, and post-process processes.

The key concepts in Industry 4.0 and data analytics are discussed in [13]. Industry 4.0 focuses on operations, while data analytics focuses on statistics and computer science. Industry 4.0 and data analytics are perfect complements of each other, as the performance of a routine operation can be improved by intelligent decisions, and support from the routine operation is needed to collect data for intelligent decisions. Research conducted during the studies has shown that Industry 4.0 applications are used in fields such as energy, health, and agriculture [13].

It is seen that all technologies get in contact with each other at some point. When implementing a digital twin application, sensors are needed to capture data, while cloud computing can be used to store this data. Big Data, Artificial Intelligence, and Cyber-Physical Systems are categorized as data conditioning, storage, and processing technologies; IoT is categorized as data transfer technology.

Based on the reviewed articles, Table 1 is prepared for this thesis, where Industry 4.0 technology, its application, and the data collected from the manufacturing environment are mapped.

Table 1: Matching of Industry 4.0 technologies and applications

Technology / Application	Big Data	Digital Twin	Internet of Things	Artificial Intelligence	Cyber-Physical Systems
Energy Efficiency	X		X		X
Process Time Optimization	X		X		X
Virtual Workshop	X	X		X	
Image Processing	X			X	
Real-Time Processing	X			X	
Quality Assurance	X	X	X	X	X
Preventive Maintenance	X	X	X	X	X
Virtual Authentication	X	X		X	

2.2 ENERGY EFFICIENCY AND PRODUCTION PLANNING

While Industry 4.0 applications make our operations more manageable, it is seen in Table 1 that many technologies are also used to provide energy efficiency. Industry 4.0 technologies contributed to energy estimation and efficiency studies [14]. The use of Big Data technologies for short-term energy load estimation is discussed in

[15]. Mathematical and statistical analyzes were performed to analyze the effect of milling cutter rotation speed, cutting feed, and depth of cut on machining time and energy consumption [15]. It can be seen that Industry 4.0 applications are used to estimate energy consumption.

In addition to Industry 4.0 technologies, production planning models are used to utilize energy efficiency in production. A mathematical model based on empirical data is presented to study the effect of production planning decisions on energy efficiency in pressure casting processes [16]. This model aims to minimize the energy required to meet the demand for finished products based on the relationship between the speeds of the machines and their energy consumption. According to [16], focusing on the energy consumption of non-machining times and the operating speed is necessary.

Other articles supporting this study showing the effect of production planning on energy efficiency are also examined. The idea that energy demands should also be considered a planning factor in production planning is presented in [7]. This study defines the ISO 50001 Energy Management System standard as an energy policy and a set of interrelated or interacting elements to establish energy objectives, processes, and procedures to achieve these objectives. It is mentioned that production planning processes are also an area that can be used to optimize energy consumption and costs based on the strategies provided by the standard. This article [7] exemplifies that the mathematical models developed for this thesis will support energy efficiency activities while estimating energy consumption.

2.3 AUTOCLAVE LOADING AND SCHEDULING

Composite materials are increasingly used in the aircraft industry [17]; however, the autoclaves' production efficiency should be improved [18]. Autoclave operating parameters such as temperature and pressure are decided according to the resin system. Autoclaves are heated electrically or by indirect gas ignition. Electric heating is preferred because this heating system is more amenable to advanced computer controls. The cooling rate is controlled by varying the coolant flow. A closed-loop cooling system is used to save water.

An unpublished doctoral thesis studied the effect of increasing the number of tools on production planning [5]. Emphasizing that energy efficiency will be achieved by increasing the number of parts to be loaded, it is stated that companies' energy consumption profiles and price tariffs should also be examined in future studies. Based on this future research motivation, studies considering energy efficiency in loading and scheduling autoclaves were investigated here. However, no comprehensive study was found. Energy-efficient autoclave loading and scheduling in aerospace composite manufacturing is a topic that has not been studied before.

A new perspective for process control in autoclave composite production is given in [4]. In this article, the researchers emphasized that the pressure and temperature parameters for curing must be adapted for each part design and material combination. In autoclaves, the temperature is monitored by thermocouples. It is mentioned in [4] that Industry 4.0 technologies can be used effectively in this process. Industry 4.0 technologies, such as thermal cameras, can be used to monitor the temperature. Weight reduction in primary aircraft structures is proposed for the energy efficiency of the curing process [4].

Mixed Integer Programming (MIP) and Constraint Programming (CP) models for parallel machine batch-scheduling problems are proposed in [19] and [20]. In [19], the objective function minimizes the sum of weighted completion time. The researchers defended that heuristics may generate fast and effective solutions, but these solutions should be tailor-made. General MIP models are slow to solve large-sized scheduling problems. This study [19] showed that the MIP model performs better for the weighted completion time objective, and the CP model performs better in minimizing makespan [20].

CP and Integer Linear Programming (ILP) models that aim to minimize the cumulative batch processing time, total setup times, and setup costs, as well as the number of tardy jobs, are introduced in [6] as an Oven Scheduling Problem (OSP). The objective function includes energy consumption as well.

A two-staged approximate algorithm can solve the parallel machine batch-scheduling problem [21]. The second stage enhances the quality of the first stage solution. CP and ILP models are evaluated by their solution quality and computation time in [22]. These models can solve problems for realistic sizes.

The articles reviewed in the literature review are classified according to their topics in Table 2.

Table 2: Classification of literature review

<table>
<tr><th>Scope / Article</th><th>Autoclaves</th><th>Production Planning</th><th>Energy Efficiency</th><th>Industry 4.0 Applications</th></tr>
<tr><td>[4]</td><td colspan="2">Tricks and methods for autoclave operations</td><td></td><td>Energy efficiency tricks for processes in autoclaves</td></tr>
<tr><td>[5]</td><td colspan="2">Effect of increasing the number of tools on production planning for autoclaves</td><td></td><td></td></tr>
<tr><td>[6]</td><td colspan="2">Constraint Programming model and Integer Linear Programming model for Oven Scheduling Problem</td><td></td><td></td></tr>
<tr><td>[7]</td><td></td><td colspan="2">Energy demand as a planning factor in production planning</td><td></td></tr>
<tr><td>[11]</td><td></td><td></td><td></td><td>Collection of accurate data with Big Data</td></tr>
<tr><td>[12]</td><td></td><td></td><td></td><td>Digitalization and predictive maintenance with sensors</td></tr>
<tr><td>[13]</td><td></td><td></td><td></td><td>Relation of data analytics and Industry 4.0 technologies</td></tr>
<tr><td>[14]</td><td></td><td></td><td colspan="2">Short-term energy load estimation and energy efficiency studies with Big Data</td></tr>
<tr><td>[15]</td><td></td><td></td><td colspan="2">Use of Industry 4.0 applications for energy consumption estimation and effects of production mode on energy consumption</td></tr>
<tr><td>[16]</td><td></td><td colspan="2">The effect of production planning decisions on energy efficiency</td><td></td></tr>
<tr><td>[17]</td><td colspan="2">Two-dimensional rectangle bin packing problem model, mixed integer programming model, and hybrid model for autoclave molding scheduling problem</td><td></td><td></td></tr>
<tr><td>[18]</td><td>Description of autoclaves and systems inside</td><td></td><td></td><td></td></tr>
</table>

Table 2 Continued

[19]	Mixed Integer Programming model and Constraint Programming model for Oven Scheduling Problem		
[21]	A two-stage approximate algorithm for batch processing machine scheduling problem		
[22]	Finding exact methods and lower bounds for the Oven Scheduling Problem		
Thesis	MIP model for Energy Efficient Loading and Scheduling of Autoclaves and use of Industry 4.0 technologies to capture energy data from autoclaves		

CHAPTER III
PROBLEM DESCRIPTION AND SOLUTION METHODOLOGY

3.1 CURING PROCESS

The composite layers are bonded with resin and joined in autoclaves in the curing process. Autoclave ovens are large pressure vessels with adjustable internal pressure and temperature. High temperature and high pressure are the main factors that enable the composite layers to be bonded. The curing process consists of pressure increase, heating, waiting, cooling, and pressure reduction stages. Each composite part has its unique temperature and pressure values required for curing. These values are called recipes. Data such as the maximum temperature and pressure during each stage and duration are also included in the recipe.

The application for this thesis is motivated by the curing processes of an aerospace parts manufacturing company in Türkiye. The parts list is ordered according to the due date of each part. Then, the parts are grouped according to their recipes. Autoclave scheduling is made with the appropriate recipe and the size of the batches. When grouping, parts with the same pressure and temperature values are taken to the same cure group for curing.

The process of bonding composite materials with resin, bagging with plastic material, and vacuuming is carried out in the clean room. A vacuum bag applies additional pressure and protects the materials from the autoclave gases. For the parts to be taken from the clean room, the expiration date of the material gains importance. When loading autoclaves, the capacity of the clean room and knowledge of the parts that can be prepared are also necessary. Molding tools are required to prepare the part to be cured. The spreading of the material layers that make up a single part is performed on the tool. These tools move with the part during the entire curing process. If there is more than one type of part in the batch, the number of tools must also be considered. Thermocouples are used to control the temperature of the part during the curing process, and vacuum ports are used to control the pressure level. One end of this equipment is connected to the part, and the other is to the autoclave. When enough parts are prepared to fill the autoclave, the parts are loaded and cured in the autoclave with the same recipe. The autoclave is first brought to the desired pressure and then heated with electricity or natural gas. When the desired temperature is reached, the material is kept at this temperature for a predetermined time. As a result of high temperature and pressure, the part is hardened. Finally, the material is cooled with fluid. Nitrogen is generally used to prevent combustion in the pressurization process. In addition, nitrogen in the autoclave is constantly circulated at high speeds during the heating, waiting, and cooling processes to obtain a homogeneous temperature distribution on the material.

After the curing process, the parts are sent to the doffing area and separated from the tools. The tools are cleaned and made ready to lay the next piece. The flow of the explained process is given in Figure 2.

The composite layers are bonded with resin and joined in autoclaves in the curing process. Autoclave ovens are large pressure vessels with adjustable internal pressure and temperature. High temperature and high pressure are the main factors that enable the composite layers to be bonded. The curing process consists of pressure increase, heating, waiting, cooling, and pressure reduction stages. Each composite part has its unique temperature and pressure values required for curing. These values are called recipes. Information such as how many degrees the autoclave will heat between the stages and how many degrees it will be put on hold are also included in the recipe.

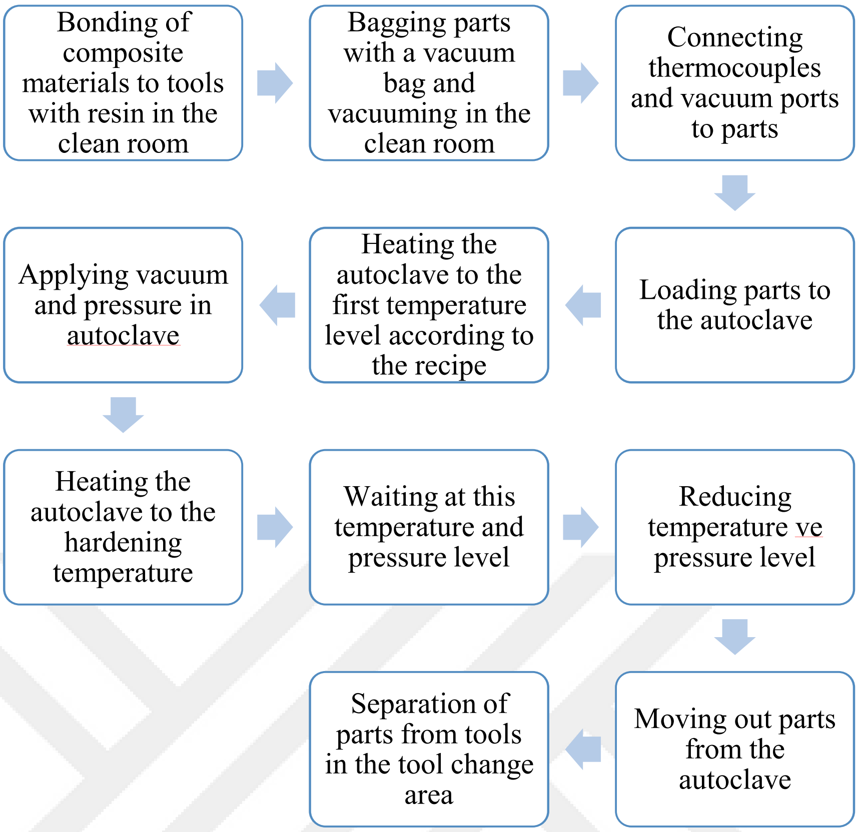

Figure 2: Cure process

Autoclaves have some advantages and disadvantages compared to other composite material production techniques. Advantages can be listed as follows:

- Ability to apply both heat and pressure in the same device,
- Being a well-known process,
- Good temperature homogeneity,
- Reasonable cost per piece when fully loaded.

Disadvantages can be listed as follows:

- High cost of capital,
- High maintenance cost,
- Take ample space,
- Due to low heat transfer:
  - High energy density,
  - Low-temperature rise/decrease rates,
  - Dwell time longer than necessary,
  - Fixed cure programs.

Figure 3: Schneider SCADA System

Energy analyzers can continuously monitor and determine electricity consumption. Automation systems such as RS-485 and CAT-6 cables are used for remote communication. Consumption records are created by making a data query over the device logs. Energy analyzers have become essential for energy efficiency studies based on the principle that you can't manage when you don't measure.

3.2 PROBLEM DESCRIPTION

Considering current conditions, the need for energy-efficient use of autoclaves cannot be denied. Although several studies about production planning, energy efficiency, Industry 4.0 applications, and autoclaves have been observed, no study covering all subjects has been found.

The main problem in the aviation industry's energy-efficient autoclave loading and scheduling is the lack of support for Industry 4.0 applications in the processes. Manual follow-ups are performed to control the processes, which are long and labor-intensive. With using of Industry 4.0 technologies, the accuracy of data increases. As a result of inefficient planning, the possibility of operating autoclaves below their capacity increases. High-priority parts are observed to be cured without waiting for the autoclave to be filled. Since the cost of heating the autoclave is primarily independent of the number of parts loaded into the autoclave, such actions will take precedence over energy efficiency. Unplanned interventions will result in more scrap. Since the cost of composite materials is high, the issue of energy efficiency is ignored during production scheduling, and a schedule is made only by considering the expiration and the due date. Unplanned parts are cured to eliminate the effects of inefficient schedules, increasing energy consumption and cost.

In practice, production planning is done manually based on experience. The current system is insufficient in efficiently assigning the correct parts and using the autoclave capacity. As a result of the meetings held with practitioners, the priority order of the issues to be considered during production planning is as follows:

1. Material expiration date
2. Delivery (i.e., due) date of the part
3. Autoclave and energy efficiency

3.3 SOLUTION METHODOLOGY

Considering the current problems, it is aimed to use the benefits of Industry 4.0 applications for energy-efficient autoclave loading and scheduling. Two mathematical models are proposed. Proposed Model 1 addresses the first and the second abovementioned issues. Model 1 considers the delay in the parts' expiration date and the due date of jobs while creating a schedule. Proposed Model 2 reschedules the jobs to minimize energy costs by using the outputs of the first model as an input. The batches scheduled in the first model can be shifted in a way that reduces the energy cost but does not allow for delays. Thus, practical considerations are considered by addressing the first and the second issues by Model 1 and then the third issue by Model 2. Hence, loading inefficiencies are solved with the proposed Model 1, and energy efficiency is achieved via the proposed Model 2

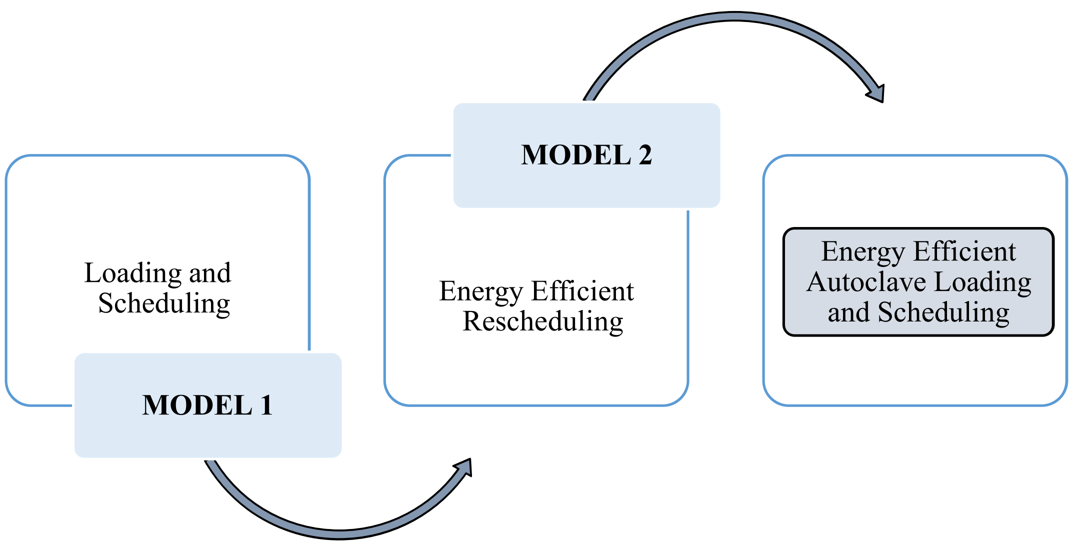

Figure 4: Proposed models

The assumptions taken into account while creating the model are listed below:

1. The setup time for loadings in the autoclave is ignored.
2. Scheduling is calculated on an hourly basis. Due date and expiration date parameters are kept on an hourly basis.

All parts can be cured in all autoclaves if they do not exceed autoclave batch capacity. There are no technical limitations.

3.4 A SKETCH OF THE SOLUTION APPROACH

Two autoclaves are assumed in the model to run with test data. There are fifteen parts (i.e., jobs) and three recipes. The planning horizon is determined as 24 hours, and it was decided to have four batches in each autoclave. The minimal number of batches is the sum of all jobs size divided by the largest machine capacity [22]. According to the given parameters, parts 4-5-7-11 belongs to recipe 1; parts 2-3-12-15 belong to recipe 2; parts 1-6-8-9-10-13-14 belong to recipe 3. Jobs in the same recipe can be cured together. The sum of the part areas cannot exceed the autoclave area. Parts are assumed to be available at the beginning of the planning horizon. Thus, the release time of all jobs is zero.

Model 1 minimizes the completion time of batches. Also, in Model 1, there is no delay in the expiration dates of materials and the due date of parts. Energy costs are not taken into account in Model 1. According to the first model, the energy cost resulting from the planned curing with the determined market clearing prices is € 2,745. The output of Model 1 is illustrated in Figure 5.

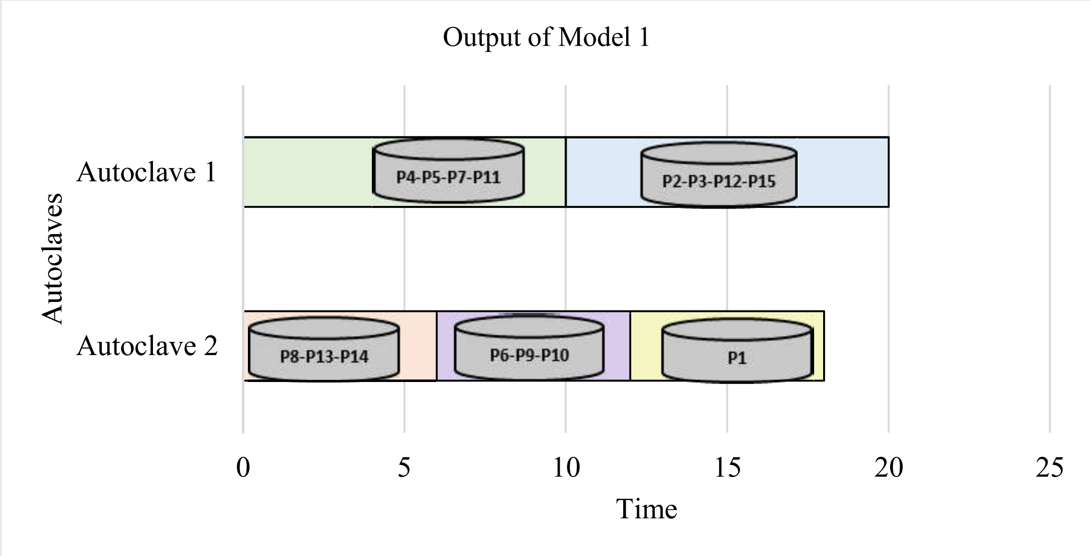

Figure 5: Illustration of Model 1 output

From Model 1 run with test data:

- Recipe information assigned to batch in the autoclave,
- Part information assigned to each batch in the autoclave,
- The processing time of each batch is given input to Model 2.

Model 2 minimizes energy costs. The energy cost varies depending on the start time of the recipe, which is used as a parameter. The time horizon constrains the completion time of the last batch. In Model 2, where energy costs are considered, the energy cost resulting from the planned curing is € 2,710. The output of Model 2 is illustrated in Figure 6.

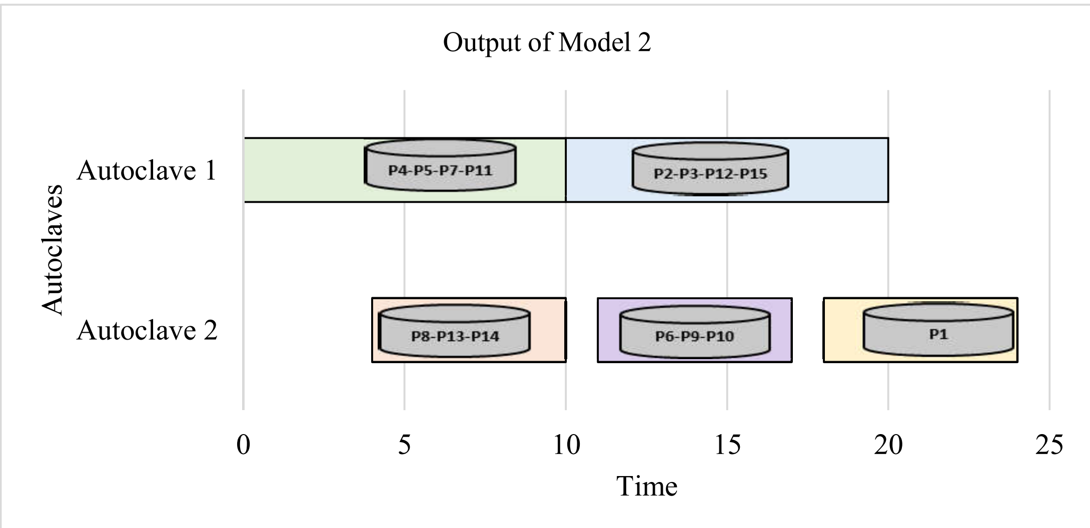

Figure 6: Illustration of Model 2 output

Thanks to the models feeding each other, energy costs can be reduced in Model 2 without making any changes in the batches in the autoclaves, the parts in the batches, and the sequences according to the outputs of Model 1.

CHAPTER IV
MATHEMATICAL MODEL

4.1 MODELING APPROACH

No mathematical model on autoclave loading and scheduling has been found that considers energy efficiency using Industry 4.0 applications. The closest study for loading and scheduling in autoclaves is [5]; maximum capacity usage is the objective. The focus of [5] is examining the effect of the number of tools on autoclave capacity usage. The electricity tariff was not considered. The due date for the parts is considered, but part expiration dates are ignored. This thesis considers the remaining time until the cure date because materials processed in a clean room should be cured until expiration.

The MIP-PA model is proposed in [19]. In [19], multiple jobs with the same recipes can be processed in the same batch. The total batch size does not exceed machine capacity. Batch processing time is equal to the family processing time of jobs. There is a release time for jobs, and the process cannot start before the release time. This thesis's proposed Model 1 utilizes a modified version of the MIP-PA model [19]. Loading constraints are taken and modified from MIP-PA.

Oven Scheduling Model is introduced in [6]. This model is similar to the model given in [19]. Jobs in the same family can be processed in the same batch. The batch cannot start before release time. The batch processing time is determined according to the maximal processing time of all jobs in a batch. Unlike [19], each job has a setup time. The model in [6] minimizes the cumulative batch processing time and energy consumption. On the other hand, the electricity tariff is not taken into account. The proposed Model 2 includes the parameters for the tariffs.

[22] provided a lower bound for the number of batches. In the proposed Model 1, this lower bound was used to find the number of batches. Considering the issues in practice and the complexity of the problem, it was decided to use a hierarchical model. Two MIP models are proposed for energy-efficient loading and scheduling of autoclaves. Model 1 can be represented by $P_m \mid r_j, \text{batch} \mid c_{max}$ using the

$\alpha \mid \beta \mid \gamma$ notation. In the first model, assignments are made to autoclaves without allowing any delay in the expiration dates of the materials and the due dates of parts. Assignments are made according to the recipes of the parts. Hence, only parts with the same recipe can be cured together. The area of the autoclave is another constraint; the total size of parts in the batch cannot be greater than the autoclave size. All parts can be cured in all autoclaves. A batch cannot start before the release time of all parts in the batch. Parts in the same recipe have equal process time. The objective of Model 1 is to minimize the completion time of all batches. Model 2 is established with some output variables obtained optimally from Model 1.

The parameters used as input to Model 2 are as follows:

- Recipe assigned to each batch in each autoclave,
- Parts assigned to each batch in each autoclave,
- Process time of each batch in each autoclave.

Model 2 takes some outputs from Model 1 and energy costs as given and reschedules the batches' start time without changing batch formation. The energy cost of a batch varies depending on the start time of the recipe and is reflected in Model 2's objective function.

4.2 MATHEMATICAL MODELS

In this chapter, the proposed models are given. Sets, parameters, decision variables, and constraints are explained for each model. The mathematical models are run in GAMS via CPLEX solver.

4.2.1 The Proposed Model 1

4.2.1.1 Sets

The indices of Model 1 are given as follows:

j : *parts* $\quad j \in \{1,2,\ldots,J\}$

b : *batches* $\quad b \in \{1,2,\ldots,B\}$

a : *autoclaves* $\quad a \in \{1,2,\ldots,A\}$

f : *recipes* $\quad f \in \{1,2,\ldots,F\}$

4.2.1.2 Parameters

The parameters of the proposed Model 1 are given as follows:

r_j *: Release time of part j*

p_f *: Process time of recipe f*

s_j *: Size of part j*

f_j *: Recipe of part j*

k_a *: Maximum batch size of autoclave a*

d_j *: Due date of part j*

e_j *: The material expiration date of part j*

L: An arbitrarily large number

T: Time horizon of the model

4.2.1.3 Decision Variables

The decision variables of Model 1 are given as follows:

st_{ba} *: Start time of batch b on autoclave a*

ct_{ba} *: Completion time of batch b on autoclave a*

c^{max} *: Maximum completion time on autoclaves*

pt_{ba} *: Process time of batch b on autoclave a*

x_{jba} *: 1 if part j is in batch b on autoclave a; 0 otherwise*

q_{baf} *: 1 if batch b on autoclave a consists of parts of recipe f; 0 otherwise*

4.2.1.4 Objective Function

The objective function minimizes the maximum completion time of batches in all autoclaves. In the constraint, c_{max} is found using the maximum batch completion times on autoclaves. The objective function is maximizing the time left over. This extra time is used for energy-efficient scheduling in Model 2.

$$Min\ c^{max} - T \tag{1}$$

4.2.1.5 Constraints

The constraints of the proposed Model 1 are given as follows:

$$\sum_{b}\sum_{a} x_{jba} = 1 \qquad \forall j \qquad (2)$$

$$\sum_{j} st_j\, x_{jba} \leq k_a \qquad \forall b, a \qquad (3)$$

$$pt_{ba} \geq p_f\, q_{baf} \qquad \forall b, a, f \qquad (4)$$

$$st_{ba} \geq r_j\, x_{jba} \qquad \forall j, b, a \qquad (5)$$

$$st_{ba} \geq ct_{b-1,a} \qquad \forall b > 1, a \qquad (6)$$

$$ct_{ba} \geq st_{ba} + pt_{ba} \qquad \forall b, a \qquad (7)$$

$$q_{baf} \geq x_{jba} \qquad \forall b, a, f = f_j \qquad (8)$$

$$\sum_{f} q_{baf} \leq 1 \qquad \forall b, a \qquad (9)$$

$$d_j \geq L\left(x_{jba} - 1\right) + ct_{ba} \qquad \forall j, b, a \qquad (10)$$

$$e_j \geq L\left(x_{jba} - 1\right) + ct_{ba} \qquad \forall j, b, a \qquad (11)$$

$$ct_{ba} \leq T \qquad \forall b, a \qquad (12)$$

$$ct_{ba} \leq c^{max} \qquad \forall b, a \qquad (13)$$

$$x_{jba}, q_{baf} \in \{0,1\} \qquad \forall j, b, a, f \qquad (14)$$

$$st_{ba}, ct_{ba}, c^{max}, pt_{ba} \geq 0 \qquad \forall b, a \qquad (15)$$

Constraint (2) ensures that each part is cured in only one batch of an autoclave. Constraint (3) is the capacity constraint for each batch in each autoclave; the total size of parts in a batch cannot be greater than the batch capacity of an autoclave. Constraint (4) calculates the processing time of the batch; the processing time of the batch is determined by the processing time of the recipe in the batch. Constraint (5) ensures that the start time of a batch is greater or equal to the maximum release time of parts in this batch. Constraint (6) represents that the start time of the batch must be greater than the completion time of the predecessor batch. Constraint (7) calculates batch completion time by the sum of start and batch process time. Constraint (8) ensures that a part cannot be cured in an autoclave batch if this part's recipe is not assigned to this batch. Constraint (9) ensures that just one recipe is assigned to one batch. Constraint (8-9) ensures that parts of the same recipe can be cured together. Constraints (10-11) prevent delays on the due date or expiration date. Constraint (12) limits the completion time of the batch with a time horizon. Constraint (13) determines c^{max} to calculate the extra time in the objective function. Constraints (14-15) are binary and non-negativity restrictions, respectively.

4.2.2 The Proposed Model 2

4.2.2.1 Sets

Sets *j, b, a,* and *f* which are included in Model 1 are used likewise in Model 2. The indices of the Model 2 are given as follows:

t : *time horizon* $t \in \{1,2,\ldots,T\}$

4.2.2.2 Parameters

Decision variables pt_{ba}, x_{jba} and q_{baf} which are included in Model 1 and have values, are included as parameters in Model 2. The parameters of the proposed Model 2 are given as follows:

r_j *: Release time of part j*

d_j : *Due date of part j*

e_j : *The material expiration date of part j*

pt_{ba} *: Process time of batch b on autoclave a*

x_{jba} : *1 if part j is in batch b on autoclave a; 0 otherwise*

q_{baf} *: 1 if batch b on autoclave a consists of parts of recipe f; 0 otherwise*

b_{ft} : *Energy cost of recipe f when a batch starts at time t*

L: An arbitrarily large number

4.2.2.3 Decision Variables

The decision variables of Model 2 are given as follows:

st_{ba} : *Start time of batch b on autoclave a*

ct_{ba} : *Completion time of batch b on autoclave a*

v_{bat} : *1 if batch b on autoclave a start at time t; 0 otherwise*

4.2.2.4 Objective Function

The objective function is minimizing energy cost by energy cost at time t for each recipe and batch starting time. The efficiency of Model 2 is constrained by the extra time that is provided by Model 1. If there is no early completion of jobs in the resulting schedule from Model 1, there is no need to run Model 2.

$$Min \sum_{b}\sum_{a}\sum_{f}\sum_{t} b_{ft}q_{baf}v_{bat} \qquad (16)$$

4.2.2.5 Constraints

The constraints of the proposed Model 2 are given as follows:

$$ct_{ba} = st_{ba} + pt_{ba} \qquad \forall b,a \qquad (17)$$

$$ct_{ba} \geq ct_{b-1,a} + pt_{ba} * \sum_{f} q_{baf} \qquad \forall b > 1,a \qquad (18)$$

$$\sum_{t} v_{bat} = \sum_{f} q_{baf} \qquad \forall b,a \qquad (19)$$

$$\sum_{t} t * v_{bat} = \sum_{f} q_{baf}st_{ba} \qquad \forall b,a \qquad (20)$$

$$\sum_{t} v_{bat} \leq 1 \qquad \forall b,a \qquad (21)$$

$$v_{bat} \in \{0,1\} \qquad \forall b,a,t \qquad (22)$$

$$st_{ba}, ct_{ba} \geq 0 \qquad \forall b, a \qquad (23)$$

Constraints (5), (6), (10), (11), and (12) are used the same as Model 1 in Model 2. Constraint 7 in Model 1 was revised and included in Model 2. Constraint (17-18) calculates batch completion time by the sum of start and batch process time. Constraint (19) ensures that only one batch can start in each autoclave batch, and this batch can contain just one recipe. Constraint (20) finds the start time of the batch. Constraint (21) allows a batch in an autoclave to start at just a moment. Constraints (22-23) are binary and non-negativity restrictions, respectively.

The representation of the inputs and outputs of Model 1 and Model 2 is given below.

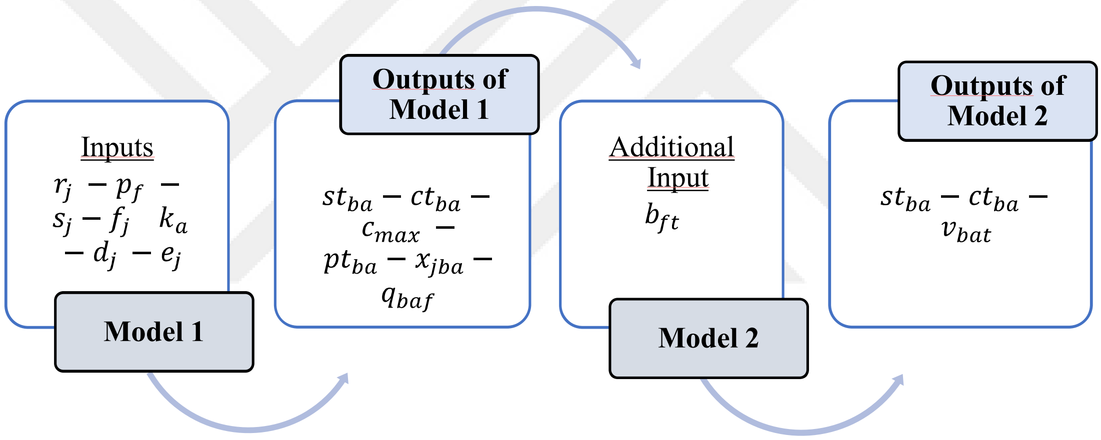

Figure 7: Inputs and outputs of proposed models

CHAPTER V
EXPERIMENTAL STUDY

5.1 DATA GATHERING

This chapter explains how the parameters used in the models were determined.

The parts to be cured are packed on the tools and loaded into the autoclave. The number of tools can be a constraint for production planning. However, since the sets produced for the parts in the facility where the study is carried out are produced as spare parts, this is not a constraint nor included in the model. Considering the production demand for the parts, increasing the number of tools is unnecessary. The cycle time of the tools after use is also not included in the model since the tools are produced as spare parts, and the cleaning time is not a constraint.

There are seven autoclaves of different sizes in the facility. All autoclaves are actively used every day. There is active manufacturing in the facility for 24 hours in three shifts of eight hours each. There is no manufacturing on Sundays.

Table 3: Technical data of autoclaves

Autoclave (AC)	**AC1**	**AC2**	**AC3**	**AC4**	**AC5**	**AC6**	**AC7**
Width-Length (m)	3,6*14	2*4	4*12	0,8*1,5	4*14	3,5*7	0,9*2
Number of thermocouples	74	15	71	12	120	96	20
Number of vacuum ports	48	20	72	6	72	64	20

In autoclaves, there is a thermocouple to control the temperature of the part during the curing process and a vacuum port to control the pressure. Each autoclave has a different number of these pieces of equipment. Since the number of thermocouples and vacuum ports in the autoclaves in the facility where the study is carried out is sufficient and does not represent a constraint for production planning, they are not included in the proposed model.

The capacity of each autoclave is different; the areas are calculated by considering the floor areas. The total size of the parts in the batches cannot be larger than the capacity of the autoclave. When considering this constraint, the width and length of the parts were taken into account, as the height of the parts is much less than the height of the autoclave. When loading, the operator can create an appropriate layout by aligning the parts, and there is no technical restriction other than size, so the parts cannot be cured in every autoclave. The area capacity of the autoclaves was determined by calculating the area based on the width and length dimensions.

Table 4: Maximum batch size of autoclaves

Autoclave (AC)	AC1	AC2	AC3	AC4	AC5	AC6	AC7
Maximum batch size (≅ m²)	51	8	48	2	56	25	2

The area of 10 parts was calculated for the study. The areas of the parts can vary considerably depending on the projects. Part areas vary for each project.

Table 5: Area of parts

Parts of Project #	**Length (m)**	**Width (m)**	**Part Area (m²)**
Project 1	0.15	0.2	0.03
Project 2	0.15	0.2	0.03
Project 3	0.8	1.5	1.2
Project 4	0.4	4.0	1.6
Project 5	0.8	2.5	2.0
Project 6	0.6	5.0	3.0
Project 7	0.6	6.0	3.6
Project 8	1.0	5.5	5.5
Project 9	1.6	6.0	9.6
Project 10	3.5	9.5	33.25

Autoclave loading data for 2021 were examined. The average load and part numbers for each autoclave every month are shown in Table 6.

Table 6: Average monthly number of loads and part

	MONTHLY AVERAGE (2021)		
	PART	**LOAD**	**PART/LOAD ≈**
AC1	638	50	13
AC2	501	68	7
AC3	697	47	15
AC4	188	49	4
AC5	1,115	50	22
AC6	699	55	13
AC7	122	30	4

Since the loadings in the model will be planned for 24 hours, daily average values will be used in the parameters.

The processing time of each recipe is unique in itself. The curing time of an average recipe is between 4 and 9 hours. Since the average cure time of a recipe is 6 hours, it can be concluded that a maximum of 4 loads per day can be loaded into an autoclave. An autoclave is loaded a minimum of 1 and a maximum of 4 times per day. When the data for 2021 is examined, the average daily loading number for each autoclave is 2.

The number of parts in the batch varies according to demand. The production schedules examined show that the number of parts is very high, especially for curing for the A35 project. To date, a maximum of 163 parts have been cured in a single batch for this project. The average number of parts in a batch is 11.

Looking at the different recipe information loaded daily, we find that the variety of recipes can be as much as the number of loads. The recipe variation is a minimum of 1 and a maximum of 4 per day for each autoclave. Each recipe has its specific temperature, pressure values, and process time. The average temperature value of the recipes is 185 °C, and the maximum curing temperature is up to 340 °C. When examining the energy consumption of the batches, it can be seen that the temperature values of the recipes and not the pressure values affect the energy consumption.

Energy analyzers are connected to each autoclave. These analyzers record data every 15 minutes through the system SCHNEIDER SCADA. Electricity consumption for June 2021 was examined. When examining the average daily electricity consumption of the autoclaves, it was found that the size of the autoclave and the energy consumption are closely related.

Table 7: Average daily energy consumption of autoclaves

Autoclave	Average Daily Energy Consumption (kWh)	Area (m²)
AC4	0.57	1.2
AC7	1.38	1.8
AC2	7.49	8
AC6	15.13	24.5
AC3	12.68	48
AC1	22.37	50.4
AC5	21.54	56

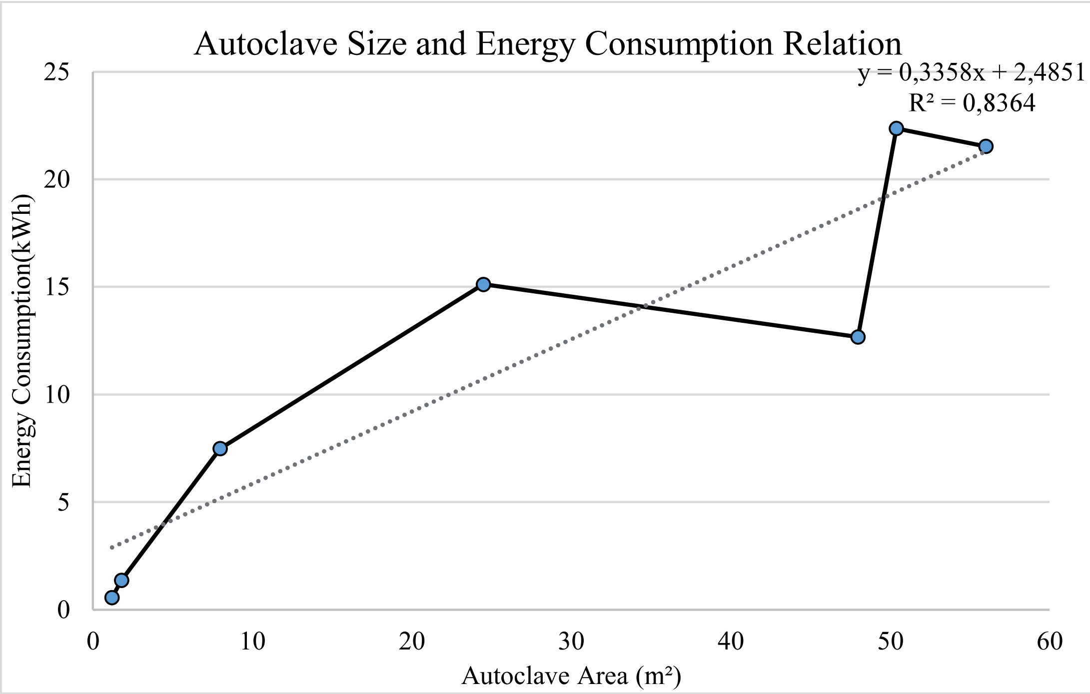

Figure 8: Autoclave size and energy consumption relationship

For example, energy consumption was studied using the autoclave and time data in which the recipes were cured. The recipes were divided into phases and examined regarding time and energy consumption. The time and energy consumption data were obtained by dividing each loading phase based on the recipes provided for a project and the information on the 12 loadings obtained. It can be seen that the most significant energy consumption occurs during the heating phases. Energy consumption data for a load divided into phases is shown below.

Table 8: Energy consumption of cure phases

Phase Start Time	Phases of Cure Cycle	Period	Instant Energy Consumption (kW)
11.03.2021 17:07	Pressure Increase	00:23:00	48
11.03.2021 17:30	Heating Up	01:29:00	713
11.03.2021 19:00	Waiting	02:00:00	184
11.03.2021 20:59	Heating Up	00:54:00	363
11.03.2021 21:03	Heating Up		
11.03.2021 21:53	Waiting	02:00:00	192
11.03.2021 23:53	Cooling Down	01:11:00	77
11.03.2021 23:58	Cooling Down		
12.03.2021 01:04	Pressure Decrease	00:26:00	37
SUM		08:23:00	1,614

Although the number of cured parts is different in the examined loadings, the fact that the energy consumption for heating has the same average value shows that the critical point is the number of loadings and not the number of cured parts.

Thus, the energy consumption values of the recipes for which production planning is done are determined by the data obtained from energy analyzers. While examining the energy consumption of the loads, the MCP values were also examined. In the study of the effect of MCP values on energy costs, hourly energy consumptions and energy costs were determined by dividing the loading hours into intervals. The MCP values corresponding to the hourly interval were used to calculate energy costs. Then, the time interval with the highest energy consumption was merged with the times when the market clearing price was low so as not to cause significant changes in loading start and finish times. As seen in Table 8, the highest energy consumption was in the second-hour interval in the loading cured between 20:45-05:00 on 03/02/2022; this hour interval coincided with the highest energy cost. For this reason, it is calculated that the cost will decrease by approximately €29.44 if the loading times are arranged 3 hours after the current situation, i.e., at 23:45.

Table 9: Energy cost of loading

Time	MCP (€/kWh)	kW	Energy Cost (€)		Time	MCP (€/kWh)	kW	Energy Cost (€)
20:00	0.10	34.59	3.50	⇨	23:00	0.08	34.59	2.61
21:00	0.10	673.04	68.15		00:00	0.07	673.04	44.38
22:00	0.09	115.07	10.31		01:00	0.08	115.07	9.48
23:00	0.08	92.60	7.00		02:00	0.08	92.60	7.63
00:00	0.07	359.87	23.73		03:00	0.07	359.87	23.73
01:00	0.08	110.22	9.08		04:00	0.05	110.22	5.78
02:00	0.08	102.05	8.41		05:00	0.06	102.05	5.71
03:00	0.07	90.10	5.94		06:00	0.05	90.10	4.75
04:00	0.05	71.25	3.74		07:00	0.09	71.25	6.33
Total Cost			139.87		Total Cost			110.42

Based on this determination, in addition to the outputs obtained from Model 1, energy costs that vary depending on the start times of the recipes are given as parameters in Model 2. Energy costs will be reduced by making changes in the batch start time without allowing delays in the production plan and without making changes in loadings or assignments.

5.2 EXPERIMENTAL STUDY

5.2.1 EXPERIMENTAL DESIGN

Since the thesis was carried out in a defense company and confidentiality prevails in this field, it is impossible to access all the data. For this reason, the experiments could not be performed with actual data and in large numbers. In addition to the data collected, experiments were designed to increase the number of runs with the proposed models. In this section, the methods used to determine the parameters determined for the experiments are mentioned.

The studies carried out and evaluated cover 24-hour periods because MCP is announced every day for just the next day. Parts that will be cured within 24 hours are determined, and assignments are made. Because MCP is announced for just the next 24 hours, the T value is 24 in models. The maximum number of loadings in each autoclave is 4 per day.

Seven autoclaves were used extensively in the company where the study was carried out were taken into account. Information about the capacities of these autoclaves is given in section 5.1. Since the part area to be cured differs for each project, it has not been evaluated over the ten samples we have. These ten examples only contain the rarely cured parts and are not an accurate reference when proceeding with average values. While determining the part area, the ratio of autoclave areas to the number of autoclave-based monthly average cured parts in 2021 is taken as a basis. The part area's minimum, mode, and maximum values were determined as (0.3, 3.95, and 1.92). The experiment's part area was randomly determined from a discrete triangular distribution. The discrete triangular distribution is a continuous distribution that takes minimum, maximum, and mode values as parameters in data scarcity.

The number of parts to be cured in the experiments was determined based on the 2021 loading and part number. As mentioned in the 5.1 Data Gathering section, monthly average loading and number of parts data are collected. Considering the average number of parts for the 24 hours, it was determined that the daily average number of cured parts was 132. The number of parts was determined by discrete triangular distribution with the minimum, mode, and maximum values (28, 132, 180).

The maximum number of prescriptions for 12 different experiments was determined as 21, considering the cases where three loadings per day occur in autoclaves, and the prescription information of each loading is different. The number of prescriptions was randomly generated from a discrete triangular distribution using the minimum, mode, and maximum values (3, 12, 21). The processing times of the prescriptions were also determined by discrete triangular distribution with the minimum, mode, and maximum values as (4, 6, 8). The recipe for each part of each experiment was assigned using the Excel Random Number Generator function. Discrete Distribution was used during the assignment, and the probability of assigning each prescription was considered equal.

The due date of the part and the expiration date of the material were randomly generated by the discrete triangular distribution method with the minimum, mode, and maximum values as (24, 48, 72). Because due date and expiration date values are greater than 24, infeasibility is out of the question for the related constraints. The release times of the parts are taken as 0 because the setup times are ignored.

Experiments were carried out over 12 different days. While determining the days for the hourly MCP values, the days were divided into seasons. The days in each season were examined by finding the same hour's minimum, maximum, and mode values. Due to the differences between the seasons, experiments were created using random days from each season.

Then, the days were examined within themselves, and the standard deviation values were found for the hourly energy costs of each day. The days with minimum, maximum, and average standard deviation values for each season were determined and used in Model 2. When determining the days, Sundays, when there is no production, and public holidays, are excluded. In addition, the days when the hourly energy costs are identical during the day are also excluded. These days the standard deviation is zero; Model 2 cannot provide any reduction in energy cost. The effect of the change in energy costs during the day and seasonality was observed. The information on the days is given in Table 10.

Table 10: Standard deviation of MCP in seasons

Run #	Season	Date	Standard Deviation
Run 1	Spring	19.04.2022	9.66
Run 2	Spring	25.04.2022	19.77
Run 3	Spring	5.05.2022	52.44
Run 4	Summer	15.06.2022	9.88
Run 5	Summer	14.07.2022	26.53
Run 6	Summer	4.06.2022	38.56
Run 7	Fall	13.09.2022	25.55
Run 8	Fall	16.11.2022	46.82
Run 9	Fall	21.11.2022	88.10
Run 10	Winter	22.02.2022	3.84
Run 11	Winter	31.12.2022	24.70
Run 12	Winter	19.12.2022	71.42

While calculating the energy costs for Model 2, the energy consumption of the recipe was made based on the recipe, which was examined as an example. The energy consumption was examined by dividing it into curing phases. As stated in section 5.1, energy consumption is directly related to the size of the autoclave. For this reason, while the energy consumption of the prescriptions was determined, the autoclave and the durations of the prescriptions were determined proportionally to the sample recipe examined.

The energy consumption is obtained from energy analyzers connected to autoclaves with an energy monitoring system and a communication infrastructure.

Although the number of parts cured between the loads is different, the average energy consumption for heating has the same value, numerically showing that the vital point is the number of loads rather than the number of parts cured in loads. The average duration and energy consumption of the phases of the examined recipes are shown in the table below.

Table 11: The average duration and energy consumption percentage of phases

Phases of Cure Cycle	Duration %	Energy Consumption %
Pressure Increase	5.00%	2.84%
Heating Up	29.56%	66.06%
Waiting	48.89%	25.57%
Cooling Down	13.88%	5.00%
Pressure Decrease	5.53%	2.14%

While calculating the energy consumption costs of the recipes, these percentages determined for the energy consumption and the duration of the curing phases were used. After the autoclaves to which the recipes are assigned are determined by Model 1, the energy costs are calculated according to the start time of each recipe by multiplying the time in the phases, energy consumption, and energy cost.

Parameters such as the models' due date and expiration date are chosen as integers. The decision variables resulted as integers because integer values are used as the right-hand side values for the constraints. For this reason, the values for start time and completion time obtained as the output of the models were set as integers.

5.2.2 VERIFICATION WITH SYNTHETIC DATA

Parameters for 12 different experiments were created as described in section 5.2.1 Experimental Design. Mathematical models were run on Windows 11 Pro 64-bit operating system with Intel Core i7 10750H CPU @ 2.60GHz, 2592 Mhz, 16GB RAM in GAMS.

In the first data set created for experiments, the number of parts to be cured was determined as 140, and the number of recipes as 14. While creating the GAMS model, the maximum loadings for each experiment are 4, the number of autoclaves is 7, and the time horizon is 24 hours. The parameters determined for the first experiment are detailed in the tables below.

Table 12: Size, recipe, due time, and expiration time of parts in Experiment 1

Part	s_j	f_j	d_j	e_j
1	2	3	34	42
2	1	4	64	49
3	2	8	53	43
4	3	8	42	57
5	2	4	49	49
6	3	9	39	45
7	2	6	46	50
8	3	9	49	35
9	1	14	50	33
10	1	9	50	51
11	2	7	39	40
12	2	10	69	42
13	2	5	29	50
14	2	4	27	50
15	2	6	39	41
16	2	6	45	66
17	2	9	53	43
18	2	11	58	56
19	1	14	55	32
20	4	9	38	47
21	2	7	39	42
22	2	9	50	43
23	2	6	35	63
24	2	13	53	48
25	3	1	62	46
26	2	7	31	31
27	3	7	52	39
28	2	2	46	40
29	2	4	53	38

Part	s_j	f_j	d_j	e_j
30	3	7	42	55
31	3	3	40	28
32	2	11	70	47
33	2	8	62	47
34	2	12	28	61
35	1	12	54	38
36	1	1	27	64
37	3	1	50	55
38	3	13	51	61
39	2	8	52	48
40	1	1	51	63
41	2	14	53	34
42	3	14	32	41
43	2	8	56	43
44	3	5	54	49
45	1	10	53	45
46	1	13	38	50
47	2	6	60	51
48	2	5	49	52
49	3	6	59	53
50	3	5	49	52
51	1	2	48	41
52	2	11	51	38
53	3	10	53	33
54	2	14	41	37
55	2	11	42	37
56	2	8	35	34
57	2	1	51	44
58	2	1	57	61

Part	s_j	f_j	d_j	e_j
59	1	1	41	31
60	3	11	48	36
61	1	9	48	56
62	1	11	40	44
63	2	9	45	67
64	3	9	28	44
65	1	5	37	45
66	1	9	50	54
67	1	2	54	45
68	1	5	39	41
69	1	14	53	53
70	2	13	52	33
71	2	14	38	39
72	3	5	62	35
73	3	2	51	53
74	2	4	41	49
75	1	11	45	45
76	3	9	52	61
77	2	14	65	65
78	3	14	48	50
79	4	6	55	45
80	2	3	40	63
81	1	3	46	38
82	2	1	51	30
83	2	7	37	47
84	1	11	49	48
85	2	1	47	46
86	1	6	50	43
87	2	4	27	57

Part	s_j	f_j	d_j	e_j
88	3	11	54	50
89	1	7	41	43
90	1	5	30	56
91	2	6	36	44
92	3	7	58	53
93	3	7	62	61
94	2	3	44	45
95	1	13	31	51
96	1	10	41	39
97	2	11	59	39
98	1	3	45	51
99	1	7	50	55
100	3	9	51	48
101	2	14	26	43
102	2	4	59	54
103	1	14	47	46
104	2	14	50	58
105	2	5	54	53
106	2	2	43	56
107	2	6	52	44
108	1	13	30	68
109	2	5	41	65
110	2	1	50	44
111	2	9	49	46
112	1	13	39	66
113	2	12	58	54
114	2	10	42	54
115	2	12	35	58
116	1	6	46	32

Part	s_j	f_j	d_j	e_j
117	2	7	45	53
118	1	14	50	41
119	3	6	61	56
120	2	13	41	52
121	3	6	63	48
122	2	9	48	52
123	1	4	50	50
124	2	12	29	48
125	3	7	39	45
126	3	3	38	40
127	2	10	41	55
128	1	2	42	55
129	2	4	40	47
130	2	8	52	59
131	3	6	61	50
132	2	5	49	51
133	2	9	47	53
134	1	5	63	33
135	1	10	67	55
136	3	6	55	50
137	2	9	59	52
138	1	5	37	52
139	1	6	65	40
140	3	12	28	27

Table 13: Process time of recipes in Experiment 1

Recipe #	p_f
1	5
2	4
3	5
4	8
5	6
6	7
7	6
8	7
9	5
10	7
11	7
12	6
13	6
14	5

The parts cured in each batch resulting from Model 1 run with the determined parameters are given in Table 14.

Table 14: Parts cured in batches as a result of Model 1

Batch / Autoclave	Batch 1	Batch 2	Batch 3	Batch 4
Autoclave 7	Part 70		Part 108, 112	Part 95
Autoclave 6	Part 2, 5, 14, 29, 74, 87, 102, 123, 129	Part 25, 36, 37, 40, 57, 58, 59, 82, 85, 110	Part 9, 19, 41, 42, 54, 69, 71, 77, 78, 101, 103, 104, 118	
Autoclave 5	Part 18, 32, 52, 55, 60, 62, 75, 84, 88, 97	Part 3, 4, 33, 39, 43, 56, 130		Part 28, 51, 67, 73, 106, 128
Autoclave 4	Part 127		Part 96, 135	
Autoclave 3	Part 13, 44, 48, 50, 65, 68, 72, 90, 105, 109, 132, 134, 138	Part 34, 35, 113, 115, 124, 140	Part 11, 21, 26, 27, 30, 83, 89, 92, 93, 99, 117, 125	
Autoclave 2	Part 24, 38, 46, 120		Part 12, 45, 53, 114	
Autoclave 1	Part 6, 8, 10, 20, 22, 61, 63, 64, 66, 76, 100, 111, 122, 133, 137		Part 1, 31, 80, 81,94,98, 126	Part 7, 15, 16, 23, 47, 49, 79, 86, 91, 107, 116, 119, 121, 131, 136, 139

The schedule obtained as a result of Model 1 operated with the specified parameters is given in Figure 9. The recipe information assigned to the batches is shown in detail in the figure.

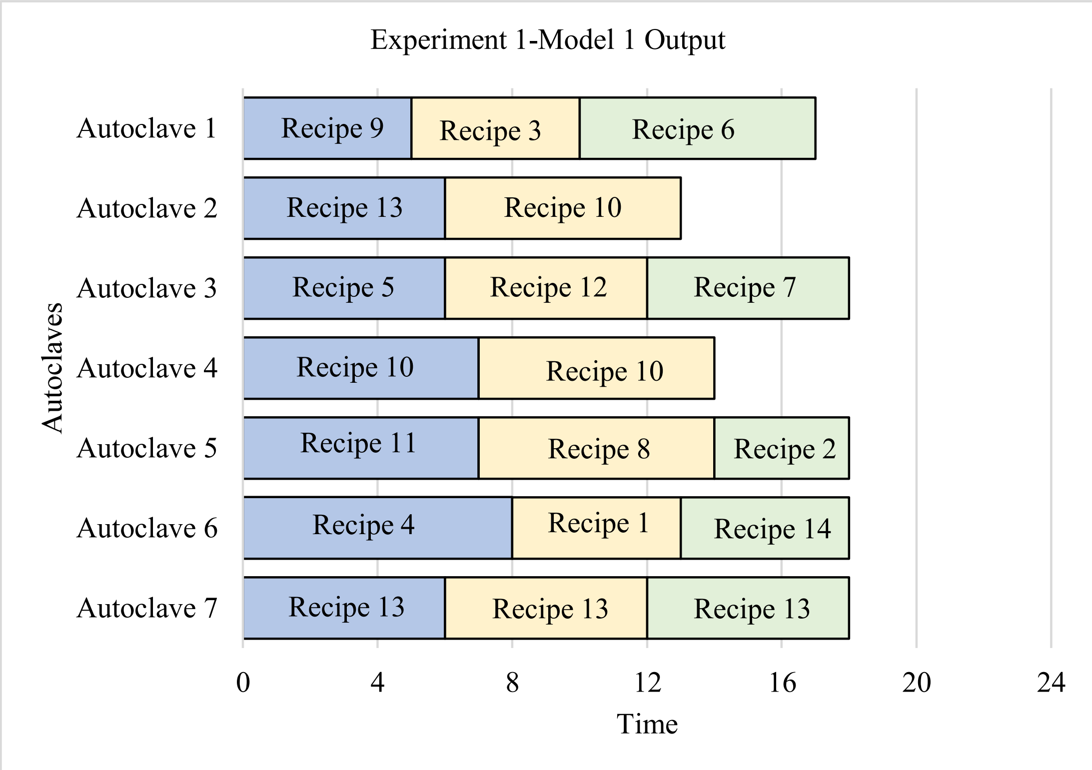

Figure 9: Experiment 1 Model 1 output

The maximum completion time of batches in autoclaves is 18. The start and completion times of the batches are listed in Table 15.

Table 15: Start and completion times of batches for Experiment 1 Model 1

Batch / Autoclave	Batch 1		Batch 2		Batch 3	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}	s_{3a}	c_{3a}
Autoclave 1	0	5	5	10	10	17
Autoclave 2	0	6	6	13	-	-
Autoclave 3	0	6	6	12	12	18
Autoclave 4	0	7	7	14	-	-
Autoclave 5	0	7	7	14	14	18
Autoclave 6	0	8	8	13	13	18
Autoclave 7	0	6	6	12	12	18

The autoclaves in which the parts will be cured are determined by Model 1. Then, the energy consumption of recipes is determined in kWh according to the processing time of recipes and the autoclave in which the recipe was cured. As mentioned, the curing process was divided into phases, and energy consumption and process time were obtained for each phase. The energy cost in € was multiplied by the actual MCP values of 19.04.2022. This process is calculated for each hour based on the start time of the recipe. Since the model covers the 24-hour time horizon, in cases where the end time of the recipe would exceed 24 hours, the energy cost was arbitrarily given a large number to prevent the curing from starting at these hours.

The table of energy costs calculated for Experiment 1 and used in Model 2 in line with Model 1 outputs is below.

Table 16: Energy costs for recipes of Experiment 1

Start Time \ Recipe	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	92 €	83 €	136 €	231 €	111 €	264 €	111 €	254 €	140 €	48 €	254 €	111 €	39 €	92 €
1	89 €	80 €	131 €	221 €	106 €	252 €	106 €	242 €	135 €	46 €	242 €	106 €	38 €	89 €
2	86 €	76 €	126 €	220 €	103 €	247 €	103 €	238 €	129 €	45 €	238 €	103 €	36 €	86 €
3	87 €	77 €	128 €	226 €	105 €	254 €	105 €	245 €	131 €	46 €	245 €	105 €	37 €	87 €
4	88 €	79 €	130 €	229 €	107 €	257 €	107 €	248 €	134 €	47 €	248 €	107 €	38 €	88 €
5	87 €	77 €	128 €	224 €	105 €	252 €	105 €	243 €	132 €	46 €	243 €	105 €	37 €	87 €
6	85 €	74 €	126 €	223 €	104 €	251 €	104 €	241 €	130 €	46 €	241 €	104 €	37 €	85 €
7	90 €	77 €	132 €	238 €	110 €	267 €	110 €	257 €	136 €	49 €	257 €	110 €	39 €	90 €
8	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
9	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
10	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
11	97 €	86 €	143 €	248 €	117 €	280 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
12	97 €	86 €	143 €	248 €	117 €	280 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
13	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
14	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
15	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
16	97 €	86 €	143 €	248 €	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
17	97 €	86 €	143 €	L	117 €	281 €	117 €	270 €	147 €	51 €	270 €	117 €	41 €	97 €
18	97 €	86 €	143 €	L	117 €	L	117 €	L	147 €	L	L	117 €	41 €	97 €
19	97 €	86 €	143 €	L	L	L	L	L	147 €	L	L	L	L	97 €
20	L	86 €	L	L	L	L	L	L	L	L	L	L	L	L
21	L	L	L	L	L	L	L	L	L	L	L	L	L	L
22	L	L	L	L	L	L	L	L	L	L	L	L	L	L
23	L	L	L	L	L	L	L	L	L	L	L	L	L	L

Decision variables that are $pt_{ba} - x_{jba} - q_{baf}$ obtained from Model 1 and b_{ft} value given in the table above is entered in Model 2 as parameters, so assignments are started with the lowest energy cost. The schedule with the curing hours re-evaluated as a result of Model 2, is represented in Figure 10.

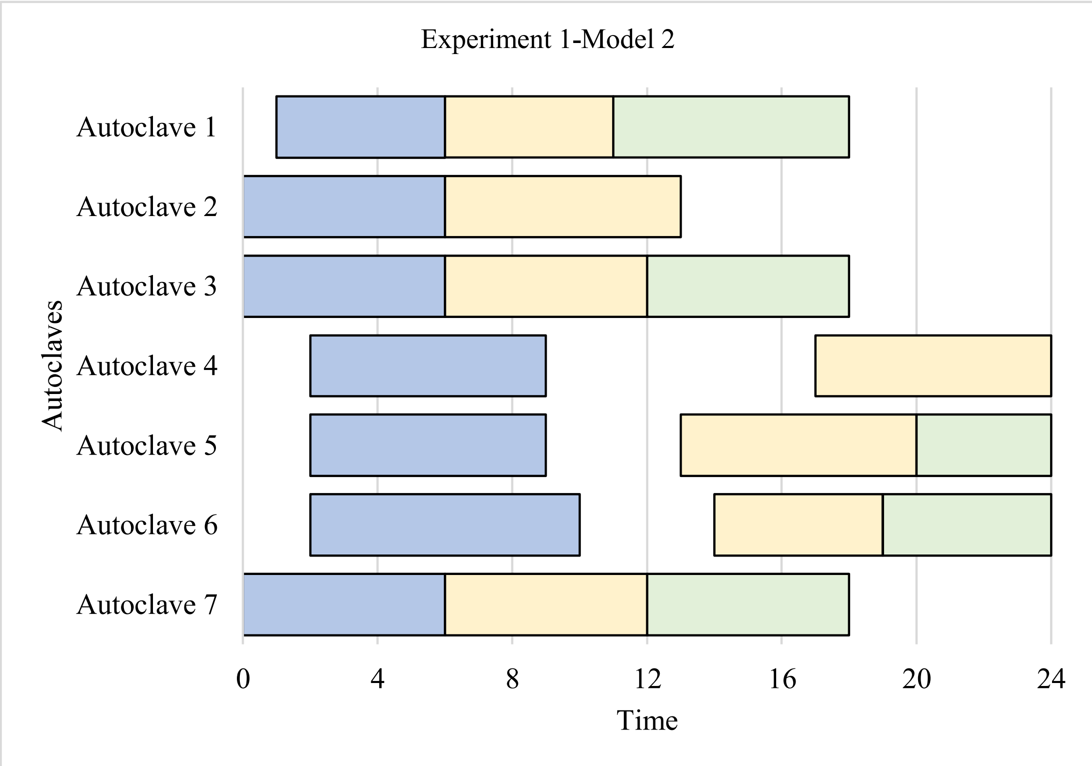

Figure 10: Experiment 1 Model 2 output

With Model 1, energy efficiency is achieved by maximizing the usage area of batch capacities of autoclaves and minimizing the number of batches. Model 2 provides minimum energy cost by considering energy price tariffs and energy-efficient Model 1.

According to the Experiment 1 Model 2 output, only the start times of the batches are changed without making any changes in the recipes and parts assigned to the batches in the autoclaves. Start time of batch 1 in autoclave 1; In autoclaves 4, 5, and 6, the start time of batch 1 was brought forward by 2 hours. For the start times of batch 2, an interval of 8 hours in autoclave 4 and 4 hours in autoclave 5 and 6 was agreed upon between batch 1.

According to the Experiment 1 Model 2 output, the start and completion times of the batches in the autoclaves are given in Table 17.

Table 17: Start and completion times of batches for Experiment 1 Model 2

Autoclave \ Batch	Gap	Batch 1		Gap	Batch 2		Gap	Batch 3	
		s_{1a}	c_{1a}		s_{2a}	c_{2a}		s_{3a}	c_{3a}
Autoclave 1	1	1	6	-	6	11	-	11	18
Autoclave 2	-	0	6	-	6	13	-	-	-
Autoclave 3	-	0	6	-	6	12	-	12	18
Autoclave 4	2	2	9	8	17	24	-	-	-
Autoclave 5	2	2	9	4	13	20	-	20	24
Autoclave 6	2	2	10	4	14	19	-	19	24
Autoclave 7	-	0	6	-	6	12	-	12	18

The energy cost of the scheduling obtained at the end of Model 1 is € 2,202. The energy cost was reduced to € 2,179 due to the Model 2.

Energy cost savings are expected to increase as the standard deviation of day-to-day energy costs increases.

The summary of the 12 experiments can be seen in Table 18.

Table 18: Summary of 12 experiments

Run	Season	Date	Number of Parts	Number of Recipes	Standard Deviation of Daily Energy Cost	Maximum Completion Time-Model 1	Energy Cost of Model-1	Computation Time of Model 1 (sec)	Maximum Completion Time-Model 2	Energy Cost of Model-2	Computation Time of Model 2 (sec)	Energy Cost Savings
1	SPRING	19.04.2022	140	14	9.66	18	2,202	1,002	24	2,179	3	1.06%
2		25.04.2022	83	13	19.77	15	1,302	1,002	19	1,208	3	7.78%
3		5.05.2022	73	8	52.44	12	530	1,002	20	356	3	48.88%
4	SUMMER	15.06.2022	135	12	9.88	17	1,458	1,002	24	1,408	3	3.55%
5		14.07.2022	128	12	26.53	18	1,565	1,002	24	1,453	3	7.71%
6		4.06.2022	124	11	38.56	15	1,478	1,002	21	1,084	3	36.35%
7	FALL	13.09.2022	143	13	25.55	17	2,457	1,002	20	2,408	3	2.03%
8		16.11.2022	119	8	46.82	11	1,575	1,002	24	1,530	3	2.94%
9		21.11.2022	120	14	88.10	16	1,261	1,002	19	1,067	3	18.18%
10	WINTER	22.02.2022	69	8	3.84	11	715	1,002	24	694	3	3.03%
11		31.12.2022	79	8	24.70	11	1,430	1,002	18	1,363	3	4.92%
12		19.12.2022	128	7	71.40	11	820	1,002	17	731	3	12.18%

For Model 1, whose aim is to minimize the completion time, the average completion time of 12 experiments is 14 hours, which is 21 in Model 2. While the average energy cost of Model 1 for 12 runs in € 1,399, this value is reduced to € 1,290 with Model 2.

As seen in Table 18, when the standard deviation increases in the energy cost during the day, the savings from the energy cost for that day also increases.

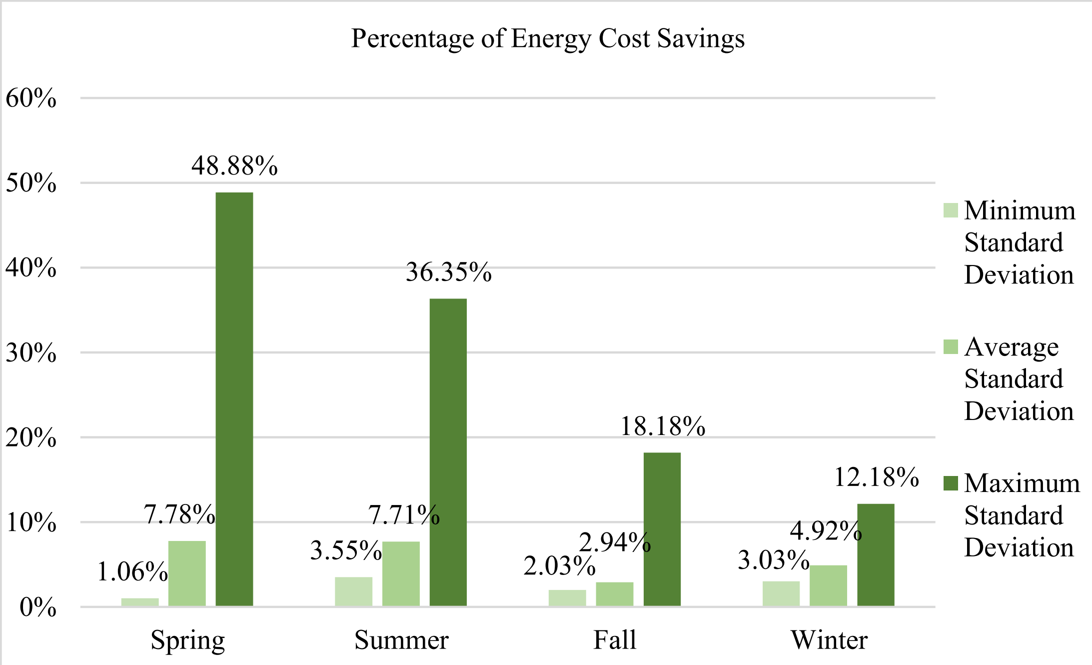

Figure 11: Percentage of Energy Cost Savings

The average energy cost-saving percentage achieved for 12 runs is 12.38%.

When MCP values for 2022 are analyzed, it can be observed that the average standard deviation for the average daily energy cost is 19.52 in Spring, 26.51 in Summer, 48.10 in Fall, and 20.97 in Winter. In Spring and Winter, there are days when the hourly energy cost does not change. This situation decreases the average standard deviation. Model 2 saves more energy costs in the Fall.

5.2.3 VALIDATION WITH REAL DATA

Actual operation data was obtained for the days of 16.11.2022, which has a standard deviation value close to the average of the standard deviation values of the days in the month for Fall, and 19.12.2022, which has the highest standard deviation value in the winter season.

On 16.11.2022, 36 pieces of 14 different recipes were cured. The schedule of the loads during the day is given in Figure 12.

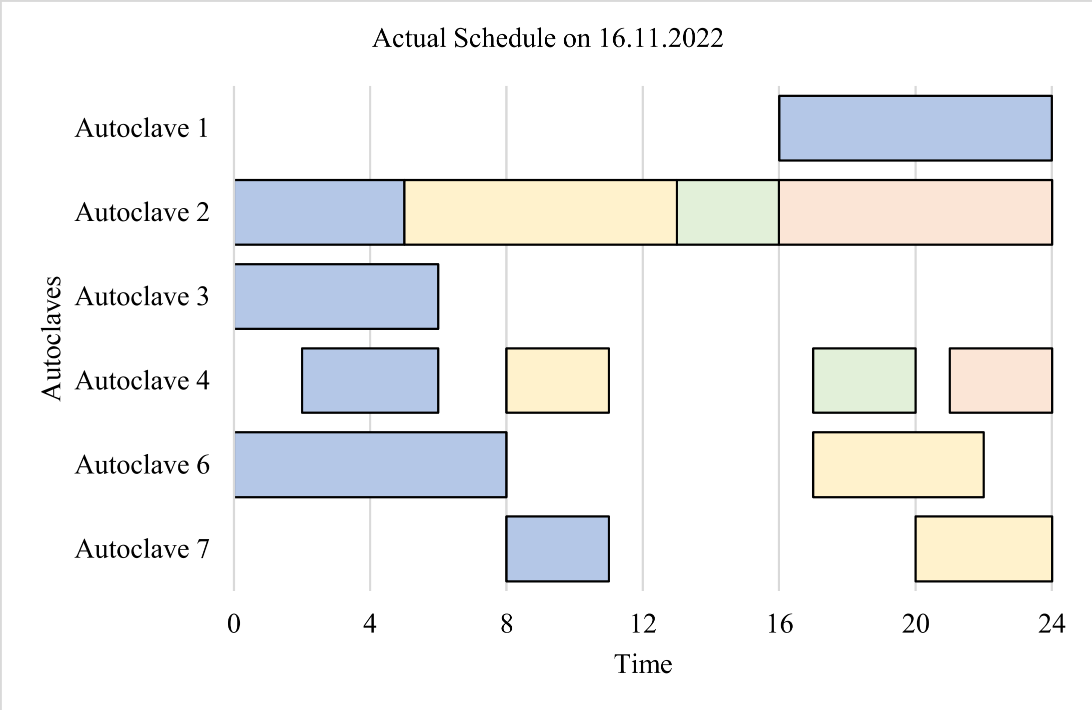

Figure 12: Actual schedule on 16.11.2022

The start and completion times of real-life scheduling are given in the table below.

Table 19: Start and completion times of the batches on 16.11.2022

Autoclave \ Batch	Batch 1		Batch 2		Batch 3		Batch 4	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}	s_{3a}	c_{3a}	s_{4a}	c_{4a}
Autoclave 1	16	24	-	-	-	-	-	-
Autoclave 2	0	5	5	13	13	16	16	24
Autoclave 3	0	6	-	-	-	-	-	-
Autoclave 4	2	6	8	11	17	20	21	24
Autoclave 5	-	-	-	-	-	-	-	-
Autoclave 6	0	8	17	22	-	-	-	-
Autoclave 7	8	11	20	24	-	-	-	-

First, the energy consumption of real-life loadings was taken from the SCHNEIDER SCADA system via energy analyzers connected to the autoclaves. The energy cost was found by multiplying the amount of energy consumed by the recipes in each hour interval with the energy cost in that hour. According to real-life scheduling, this value is € 964.

Then, real-life scheduling information was given to Model 2 as a parameter, and energy cost savings could be achieved by changing the start times of the batches observed.

Model 2 schedule, whose energy cost is € 874, is given in the figure below.

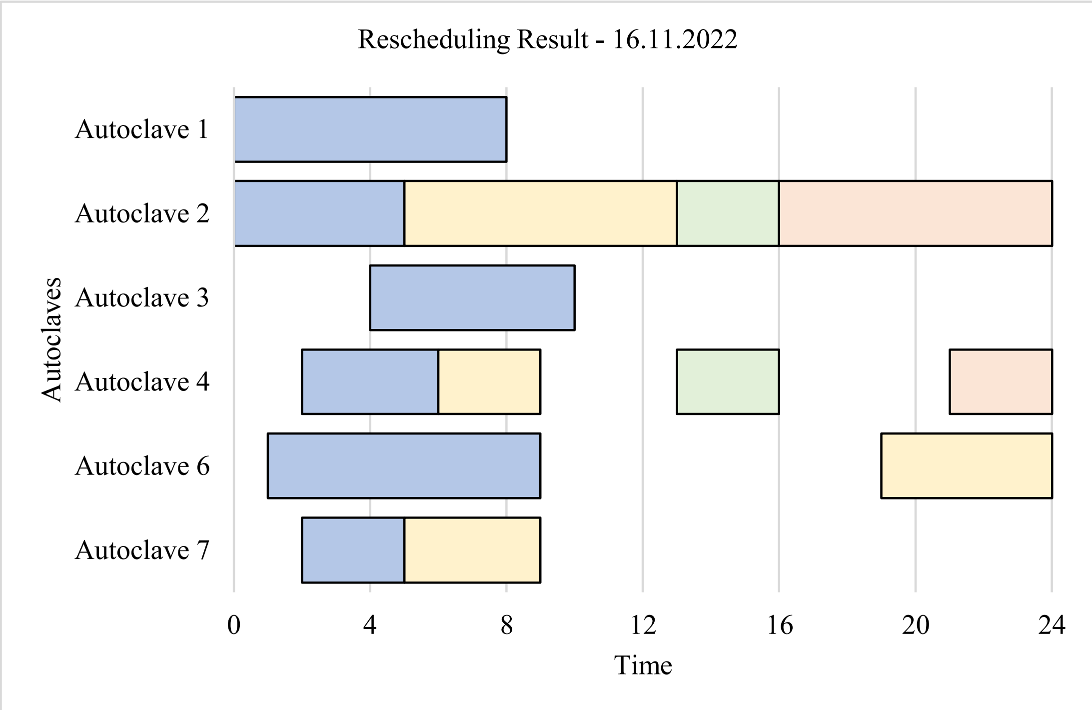

Figure 13: Rescheduling Result - 16.11.2022

After arranging the start times of the batches in a way that will reduce the energy cost, the current start and completion times are given in Table 20.

Table 20: Start and completion times of the batches on rescheduled 16.11.2022

Autoclave \ Batch	Batch 1		Batch 2		Batch 3		Batch 4	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}	s_{3a}	c_{3a}	s_{4a}	c_{4a}
Autoclave 1	0	8	-	-	-	-	-	-
Autoclave 2	0	5	5	13	13	16	16	24
Autoclave 3	4	10	-	-	-	-	-	-
Autoclave 4	2	6	6	9	13	16	21	24
Autoclave 5	-	-	-	-	-	-	-	-
Autoclave 6	1	9	19	24	-	-	-	-
Autoclave 7	2	5	5	9	-	-	-	-

10.30% savings were achieved in energy costs without changing real-life loadings' recipes, parts, and autoclave conditions. A run was taken for these parameters to examine the energy cost that would occur when the same parts and recipes were scheduled with the Proposed Model 1 and Model 2.

The figure of the Model 1 schedule, run with the data of 36 parts and 14 recipes, is given in Figure 14.

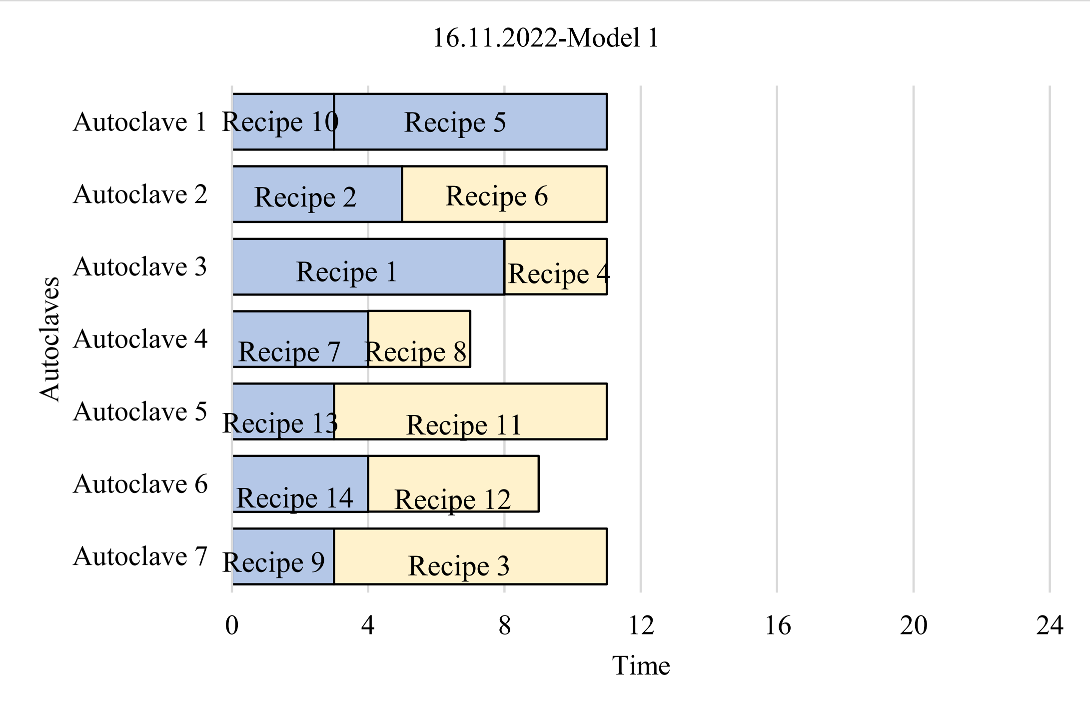

Figure 14: 16.11.2022 Model 1 output

The maximum completion time, 24 hours in actual scheduling, was found to be 11 in Model 1. The start and completion times of the batches are listed in Table 21.

Table 21: Start and completion times of the batches for 16.11.2022 Model 1

Autoclave \ Batch	Batch 1		Batch 2	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}
Autoclave 1	0	3	3	11
Autoclave 2	0	5	5	11
Autoclave 3	0	8	8	11
Autoclave 4	0	4	4	7
Autoclave 5	0	3	3	11
Autoclave 6	0	4	4	9
Autoclave 7	0	3	3	11

The energy cost of Model 1 is € 890. The run is taken for Model 2 with the assignment information to reduce energy costs.

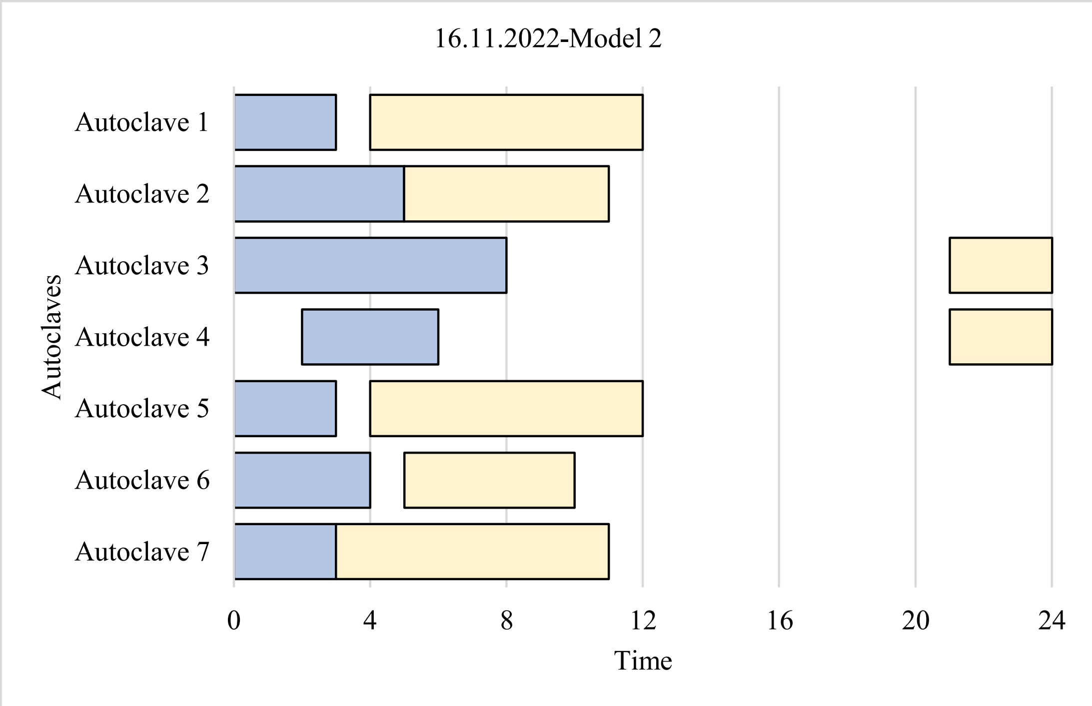

Figure 15: 16.11.2022 Model 2 output

The start and completion times of the batches in the autoclaves according to the Model 2 output are given in Table 22.

Table 22: Start and completion times of the batches for 16.11.2022 Model 2

Autoclave \ Batch	Gap	Batch 1		Gap	Batch 2	
		s_{1a}	c_{1a}		s_{2a}	c_{2a}
Autoclave 1	-	0	3	1	4	12
Autoclave 2	-	0	5	-	5	11
Autoclave 3	-	0	8	13	21	24
Autoclave 4	2	2	6	15	21	24
Autoclave 5	-	0	3	1	4	12
Autoclave 6	-	0	4	1	5	10
Autoclave 7	-	0	3	-	3	11

The energy cost was reduced to € 863 due to the Model 2.

In this example, created with the data of real-life curing parts, the proposed models were loaded in all autoclaves, and the energy cost was reduced by 11.70% compared to the actual energy cost.

The same study was conducted for the day 19.12.2022, with the highest standard deviation in energy costs during the winter season. Since the standard deviation value for this day is higher, the energy savings to be provided for today are expected to be higher.

On 19.12.2022, 160 pieces of 9 different recipes were cured. The chart of the loadings during the day is given in Figure 16.

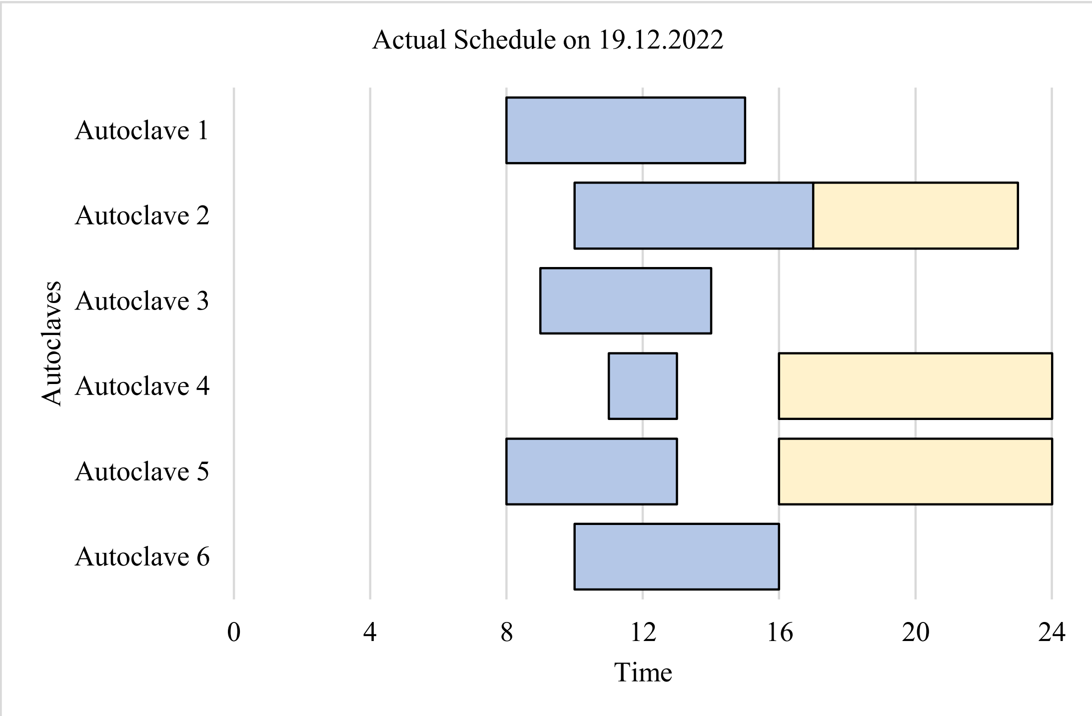

Figure 16: Actual schedule on 19.12.2022

The start and completion times of real-life scheduling batches are given in the table below.

Table 23: Start and completion times of the batches on 19.12.2022

Batch / Autoclave	Batch 1		Batch 2		Batch 3		Batch 4	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}	s_{3a}	c_{3a}	s_{4a}	c_{4a}
Autoclave 1	8	15	-	-	-	-	-	-
Autoclave 2	10	17	17	23	-	-	-	-
Autoclave 3	9	14	-	-	-	-	-	-
Autoclave 4	11	13	16	24	-	-	-	-
Autoclave 5	8	13	16	24	-	-	-	-
Autoclave 6	10	16	-	-	-	-	-	-
Autoclave 7	-	-	-	-	-	-	-	-

First, the energy consumption of real-life loadings is taken from the SCHNEIDER SCADA system. The energy cost was found by multiplying the amount of energy consumed by the prescriptions in each hour interval with the energy cost in that hour. According to real-life scheduling, this value is € 997.

Then, real-life scheduling information was given to Model 2 as a parameter, and energy cost savings could be achieved by changing the start times of the batches observed.

The energy cost of € 451 according to Model 2 outputs is given in the figure below.

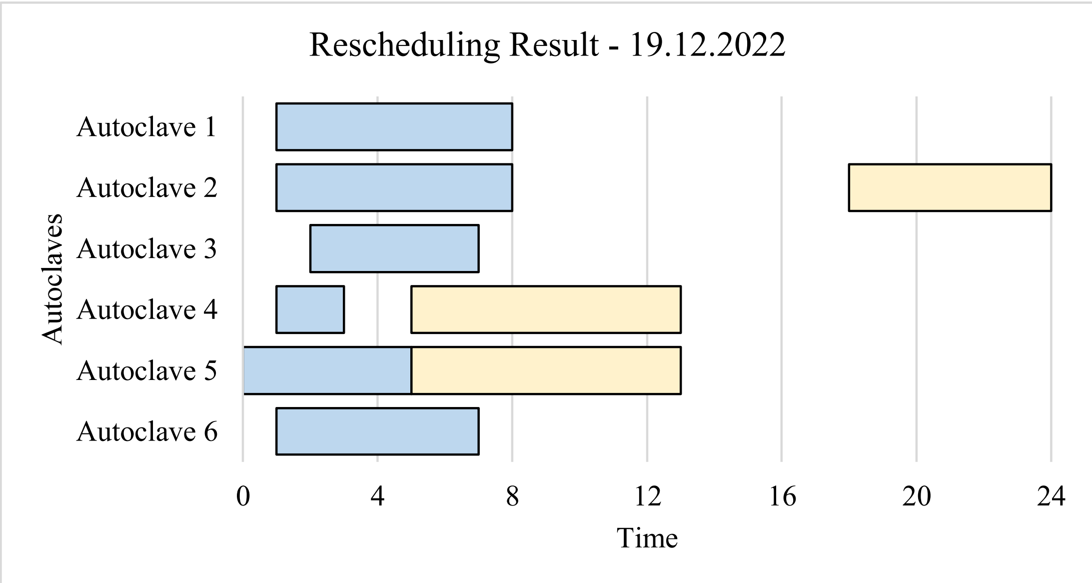

Figure 17: Rescheduling Result - 19.12.2022

After arranging the start times of the batches in a way that will reduce the energy cost, the start and completion times are given in the table below.

Table 24: Start and completion times of the batches on rescheduled 19.12.2022

Batch / Autoclave	Batch 1		Batch 2		Batch 3		Batch 4	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}	s_{3a}	c_{3a}	s_{4a}	c_{4a}
Autoclave 1	1	8	-	-	-	-	-	-
Autoclave 2	1	8	18	24	-	-	-	-
Autoclave 3	2	7	-	-	-	-	-	-
Autoclave 4	1	3	5	13	-	-	-	-
Autoclave 5	0	5	5	13	-	-	-	-
Autoclave 6	1	7	-	-	-	-	-	-
Autoclave 7	-	-	-	-	-	-	-	-

55% savings in energy costs is achieved without changing real-life loadings' recipes, parts, and autoclave conditions. These savings are calculated as follows.

$$Energy\ Cost\ Saving = {}^{(997-451)}/_{997} \qquad (24)$$

A run was taken for these parameters to examine the energy cost that would occur when the same parts and recipes were scheduled with the proposed Model 1 and Model 2.

The figure of the Model 1 schedule, run with the data of 160 parts and nine recipes, is in the figure below.

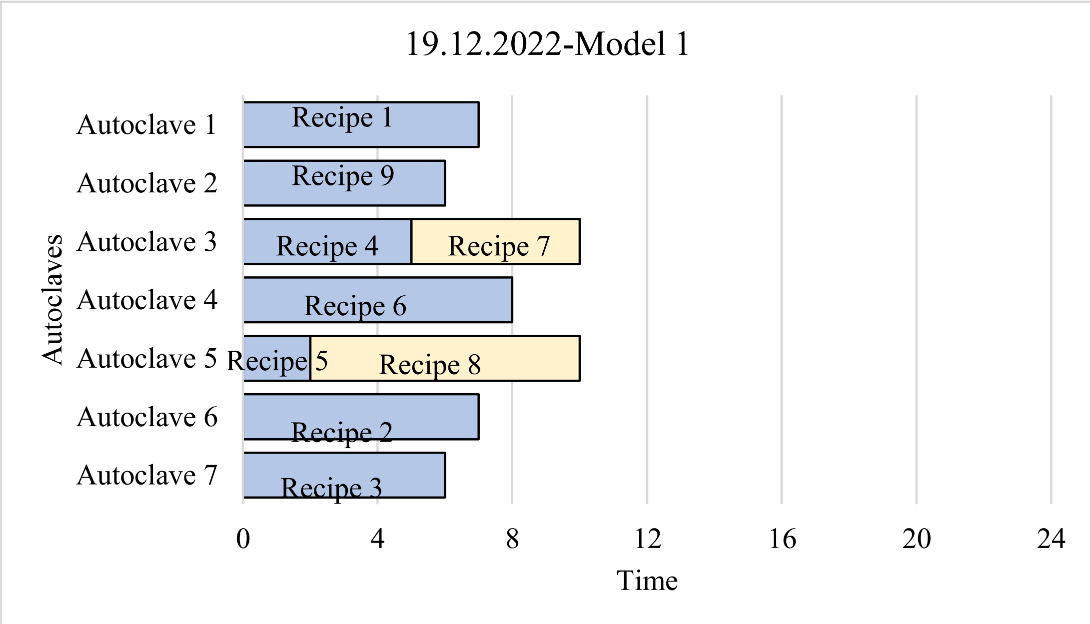

Figure 18: 19.12.2022 Model 1 output

The maximum completion time, 24 hours in actual scheduling, was found to be 10 in Model 1. The start and end times of the batches are listed in Table 25.

Table 25: Start and completion times of the batches on rescheduled 19.12.2022

Batch / Autoclave	Batch 1		Batch 2	
	s_{1a}	c_{1a}	s_{2a}	c_{2a}
Autoclave 1	0	7	-	-
Autoclave 2	0	6	-	-
Autoclave 3	0	5	5	10
Autoclave 4	0	8	-	-
Autoclave 5	0	2	2	10
Autoclave 6	0	7	-	-
Autoclave 7	0	6	-	-

The energy cost of Model 1 is € 413. The run is taken for Model 2 with the assignment information to reduce energy costs.

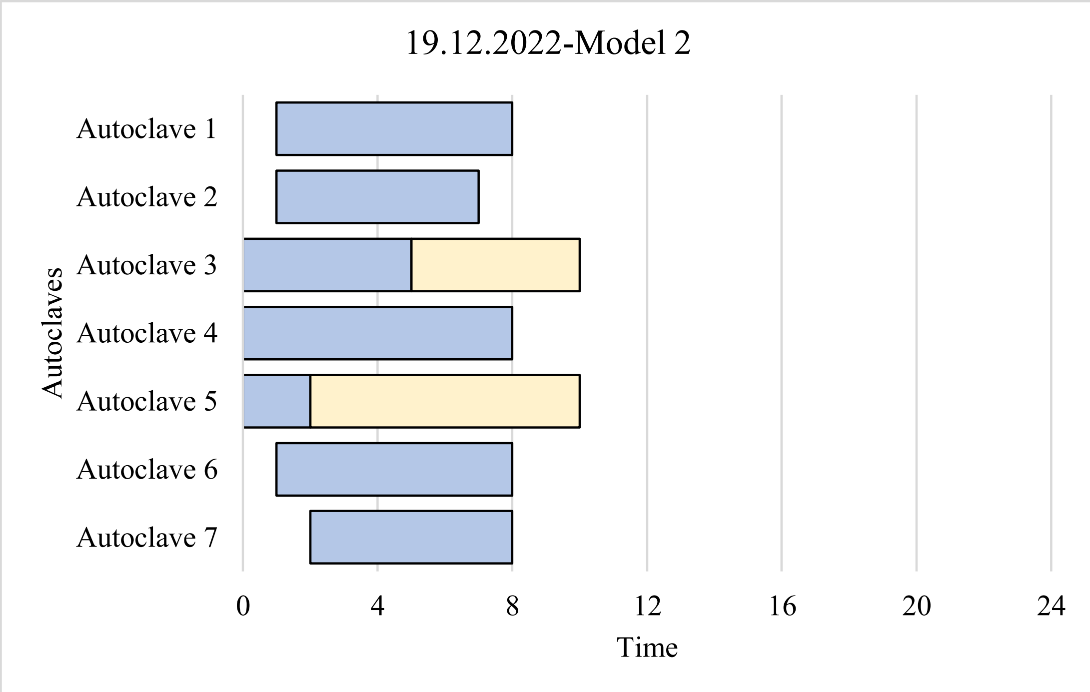

Figure 19: 19.12.2022 Model 2 output

The start and completion times of the batches in the autoclaves according to the Model 2 output are given in the table below.

Table 26: Start and completion times of the batches for 19.12.2022 Model 2

Autoclave \ Batch	Gap	Batch 1		Gap	Batch 2	
		s_{1a}	c_{1a}		s_{2a}	c_{2a}
Autoclave 1	1	1	8	-	-	-
Autoclave 2	1	1	7	-	-	-
Autoclave 3	-	0	5	-	5	10
Autoclave 4	-	0	8	-	-	-
Autoclave 5	-	0	2	-	2	10
Autoclave 6	1	1	8	-	-	-
Autoclave 7	2	2	8	-	-	-

The energy cost was reduced to € 381 due to the Model 2.

In this example, created with the data of real-life curing parts, the proposed models were loaded in all autoclaves, and the energy cost was reduced by 62% compared to the actual energy cost.

Studies with actual data also support the designed experiments. On a day with a high standard deviation value, the percentage of savings in energy costs increases. Even if the autoclaves and batches where the parts will be cured are specific, small changes in process start times may result in significant energy cost savings.

CHAPTER VI
CONCLUSION

This thesis investigates the problem of energy-efficient autoclave loading and scheduling. Two models have been proposed. Model 1 is a modified version of a previous study [19]. Model 1 aims to minimize batch processing time and maximize the time left over. In this model, the total part size in a batch cannot exceed the autoclave batch capacity. Batches cannot start before the parts release time in this batch. The batch processing time equals the recipe duration time cured in the batch. The part cannot be cured in the batch if the recipe of it is not assigned to this batch. Just the same recipe's parts can be cured together. Proposed Model 1 prevents delays on the due date of part and expiration date of the material. As a result of consultation with practitioners, model 1 does not consider energy efficiency firstly because the priority of material expiration date and parts' due date is higher than energy efficiency. The cost of materials is more than the energy costs.

The extra time in the Model 1 schedule saves energy costs in the Model 2 reschedule. Proposed Model 2 reschedules the batches to minimize energy costs by using the outputs of Model 1 as an input. In this model, the parts and recipes assigned to the batches do not change; the curing start time is changed. The energy cost of recipes depends on the start time of the batch given to this model as a parameter.

This study was carried out in a defense industry company. Autoclaves' batch size, part sizes, the average number of parts cured, and the average number of recipes are obtained from this company. Also, energy consumption in autoclaves is obtained from this company via an energy SCADA system. It was not possible to obtain all data because of confidentiality rules. Data sets are randomly created with different methods to increase the number of runs with proposed models. Part area, the number of parts, the number of recipes, the processing time of a recipe, the due date of the part, and the expiration date of the material are randomly generated by discrete triangular distribution. The recipe for each part of each experiment was assigned using the Excel Random Number Generator function. Discrete distribution was used for this assignment. Twelve different experiments were run. While determining the days, the MCP values of these days are examined. In each season, three days were selected. The first days of each season have a minimum standard deviation for the hourly energy cost in a day. The second day has an average standard deviation, and the third day has a maximum standard deviation. In addition to the data sets created with average values, real-life values were taken for two days, and scheduling was made with the proposed models.

The findings we obtained at the end of this study are as follows. On a day with a high standard deviation value, the percentage of savings in energy costs increases. After the MCP values of the day are determined, if the standard deviation of that day is high, it can be said that energy should be especially taken into account. MCP values for 2022 show that the standard deviation in average daily energy costs is higher in Fall. For this reason, it can be said that Model 2 will be more beneficial in reducing energy costs in the Fall.

This study and the models given in the thesis can be extended. MCP values can be estimated for different time horizons, and the loading and scheduling of autoclaves can be planned for a longer time. The capacities of the clean rooms, where the parts are prepared for curing, can be added to the models as a constraint. On the other hand, the company has a cogeneration unit. In the cogeneration unit, electricity is generated by using a heat engine. The price of electricity that is generated in this unit is different from the MCP. This cost may be higher at times and lower at other times. In future studies, the difference in this energy cost and the issue of whether the energy will be purchased or generated by the cogeneration plant can be examined.

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