# AN AUTONOMOUS STORAGE MANAGEMENT SYSTEM PROPOSAL FOR CONSTRUCTION SITES

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# ABSTRACT

## AN AUTONOMOUS STORAGE MANAGEMENT SYSTEM PROPOSAL FOR CONSTRUCTION SITES

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Recently, with the popularity of high-rise buildings and skyscrapers, construction sites in the busy city environments have shrunk in terms of available area, and as a result, temporary facilities such as storage spaces and workshops have been moved into the buildings under construction. Due to this the planning of such spaces and scheduling have become more important. While the management of workspaces, storage spaces, paths, and workshops in the site were traditionally carried out by the project managers or site managers according to construction process progress, it is now necessary to do so in accordance with construction schedule and plan. For these reasons, site management practice has emerged. Site management is important for preventing spatial conflicts and delays. In case of irregular spaces within the construction site, unnecessary labor and material losses arise and the duration of activities increase. Nowadays, the planning of temporary spaces to be established within the construction site is carried out at a larger scale.

This research aims to minimize the material losses and the time spent for the transportation of materials by examining the storage areas in construction sites at a micro level. For this purpose, an optimization function has been developed for finding the optimal placement of the materials into the storage space. In the proposed system it is envisioned that the optimization data is transferred to the automated transportation

robots in construction sites, and the labor cost and time spent for material transportation is reduced to a negligible level. In other words, in this study, a connection algorithm is created between the schedule and space planning tools and the transportation robots to create autonomous storage system in construction site and minimize material transportation time.

Keywords: Site Management, Space Management, Optimization, Robotics, Storage Management System

# ÖZ

## İNŞAAT SAHALARI İÇİN OTONOM DEPOLAMA YÖNETİM SİSTEMİ ÖNERİSİ

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Son zamanlarda, yüksek katlı yapıların ve gökdelenlerin artmasıyla beraber, yoğun şehir ortamlarındaki inşaat alanları küçülmüş ve bunun sonucunda inşaatlarda bulunan depo alanları ve atölye alanları gibi geçici süre ile kurulan alanlar binaların içerisine taşınmıştır. Bu alanların binaların içerisine taşınmasıyla beraber, bina içerisinde mekanların ve iş programının planlaması daha önemli bir hale gelmiştir. Bina içerisinde bulunan iş alanlarının, depo alanlarının, yürüyüş güzergahlarının ve atölyelerin yerleşimi geleneksel olarak proje müdürleri ya da şantiye şefleri tarafından, inşaat sürecinin ileryeyişine göre yapılırken, artık inşaat başlamadan önce iş programına uygun bir şekilde yapılması gerekmektedir. Bu nedenlerden dolayı, saha yönetimi kavramı ortaya çıkmıştır. Saha yönetimi, mekânsal çakışmaların önlenmesi ve iş gecikmelerinin engellenmesi için önemli bir kavramdır. Şantiye alanı içerisinde mekanların düzensiz olması durumunda gereksiz işgücü kaybı ve malzeme zayiatları artmakta, yapılacak olan işlerin süresi uzamaktadır. Günümüzde, şantiye içerisinde kurulacak olan geçici mekanların planlanması ve saha içerisinde yerleştirilmesi büyük ölçeklerde yapılmaktadır. Büyük ölçekte yapılan bu planlama ile, işgücü ve zaman kaybı azaltılabilse de bu kayıplar en aza indirilememektedir.

Bu çalışmada, şantiye alanı içerisinde bulunan depo alanları daha küçük ölçeklerde incelenerek oluşabilecek malzeme zayiatları ve malzemeleri taşımak için harcanan

süreler en aza indirilmek amaçlanmıştır. Bunun için, malzemelerin depo alanları içerisine en uygun şekilde yerleştirme amacıyla bir optimizasyon problemi geliştirilmiştir. Ayrıca bu optimizasyon verileri şantiye içerisinde kullanılmasını önerilen taşıma robotlarına aktarılarak, malzeme taşıması için harcanan işgücü ve zamanı ihmal edilecek kadar küçük seviyelere indirmek hedeflenmiştir. Başka bir deyişle, bu çalışmada iş ve mekân planlaması için kullanılan BIM tabanlı programlar ile taşıma robotları arasında bir bağlantı algoritması oluşturularak, malzeme taşıma sürelerini en aza indirmek ve otomatik bir depolama sistemi oluşturmak amaçlanmıştır.

Anahtar Kelimeler: Saha Yönetimi, Mekan Planlaması, Optimizasyon, Robot Bilimi, Depolama Yönetim Sistemleri

To my family

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## LIST OF ABBREVIATIONS

2D Two-Dimensional

3D Three-Dimensional

4D Four-Dimensional

5D Five-Dimensional

BIM Building Information Modelling

CAD Computer Aided Design

CPM Critical Path Method

FIFO First-In-First-Out

GA Genetic Algorithm

JIT Just in Time

LBMS Location Based Management System

LBS Location Based Scheduling

LCI Lean Construction Institute

LoB Line of Balance

LSM Linear Scheduling Method

# CHAPTER 1

# INTRODUCTION

In this chapter, previous researches and background information about site management, construction planning, scheduling tools, and robotics are explained. Aim and objective, problem statement, contribution, and disposition of research study are outlined.

## 1.1. Background Information

Construction Industry is a sector that is growing exponentially. Nowadays, mega, linear and high-rise building projects which are complex and dynamic in nature, are being constructed at every metropolis area. With these kind of projects, site management, scheduling, and work follow-up has become a critical issue for the efficient delivery of buildings. In high-rise buildings, management of construction site, material stock, and waste has become even more difficult in terms of time and complexity as the number of activities, materials, materials and equipment has increased (Razaei, 2015). This stems from the fact that at a high-rise building project, construction site has limited area for storage and workspace. Due to limitations of space resources, storage area and workspaces have to move or change constantly, leading to increases in workmanship and material waste. Planning of activities at macro and micro level, creating a continuous flow of resources, and ensuring space availability for activities is very important for achieving planned target. The success of a project highly depends on effective site management, scheduling and delivery of materials. Poor management may cause delays and cost overruns (Arditi, Sikangwan, & Tokdemir, 2002).

Construction planning is one of the major activities in project management. A good construction plan is the basis for developing budget and schedule. Project

Management is the overall planning, controlling and coordinating of the project in term of time and cost. Scheduling tools and methods has become critical in construction projects (Ghosh, Krishnaraj, & Namachivayam, 2015). Li et al. (2003) thought that inadequate tools for planners may result in false or lack operation planning which may cause reworks during the construction. Although traditional scheduling techniques such as Critical Path Method (CPM) or Bar Chart are widely used in construction industry, these techniques are not adequate for high rise building since these techniques do not include spatial resource requirement of an activity. Because of the deficient management of construction and discontinuous work flow of resources, CPM has been criticized. For solving this issue some alternative scheduling techniques were explored such as Location Based Management Systems (LBMS). The location-based scheduling tools provide useful solutions in representing work-flow, project progress, location correspondence, and optimization of the schedule (Shankar & Varghese, 2013). One other major activity in project management is site management. Formation, positioning, and timing of the temporary facilities which are used to carry out a construction project are related with the construction site plan. Formulating and solving such problems are complicated since their occurrence is temporal. However, they are very important for project, because site layout directly influence the time and cost, thus, success of the project. Different activities are usually carried out by subcontractors within a limited area on the construction site. Every subcontractor needs specific work place for worker movement, material allocation and equipment movement. Then labor crew and equipment / material required by an activity needs the same space at the same time with another activity, it causes lack of space or space overlap. This situation causes congestion conflict. One of the most common issue is overlapping in the spaces where subcontractors need to do their tasks (Zhang, 2016). Project managers have to create detailed site management plans in order to improve productivity of work flow. It should consist of both space allocation required for activities and specific time frame for doing it. Otherwise, multiple activity crews may clash with each other. A crowded jobsite may cause to decrease productivity and delay. Also, conflicts may cause bad results such as accidents,

collisions, or failures (Moon, Dawood, & Kang, 2014). Thus, minimizing conflicts is essential. A detailed site planning which shows the space allocation for crews will also identify space conflicts; thus, it may improve the overall work flow and efficiency. In contrast, a jobsite can become chaotic, filled with interfered crews, inefficient works, and schedule delays without a proper space management plan (Guo, 2002). Even experienced and professional project managers may have difficulties in solving these conflicts. Thus, project managers are looking for new approaches and tools that can identify space conflicts at earlier stages since managing the workspaces on construction sites affects cost and duration of the project (Chavada, Dawood, & Kassem, 2012).

Lean Construction is a new paradigm for project management. Lean Construction is a planning and controlling technique which reduces waste by improving work flow. The goal of the Lean Construction is delivering product while maximizing value and minimizing waste and produce reliable workflow (Ballard & Howell, 2003). The Lean Construction Institute's (LCI) aim is to develop project management and deploy a new way of thinking about management. Effective use of resource and elimination of waste is supported by LBMS which is also same for Lean Construction principles (Andersson & Christensen, 2007). Efficient resource usage and eliminating waste time are key connections between LBMS and Lean Construction (Kankainen & Seppanen, 2012). Increasing work-flow efficiency and decreasing waste is basis for this research. The flow line of a LBMS schedule is adapted to planning of smooth work flow where crews can work without interruptions caused by others crews working in same location. Thus, LBS supports the continuous activities and a resource usage with minimum waiting time and avoidance of work disturbance; thus, LBS promotes the efficient use of resource and minimization of waste which is also same with Lean Principles. LBS allow the management of projects within Lean concept, including work flow, just in time delivery and supply chain management. LBS is a key for improving the Lean construction techniques. This argument rests upon the difficulties of identifying continuous workflow in traditional schedule methods (Kenley, 2004).

The motivation of the research is to benefit from Lean Principles by preparing an effective scheduling approach.

The use of robots in many other industries has become the norm. They are widely used in serial production lines for manufacturing, in warehouses for stock management, and even in hospitals for intricate operations on humans. However, robots have not become a common scene in building production. Robots can automate various menial tasks and reduce the need for workforce, leading to increased production rate, reduced errors; thus, increased productivity. Moreover, robots can continuously measure and report various physical characteristics related to the environment, improving the project related intelligence. Robots are an important part of lean production system. Increasing use of information technology in construction sites via more capable software systems and sensing platforms can provide an opportunity for the utilization of robots for various tasks. Also, proliferation of various technological advancements in the field of robotics leads to highly capable robots at lower costs. Therefore, there is a potential for the use of robots in the construction sector.

In this research study development process of project management and problems and difficulties of project management is discussed. Project management tools such as site management tools or planning tools are explained. Building Information Modelling and how it can help to project managers is explained, and an investigation of the field of robotics and its applications in other manufacturing industries will be presented and potential use-case scenarios for robotics in repetitive high-rise construction projects will be illustrated. Finally, research will focus on a particular application on automated storage management.

### 1.2. Aim and Objective

This research aims to define and investigate the problems for temporary storage spaces in construction sites and propose an optimization system for organizing and automating storage spaces via industrial stock management robots. Also, this research assumes that BIM based software packages and transportation robots can work with

harmony. The optimization created for defining and managing storage space can be a bridge between BIM and robots.

The objectives of this study are:

- To develop a system for arrangement of storage spaces in construction
- To decrease unnecessary time and cost waste in material transportation
- To use robots in construction site for material transport
- To find out the effectiveness of robot usage in construction site

### 1.3. Contribution

According to previous researches, there are many opinions and approaches proposed for managing site spaces to decrease unnecessary movement and cost. It is identified that arrangement of site is an important topic for decreasing material waste, spent time for unnecessary movement, and cost. Most of them are related with the strategy of arranging and placing temporary facilities in and around constructed facility. In brief, previous approaches examined the site arrangement and site management at a larger scale. In contrast, this research presents a method for material and storage space arrangement at a minor scale.

### 1.4. Disposition

This research consists of five chapters. The first part is the introduction chapter which gives information about topic and explains the problem and objectives of the work. The second part is literature review chapter which explains project management, site management, problems in site management and site layout, construction planning and scheduling methods, building information modelling in project management, and robotics.

The third part is materials and method chapter of the research. In this part, the proposed approach and optimization are explained. After that, the materials of optimization are presented. Also, software that are used for creating optimization function are presented. Inputs, outputs, and process of algorithm are given. Lastly, a

case is described in three different ways. First one is the placement of materials according to first-in first-out (FIFO) strategy. Second one is the placement of materials according to a survey done with professionals. Third one is the placement of materials according to optimization.

The fourth part is result and discussions chapter where analysis, discussions and results are given. Results of case study and working principles of BIM, the proposed algorithm, and robotics are discussed. Results of comparison between human labor and robot-based material placement are discussed.

The fifth part is conclusion chapter which gives a brief information about study and findings. At the end, the limitation of the study and proposals for future research are provided.

# CHAPTER 2

# LITERATURE REVIEW

In this chapter, recent researches about thesis topic and literature are presented. These include site management, scheduling tools, computer-based construction planning, material procurement and storage on construction sites, and robotics. In the site management part, definition of site management terms, problems in site management, site layout elements, and space conflicts are explained. In the scheduling tools part, critical path method, linear scheduling, line of balance method, and space planning are explained. In the computer-based construction planning part, information about 4D BIM is given. In the material procurement and storage on construction site part, usage of material and storage on construction site and just in time delivery terms are explained. In the robotic part, robotics and usage of robot is explained. In the last part, the literature of thesis topics is critically reviewed.

## 2.1. Site Management

Organization of activities, trades, resources, and space is the core of construction management process. These should be carefully arranged for reliable and continuous workflow through different locations (Björnfot & Jongeling, 2007). Among others, space is the major limited resource in construction sites. Many researches were conducted for defining construction spaces required by activities. All these researches suggest that activity spaces should be managed in the construction planning process. According to Akinci et al. (2000), management of construction space is more demanding as against other construction resources. Thus, site management term has arisen to manage construction space.

Building construction process needs spaces for moving, storing, fabricating, and performing the works. These space needs change in construction according to the

progress of work. Different activities may occur in close proximity and spaces may become congested (Riely & Sanvido, 1995). Various subcontractors work in a constrained area in construction sites. Each subcontractor needs their own workspace, equipment and material storage space, unloading areas for materials, paths, and temporary workshops. This situation causes a crowded jobsite and this cause loss of productivity and schedule delays (Guo, 2002). These space requirements should be arranged and managed by construction managers for minimizing congestions. If these spaces are not arranged, they may cause loss of productivity, safety hazards, and loss of quality in works (Riely & Sanvido, 1995).

Site layout and site management terms are arisen for determining the requirement and positioning of temporary works and its requirement in space and time throughout the project (Guo, 2002). Site layout is a way to improve reductions in the project cost, increases in the quality of the work, facilitate safety operations on the project, and regulate environmental aspect of the work. These features are related with the site management and problems of project planning. Site layout planning and site management is fundamental for increasing efficiency, productivity, and safety. Site management consists of temporary facilities which are needed for construction operations, identifying their positioning, size, and shape within construction site. Site management is the optimization, integration and management of different objectives. A proper site plan reduces cost by minimizing transportation time (Papadaki & Chassiakos, 2016). Travel time and unnecessary movement of material and labor can be minimized by a well-planned site layout. Defining best site layout plan is difficult because what is an important thing one day may not be important on other days. Also, site layout plan is related with other planning tasks and construction methods. Thus, site layout plan cannot be precisely defined before other topics are determined. Because of these reasons site layout plan should be continuously developed and it is hard to generalize (Fenn & Gameson, 1992).

### 2.1.1. Problems in Site Management and Site Layout

Site layout management has long been recognized as important topic, but there are no complete solutions that have been proposed in the previous researches. Site layout problems grow with the number and size of temporary facilities. Site layout problems can be defined as facility to location assignment which assigns facilities to predefined locations on site and facility to site assignment which assigns facilities to any unoccupied space available on site. Facility to site assignment is more complicated because several constraints must be satisfied at once (Papadaki & Chassiakos, 2016). Current method cannot guarantee a solution but there are some guidelines for leading to field managers (Rad and James 1983).

**Site Layout Elements**

***Paths:*** All construction sites need paths for moving, bringing and taking off of resources. Also, paths can be defined as access routes which are movement onto and off sites and traffic routes which are movement around the site. Construction professionals suggest that paths should be arranged without crossing across each other and also through working areas. Also, According to Riely & Sanvido, paths can be classified as;

- *Material Paths:* Paths for moving materials between unloading areas, storage space, and workspace
- *Personnel Path:* Paths for workers to move between access points, storage spaces, workspace, and prefabrication space.
- *Debris Path:* Paths for garbage disposal.

***Storages:*** Materials which are brought onto a site are usually not used instantly. In this situation, materials need stock areas. Also, different materials have different needs for stock area. For instance, some material needs to be protected from theft, sun-shine, or dust. Also, handling of material is expensive, so they should be arranged according to minimize double handling and unnecessary movement (Fenn & Gameson, 1992).

***Unloading Areas:*** Spaces required for placing materials onto storage areas at access point.

***Tools and Equipment Areas:*** Spaces required by temporary facilities is used to support other works.

***Security Areas:*** Spaces for providing security. Round of the cranes or work machines can be example of security space.

***Working Areas:*** Spaces required for performing activities.

***Temporary Workshops:*** Workshops should be located according to ease access and short routes to the work space related with it.

### 2.1.2. Work Space and Time Space Conflicts

Construction space is accepted as a limited resource. Especially when more than one trade works at the same space it becomes apparent. These are called as space conflicts which frequently occur and may cause productivity and material loss (Wu & Chiu, 2010). Workspaces have become an important issue in high-rise buildings constructions because construction companies use space buffers to free site space capacity. According to Thabet and Beliveay (1994), incorrect or false decision by project managers may result in chaos on site. Thus, a method is needed for analyzing workspace. Construction workspace includes construction elements, storage spaces, working areas, material path, personnel path, tool and equipment area, and unloading areas. Structural or design components such as wall, slab or façade create a workspace. These workspaces include both components' physical space and buffer space which is need for keeping a safe distance around physical space. Crew workspace consist of a space that labor's need for working safely and efficiently and equipment spaces which is needed for equipment such as crane, pump or excavator. Also, storage areas, camp places, roads and construction site create site layout. In addition, Guo S. (2002), divided construction space to four categories which are exterior of the jobsite, interior

of the job site, inside the structure, and temporary structures. A hierarchical structure for construction spaces is created by using Guo S.' data (Figure 2.1).

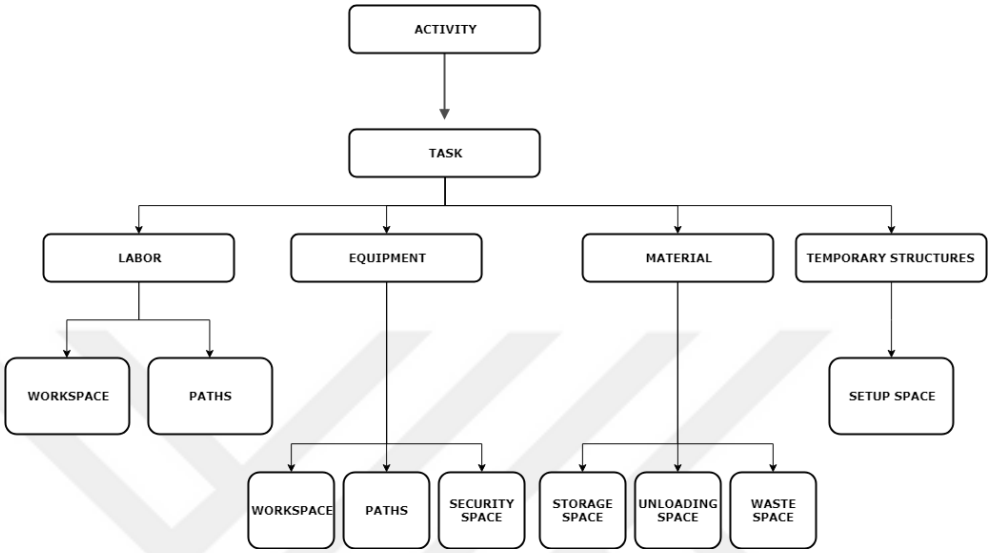


*Figure 2.1.* Hierarchical Structure of Construction Spaces (developed by Guo S., 2002)

On a construction site, different activities are carried out by subcontractors in a limited area. Every activity has its own specific requirements, material and movement. Work space conflicts occur when there is collision of time schedule between different crews and when the work space is occupied by material or equipment. Time space conflicts mean that interfering two activity's requirements in same location. Space conflicts are one of the main reasons of productivity loss (Wu & Chiu, 2010). According to Sanders et al. (1989) productivity losses of up to 65% based on crowded workplace and losses up to 58% based on limited access. Conflicts are not long-term issues but conflicts can cause delays. When phase planning is not correct or proper for each activity, it can cause conflicts (Zhang, 2016). Work space conflicts have three characteristics different than design conflicts which have temporal aspects; they occur at a certain time, they can occur in different forms, and they cause different type of problems.

Time space conflicts are different than work space conflicts. When work space conflicts focus on location, time space conflicts focus on date and location together. More specifically, time-space conflict describes situations in which two activities overlap in time and their work-spaces interfere during the time overlap (Moon et al., 2014).

Also, there are some other factors may lead to work space congestion or time space conflict. For instance, inadequate or inaccurate information from the clients will disrupt the construction flow significantly. When the information is delayed or when clients change their minds, information cannot be delivered to the construction site on time. Thus, there is a high chance of conflict creation (Zhang, 2016).

### 2.2. Construction Planning and Scheduling Methods

Construction planning is the management and accomplishment of construction projects. Construction planning consists of task definition, estimation of resources and durations, and definition of relationship between tasks. Construction planning is the basis for creating and developing the budget and schedule. Schedule developed by professionals creates logical sequence of activities and specify the start and end dates (Hendrickson, Chris, 1998). Construction planning not only is the interpretation of schedule, it also has the ability to collect information about construction elements and identifying and solving problems that occurs during construction process. Construction planning as a determination of what has to be done, how they are performed, what is needed in terms of resource and budget, and when they have to be done (Laufer et al., 1992). It means that, construction planning includes:

- Working Methods
- Work sequence
- Project Schedule
- Budget

The term schedule is defined as “the plan for completion of a project based on a logical arrangement of activities (Popescu and Charoenngam, 1994). Scheduling is used for

showing activities and their relations, allocating resources, and defining duration times of activities. Schedules are also used for communicating with project participant, controlling a project and helping project managers for decision making (Yuksel & Connor, 2000). Current planning methods are limited to site layout and logistic in practice. Space needs for activities in building is usually neglected. There may be some problems which could occur when coordinating the processes across different subcontractors on the construction site. For an effective coordination, a smooth working plan is required (Riley, 1997). Lack of information or ineffective plan can cause delays. According to Laufer and Cohenca (1990), construction planning should begin before design process has ended. Coordination problems can be solved by integrated construction environments. According to Heesom (2004) the use of these environments can make process less problematic while maximizing efficiency. According to Riley and Sanvido (1997), space planning methods helps construction managers to identify:

- Spaces needed for activities
- Location of spaces
- Potential space conflicts

Although construction plan starts before construction, it should be updated constantly. Updating process is critical for the checking process. For updating process, all parties should be communicating extensively. Construction plan is not a self-created plan. It cannot be created by one party (Laufer et al., 1992). Also, Sun and Aouad (2000) state that communication between different parties is critical.

Choice of planning methods is critical for success of the project. The choice of planning methods directly affects the cost and duration of task. Formulating a number of construction plans is necessary in selecting alternative methods (Hendrickson, Chris, 1998). There are several scheduling methods such as linear scheduling, line of balance, and bar chart (Yuksel & Connor, 2000). Activity based scheduling techniques is commonly used for scheduling in construction industry. These techniques are based

on activities and their relationship with each other. But these techniques are limited in terms of spatial configuration of project. Where activities are executed cannot be seen in the traditional way. This makes it difficult to manage activities and resources (Jongeling, 2006). Akinci et al. (2000) proposed group planning approaches for category and shows their input and output (Figure 2.2) which are:

- Static or Dynamic Layout Planning
- Line of Balance
- Path Planning
- Space Scheduling

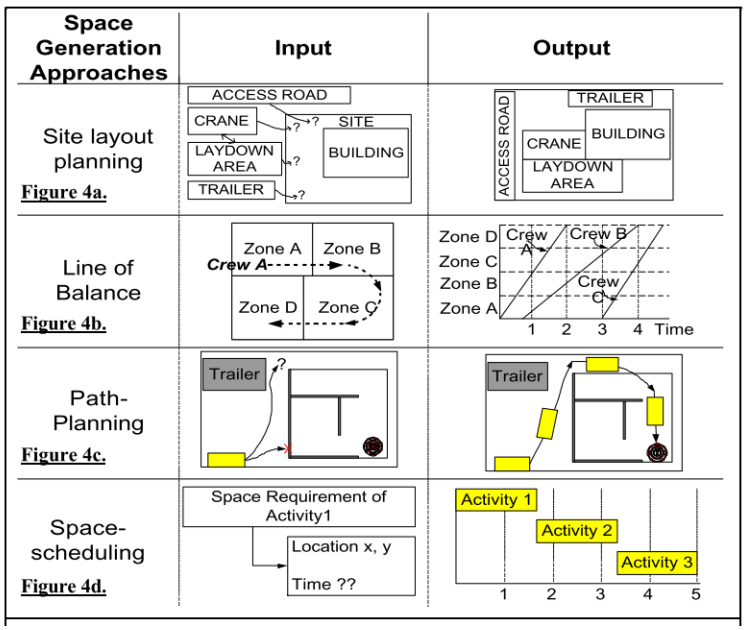


*Figure 2.2.* Inputs and Outputs of Planning Approaches (Akinci et al., 2000)

The Critical Path Method (CPM) is a technique for planning and scheduling of construction projects which was introduced by Du Pont and UNIVAC in 1957 (Türkoğlu H. et al, 2016). CPM calculates the minimum completion time for a project. It is also known as network diagram. The most common tool for scheduling method

is Critical Path Method or Gannt Chart. The Critical Path Method is preferred because connecting activities is simple than other methods. The CPM network shows the logical dependencies of activities and it estimates the completion date of a project based on mathematical calculations (Cheng, 2005). The Critical Path Method shows the logic of activities. Activities and relations are shown by arrows and circles in CPM. Circles are representing the tasks and arrows represent the activities. Bold arrows are representing the critical path (Figure 2.3).

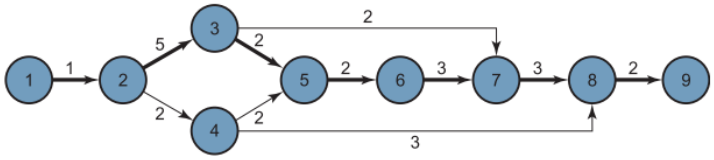


*Figure 2.3.* Representation of CPM

CPM has some advantages which are:

- They are simple to prepare
- They are easy to understand because relations of activities are shown with arrows
- They can include cash flow and man hour diagrams

However, CPM is not suitable for complex construction projects due to lack of ability to cope with unexpected constraints and difficulties in plan evaluation and communication. In addition, CPM does not include spatial information. It does not show the relations of the activities with the spaces and the spatial conflicts that may occur. In order to detect and prevent spatial conflicts, the concept of linear scheduling method has emerged as an alternative to CPM.

Linear scheduling method is a location-based method using for horizontal repetitive projects. There are different types of linear scheduling methods which are Line of

Balance, Time space scheduling, vertical production, time location matrix, and flowline (Jongeling & Olofsson, 2007). The most common two type of linear scheduling method are Vertical Production Method is using in high rise buildings and Line of Balance method can be used for any repetitive projects. Linear Scheduling Methods are based on the relationship between time and distance (Agrama, 2011).

The Linear Scheduling Method is a technique that provides a practical way to monitor and control linear projects. Linear Schedules provide information about crews and their workspace that enable to plan of smooth workflow avoidance of overlapping which two or more crews working at same location (Andersson & Christensen, 2007). LSM has improved overview of the project schedule from the flow line view of LSM supports in terms of communication with subcontractors and other involved parties. The earliest representation of the method was the time-distance diagram. Work progress of the activities can be seen with better presentation by using Linear Scheduling Method (Behnam, Harfield, & Kenley, 2016). Production rates of activities can be determined by the slope of the lines on time-distance diagram. As shown in Figure 2.4, a linear schedule developed with time (y axis) and distance (x axis). The progression of the activities in relation with location and time can be showed on the chart. Activities can be determined in progress at particular location. Also, the continuous flow of work is driving factor in linear projects. Thus, continuous resource usage is critical for project duration (Rogier, 2006). Also, LOB is a kind of linear scheduling method used for planning and controlling repetitive works.

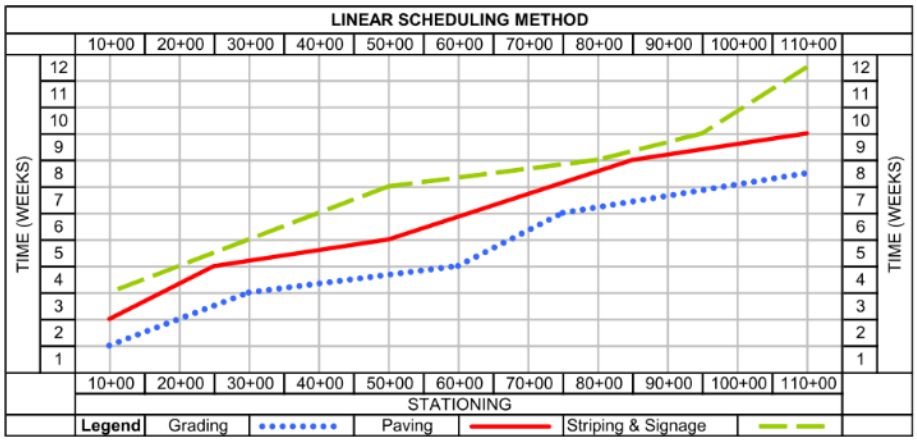


*Figure 2.4.* Representation of Linear Schedule of Repetitive Activities

LoB is a kind of linear scheduling method that includes activities continuously performed. It is easy to plan resources because it includes location data that can reduce work flow variability, risks, duration, and cost of the project (Björnfot & Jongeling, 2007). Line of Balance Method is best suited to projects that display repetitive characteristics, but use of Line of Balance Method is limited in construction industry when activity number is higher. Line of Balance method was introduced as an alternative method to CPM in order to manage linear building construction processes. Line of Balance Method is a Linear Scheduling Method that also uses network technology. Line of Balance Method is better for determining errors in man hour and crew sizes. The main benefit of this method is that this method has simple graphical format. This method is suitable for highways, tunnels pipelines and high-rise constructions. When LOB method is using for high rise buildings, it is difficult to show all activities on one chart (Arditi et al., 2002).

In 1986, according to Arditi and Albulak's explained the advantages of using LoB as:

- Linear scheduling is sensitive to productivity estimates for each activity
- Stage buffers are useful for accommodating variations in productivity

- The preparation of LOB is easier than network schedule in these kind of projects
- The LOB schedule should be as simple as possible
- The visual presentation of LOB scheduling is helpful for controlling project

Although spatial conflicts can be detected with LSM, it is difficult to plan at minor scales, as spatial relationships and spatial information are shown only graphically. The representation of the relations of the spaces with each other, the proximity of each other, or their positions remained simple. The concept of space planning has emerged in order to show spatial relationships in more detail and to make plans at minor scales, with the concept of scheduling being inadequate in planning.

### 2.2.1. Space Planning Methods

Scheduling methods focus on one dimensional approach which means that these methods only focus on time. In the planning process, current methods do not include space required by activities (Nutt et al., 1998). However, space is a key for construction planning. According to current models, activity space requirements should be managed while construction planning is being prepared (Akinci, Fischer, Kunz, & Levitt, 2000). Time-space conflicts in which an activity space intersect with other activity spaces may occur because of lack of management of activity space in construction planning (Riley and Sanvido, 1997). Labor, equipment, and material resources change over time. However, space need for activities change in three dimensions and over time. Also, activities require different types of space, and spaces have different positional need. Spaces can be classified into three categories which are macro level spaces, micro level spaces, and route paths. Macro level spaces are huge spaces such as main material storage areas and site offices. Micro level spaces are smaller spaces such as workspaces and temporary storage spaces. Paths are connection areas between macro level space and micro level space. Paths are used for transportation of material and crew (Akinci et al., 2000).

Riley et al. (1995) describe a construction model (Figure 2.5) in terms of space behaviors, and space patterns. The inputs of construction model define the needs information necessary to create the construction model. Material information includes quantities, availability of materials, delivery time, storage needs, and storage methods. Design information includes the shape of materials and relationships of activities. Construction schedule includes logic network, relations, and durations of activities. The outputs of construction model define information tools for construction managers. Work sequence defines the success of activities. Layout sequence defines the graphical representation of spaces during work time. The delivery sequence defines the quantities of materials which are unloaded onto site. All these sequences are related with the available space such as storage area and material paths on the site (Riley, 1997).

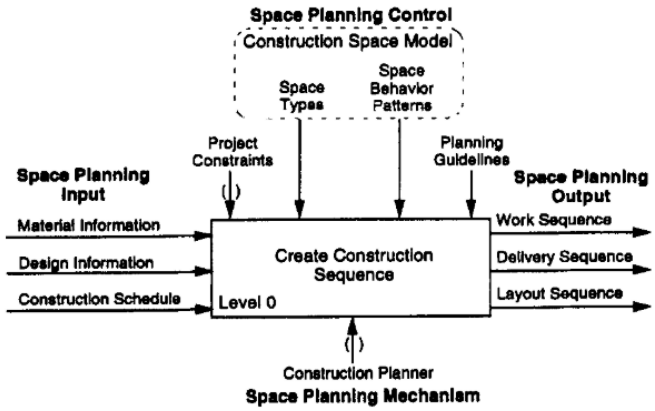


*Figure 2.5.* Construction Model (Riley and Sanvido, 1997)

Construction Space Model originally proposed by Akinci et al. defines 12 space types required by activities (Figure 2.6). It shows that the amount of available space that constricts workspace. This research is based on the understanding of micro-level space. Also, it is shown that location, size, and type of the workspace can change according to the phases of tasks. A false plan can cause inefficiency and waste.

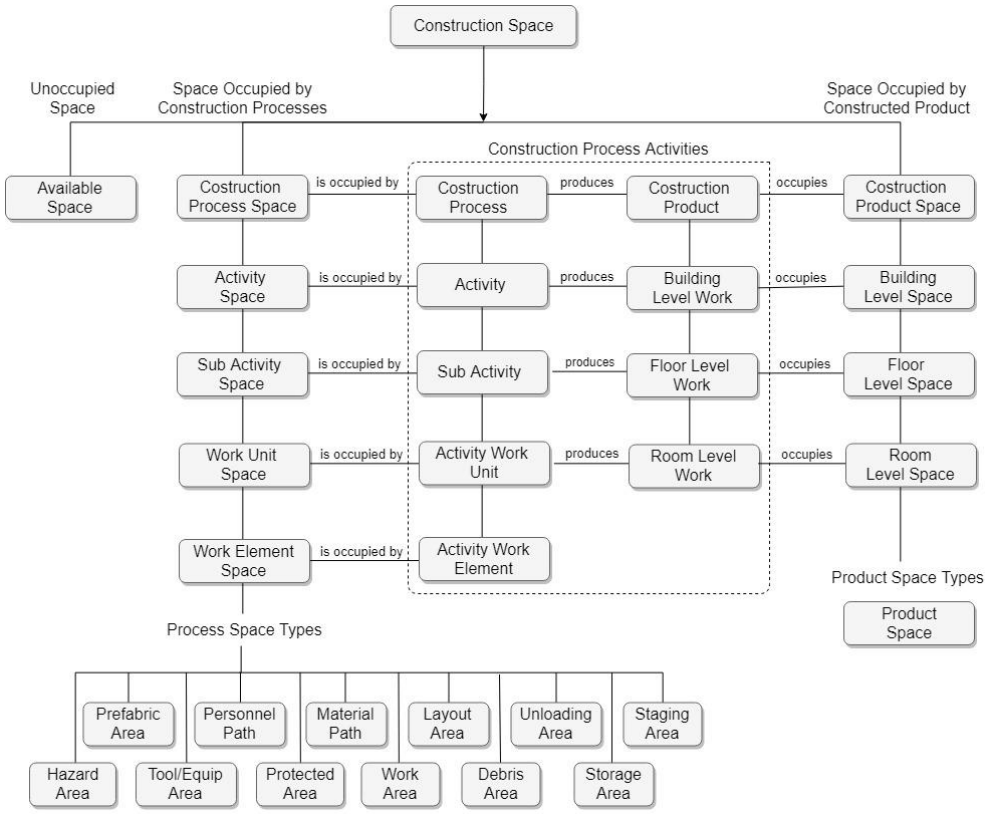


*Figure 2.6.* Construction Spaces (Redrawn from Akinci et al, 2000)

In addition to space type, space behaviors and space pattern should be determined for space planning. Work element's need affects the location or condition of required space. For example, some materials should be protected from dust. These materials should be placed in a clean space. Also, some material needs more protected space. Also, method of work can be represented by a pattern. Pattern shows how space is used to perform working elements. Riley (1995), classified patterns into three categories which are working area, storage area, and temporary spaces.

Work area patterns were proposed as Linear, Random, Horizontal, Vertical, Spiral, and Building Face. Linear pattern follows a continuous linear work area such as duct or pipe works. Random pattern doesn't have any distinct order. It can work in any

pattern. Horizontal works complete a series of horizontal units such as drywall. Vertical units complete work vertically such as an elevator. Spiral units follow a spiral pattern around core of the building. Building Face unit follow one face of building at a time (Figure 2.7).

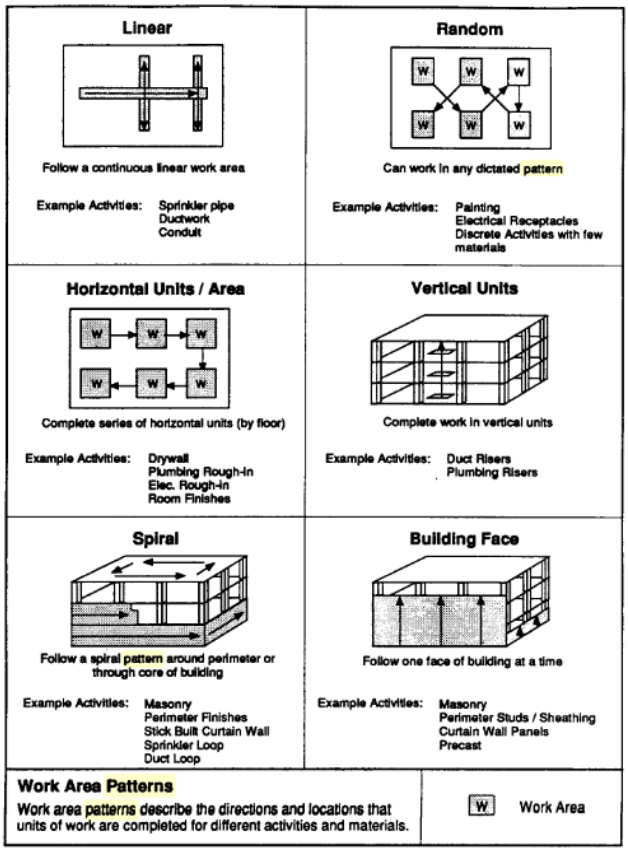


*Figure 2.7.* Workspace Patterns (Riley and Sanvido, 2015)

The important part of the space planning is understanding the behavior of activities. Different activities need different temporary space for prefabrication areas before final installation. These locations can be different in terms of size and location. Riley (1995), classified temporary spaces in three categories according to space level which are room level, floor level, and building level (Figure 2.8).

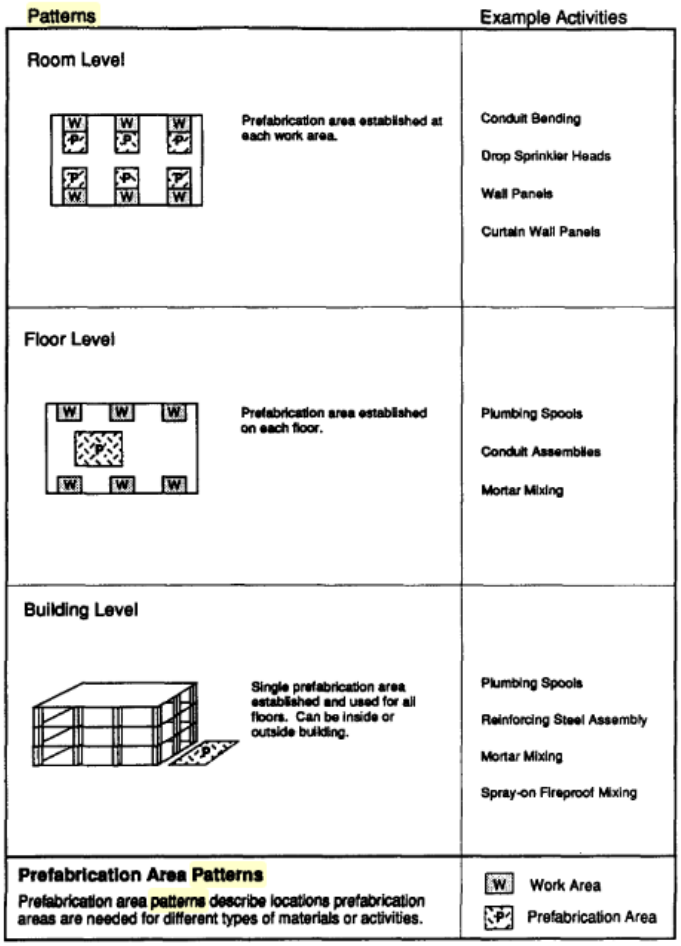


*Figure 2.8.* Temporary Area Pattern (Riley, 1995)

Every activity needs different material and these materials need different requirements in terms of space and behavior. Thus, storage patterns depend on the needs of materials. Some materials are distributed to all floors, some materials are stored in one location, some materials spread out to locations that are in the vicinity of several work areas, and some material are stored off site (Figure 2.9). Riley's construction-space model (Riley, 1995) explained what kind of spaces needed by activities and how these spaces act over time. This model can help for defining relationships between different activity spaces.

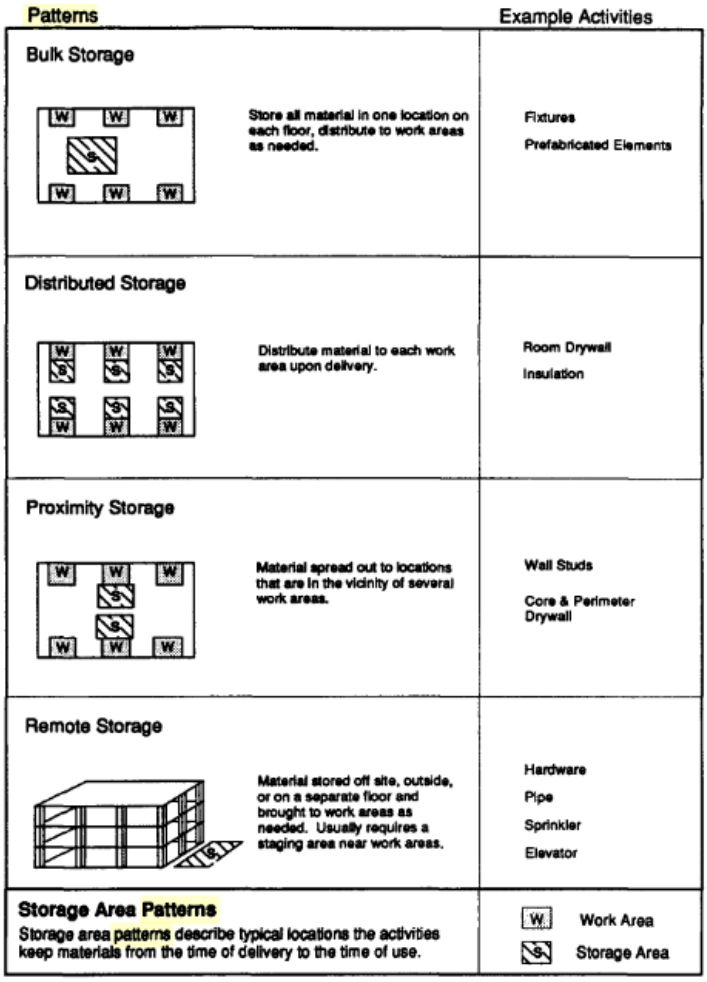


*Figure 2.9.* Storage Area pattern (Riley, 1995)

In detailed construction model (Figure 2.10), there are four main steps which are (1) identifying required space, (2) generating layout, (3) sequencing activities, and (4) resolving conflicts. Schedule of activities, material information, and space needs are using in identifying activity working space and material spaces. Initial construction plan is used for identifying activities that space plan includes. Physical features of materials, spatial attributes, availability of materials, and construction methods are identified by using design information. In generating layout process, space behaviors, positions of work areas at room level space, loading areas, unloading areas, and paths in building level space, positions of storage space in floor level areas, and graphical

plan which shows all locations of spaces are defined. In sequence activities process, work sequence, and working logic of activities, working direction and behavior of activities, and material delivery times are defined. To resolve conflicting processes, overlapping spaces and interferences are defined. Which activity's space can be altered to interference is identified. Methods, sequence, storage location and delivery dates are determined for conflict resolution.

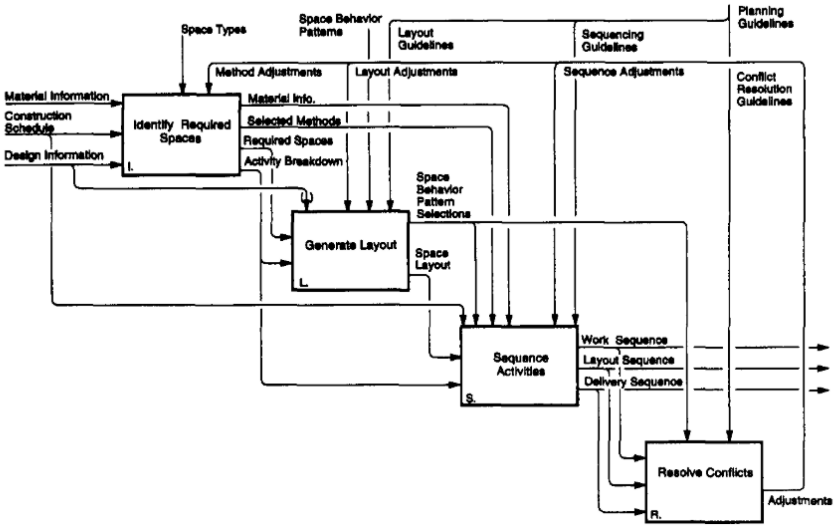


*Figure 2.10.* Detailed Construction Model (Riley and Sanvido, 1997)

With the development of technology, computer-based planning tools have emerged. These planning tools were prepared on the basis of the spatial planning concepts put forward and provided the works to be shown together with the spaces. In this way, it has become easier to make plans at smaller scales and to follow up the plans during construction phase.

Recently, computer-based planning and scheduling approaches has become widespread. New techniques show up by the increased computer technology. According to Abourizk and Mether (2000) computer-based planning and visualization

may positively impact the construction planning. There are lots of advantages of using computer-based planning methods in construction.

In the past, construction plans were created as 2D diagrams or bar charts such as CPM or network chart. But, these types of plans cannot provide spatial features of construction. With the spatial need, construction planners start to use 3D visualization tools. However, those visualization tools cannot give current situations of project and show the exact status of a project. They just give an image of a project. Construction planners must rely on their knowledge, experience, and capabilities to prepare appropriate construction plan because they don't have any visual representation of construction site which include progress and usage of space. 4D BIM term arisen for making it possible to integrate construction information with 3D model. 4D BIM is an integration of 3D drawing and process information and it is making it possible to show schedule (Wang et al., 2004). For effective and better planning 3D design is integrated with schedule information. 4D BIM ease the visualization of sequential construction process for construction managers (Kim, Kim, Park, & Kim, 2011). 4D BIM provide a clear picture and spatial insight of schedule information and it helps stakeholders to communicate more quickly and clearly. 4D BIM was used by Center for Integrated Facility Engineering (CIFE) for the first time. First 4D software tools can give an animation of activities which show the sequence of activities and help to understand construction schedule more realistic. Then, researchers worked on 4D BIM and they generate 4D movie of a construction with connecting 3D model with schedule. At present, 4D BIM can collaborate Architectural, Engineering and Construction (AEC) models (Wang et al., 2004).

Most important point in 4D BIM is space detection, site planning, and work space analysis. In recent researches, 4D BIM was used for site management, scheduling, predicting work space requirement, and visualizing dynamic plan of construction. Also, 4D BIM is used for detecting and solving workspace conflicts. Kim C. et al. states that one of the main strategies of 4D BIM uses is by combination with other technologies. Kang et al. (2007) integrate 4D BIM with web to provide easier access

to BIM information. Also, Dawood et al. (2003) create a database for 4D simulations. In addition, in past researches, BIM was combined with radio frequency technologies to improve monitoring (Kim et al., 2011). Hu & Zhang (2011) show function of 4D BIM (Figure 2.11).

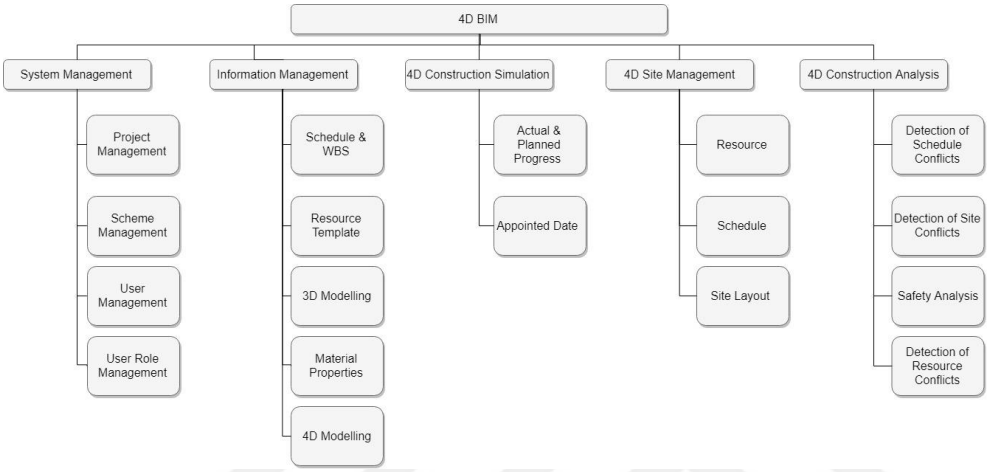


*Figure 2.11.* Function of 4D BIM

With the developing planning methods and tools, it has become possible to make space planning at smaller scales. In this way, the planning of the temporary facilities in the construction site, as well as the internal arrangements of these spaces can be planned. In the past researches, a lot of work has been done on how temporary facilities in construction sites should be placed in the construction site. However, these studies do not include how the temporary spaces within the building floors should be placed and how these areas should be planned. In this study, it is aimed to produce a system on how the storage areas in the building floors should be planned. Also, it is aimed to create autonomous storage system in construction site by using transportation robots.

## 2.3. Material Procurement and Storage on Construction Site

Any inefficiency that causes the use of more than necessary amount of equipment, materials, workmanship and principal required for the production of a structure is called as waste (Koskela, 1992). According Liker (2004), storage and transportation of material are two results of waste. Mazlum and Pekeriçli (2015), showed 8 reasons of waste. They state that unnecessary movement of material is one of these reasons. Material procurement and storage on construction sites should be planned properly for preventing the material shortage and uncontrolled material inventory in construction site. The main causes of time delay, loss of productivity, material waste, and financial losses is the deficiencies in the flow, store, supply, and movement construction material (Thomas et al, 2005). Material ordering and storage planning has become key points for decreasing time and cost delays. Ordering smaller quantities of materials can decrease the waste, but it may cause material shortages. Moreover, ordering larger quantities of materials can decrease the shortage and delays, but it needs larger storage areas. As more and more tall buildings are constructed in densely populated locations, storage areas in construction sites are decreasing. Thus, the critical trade off during ordering and storage on site should be considered carefully (Said & El-Rayes, 2011).

Exterior space is used for material storage in construction. However, in the congested and limited construction sites, interior building space is also used for material storage. According to Said & El-Rayes interior storage decrease the material supply cost, but it may increase the shifting cost of material (Said & El-Rayes, 2014).

Considering the limited availability of material areas on the construction sites and the availability of these areas, material supply should be provided in a coordinated manner with suppliers. In the absence of this supply, material losses can be noticeably increased. In accordance with the Lean concept, concepts such as six sigma and just-in-time delivery have emerged to reduce material loss. Just-in-time (JIT) delivery is a system that adjusts the material orders from the supplier according to the project schedule, in a way that does not stop the work. In contrast to traditional purchasing

methods, the JIT delivery system supplies small quantities of goods and delivers more frequent shipments. This reduces the space requirement for storing materials. In addition, since material shipments are made only when material will be used, unnecessary space occupancy of the materials that will not be used is prevented.

In addition, the first-in-first-out method (FIFO) is another method used to comply with lean principles and reduce waste in storage systems. According to the FIFO method, the order of use of the materials must be the same as the order of purchase. That is, the material that comes to the construction site first is used first. During storage, the first incoming materials are placed in the first exit zone of the storage area. This prevents over-waiting of the materials. For example, if a gypsum waits for a long time in the construction site, that gypsum may deteriorate due to construction site conditions. FIFO is also important for cost balancing. Since the initial materials are purchased at lower prices, they have a higher profit margin. Subsequent materials may increase or decrease in value. Thus, not only waste of material but also cost waste is prevented.

## 2.4. Robotics

### 2.4.1. Characteristics of Robots

Robotics Industries Association defined robots as a reprogrammable, multifunctional manipulator machines which move material, part, or tools through various programmed motions (RIA, 1979). While the traditional robot representation is made as a generic autonomous means with an android (human-like) form, most of the robots that have entered our daily life have become auxiliary devices that fulfill very special purposes. The definition of the robot is no different today than it was 30 years ago; robots are devices that perform a very specific production sequence without direct human intervention (Warszawski & Sangrey, 1985). Among the robots that have used successfully in our daily life are autonomous house cleaning tools (i.e., iRobot Roomba, Neato BotVac), various bread making machines, and even autonomous grass mowers. Machines that we used without even realizing, have actually gained many

autonomous properties, such as washing machines, dishwashers, home automation tools (i.e., Google Nest), automobiles and even social robots (i.e., Amazon Echo, Google Home). These machines have been integrated into daily lives and have become indispensable for many people. Many of the robotics are helping people by taking the burden of routine and simple tasks from their work. In other words, it is not andro-formed machines portrayed in the 70s and 80s, but today's robots are specialized tools embedded in the daily life. In this context, robot technologies, which are actually proposed for built environment production, should not be the tools to replace direct human beings but should be expected to be helpers to speed up and serialize the tasks that people will have difficulty doing.

### 2.4.2. Potential Uses of Robots in Construction Site

Robots which have ability to function on their own have the potential to improve safety for all workers. Robots can take the role of completing mundane tasks, so workers can use their time to do more skilled work. This bolsters efficiencies and timeline management for construction job sites.

Warszawski and Sangrey (1985) present the following basic skills of robots in terms of construction sector:

- *Manipulation:* The ability to move object and change their position on different axes and coordinates. There are some examples of more common manipulation systems shown in Figure 2.12. Fig 2.12(a) represents the three axial translations in rectangular coordinates. Fig 2.12(b) represents rotation and biaxial translation in circular coordinates. Fig. 2.12(c) represents two axial rotation and circular transportation. Fig. 2.12(d) represents three axial rotations in revolute coordinates (Warszawski & Sangrey, 1985).

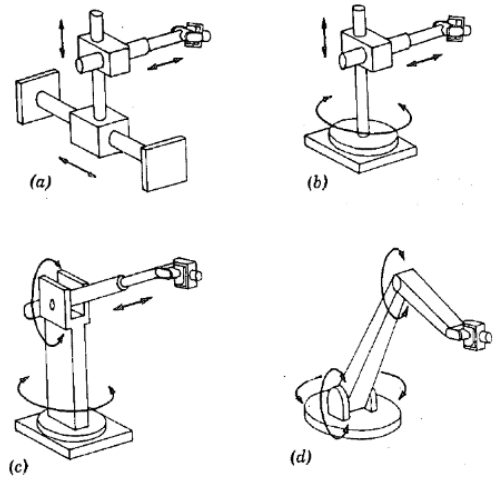


*Figure 2.12.* Manipulation Movements of Industrial Robots

- *Effectors*: The ability to attach different talented equipment according to their arms. Finger grippers, suction grippers, magnetic grippers and tube grippers are more popular types of effectors which shown in Figure 2.13. For general application, welding guns, painters, and drills are typical tool effectors. Effectors work with manipulators for orienting and positioning.

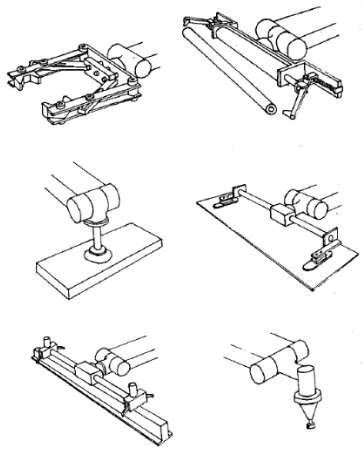

*Figure 2.13.* Effectors of Robots

- *Control:* The ability to have different levels of control and artificial intelligence. The Japanese Industrial Robots Association (1981) classified robots in six groups which are manual control, fixed sequence, variable sequence, playback, numerical control, and artificial intelligence.
- *Sensors:* The ability to measure and report various physical characteristics related to the object and environment.
- *Mobility:* The ability to move within various restrictions.

Some simple tasks can be done on the construction site with the various combination of these abilities. Although it is not widespread, we can see various special applications in Warszawski & Sangrey's paper (1985):

- Assembling Robot
- Interior Finishing Robot
- Exterior Wall Finishing Robot
- Mobile Ceiling drilling Robot
- Demolition Robot
- Robotic Drones
- Transportation Robots

Assembling robots (Figure 2.14) are used for moving and carrying large building elements such as steel beams, precast concrete blocks. Assembling robots have an anthropomorphic arm such as cranes or excavator's arm. The differences of anthropomorphic arm and crane's arm are that anthropomorphic arm is more flexible in payload (Jackson, 1990).

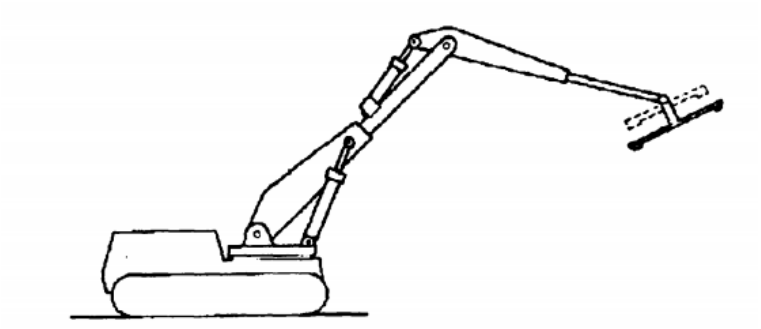

*Figure 2.14.* Assembling Robot

Floor finishing robots (Figure 2.15) used for performing interior finishing operations such as painting, plastering, or tile. This kind of robots can be reprogrammed for performing different type of activities. Size of the robot's manipulators can change according to dimensions of work place (Jackson, 1990).

*Figure 2.15.* Floor Finishing Robot

Ceiling drilling robots (Figure 2.16) are used for drilling. Drilling robots can perform about 10 times faster than manual labor. Also, it is safer to use robots due to health and safety concerns in these kinds of activities.

*Figure 2.16.* Ceiling Drilling Robot

Demolishing is a hard, time-consuming, and hazardous activity. Thus, demolishing robot (Figure 2.17) can do such activities faster and safer. Demolishing robots look like a mini-excavator, but they don't have cabs. These robots can assist human workers on the construction site.

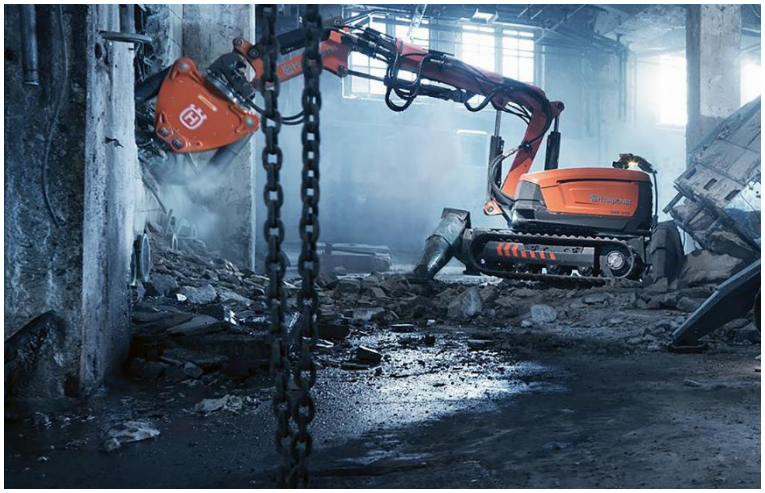

*Figure 2.17.* Demolishing Robot

Robotic drones (Figure 2.18) are unmanned aerial robots which can be controlled remotely by human interface. Robotic drones can be used for creating 3D model of a place or an object. These types of drones can work with 3D printing robots. Also, drones can be used to transport light elements. In addition to transportation, drones can be used for surveying a place. These types of drones can take images, 360˚ panoramas, and aerial shots of a place. Drones can work autonomously and perform tasks assigned to them, such as bridge inspections (Yoder & Scherer, 2015).

*Figure 2.18.* Transportation Drones

Transportation robots (Figure 2.19) are used for transporting heavy or large elements. These robots are able to accomplish trough GPS or indoor/vision tracking. However, the terrain needs to be flat for moving. Also, transportation robots are used in warehouses.

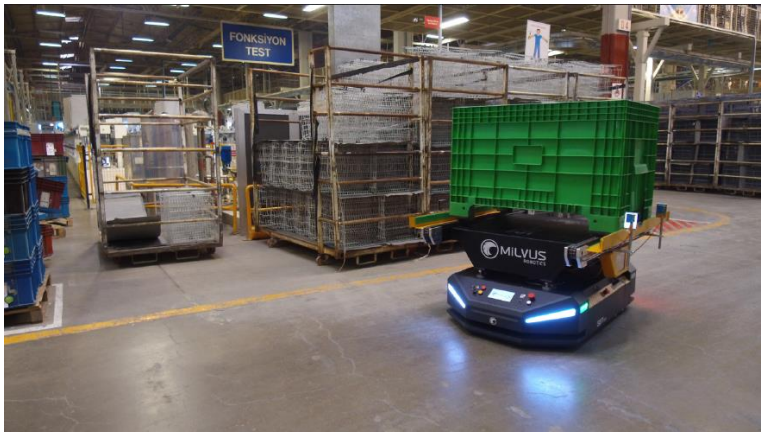


*Figure 2.19.* Transportation Robots

Howe (2000) presented a roadmap for the adaptation of robots to construction industry. Among these, the design approaches that support automation, the proposal on the transport and organization of construction materials is interesting. Indeed, the faster way to work in the construction industry is to continually extended supply chain to the final assembly point. In this context, Lee and his colleagues (2001) report on the use of intelligent space for robots. This proposal is essentially about tracking and directing mobile robots in distributed networked sites with distributed sensor tools. Cusack (1994) stated that there are major shortcomings in the transfer of building design knowledge to robots.

In particular, the material distribution and organization can be made by evaluating the recommendations of Lee et al. (2001) and Kim et al. (2004), along with vertical construction and linear programming, by ensuring conformity to BIM. In this research project, the high requirements of the material framework proposed by Skibniewski and Wooldridge (1992) will be addressed with the requirements of linear job programming tools, BIM, distributed sensor networks and a smart algorithm.

## 2.5. Critical Analysis of the Literature

Nowadays, contractors try to complete construction projects as fast as they can. Construction time has to get shorter. However, short construction period causes loss of material and labor force. Contractors spend more money and time while they try to finish faster. Contractors need proper construction plan for preventing these losses. Also, cheaper, safer and faster construction can be managed by collecting more intelligence during the construction process.

The existing researches about site layout planning ignore cost and time related parameters (Papadaki & Chassiakos, 2016). While the understanding of construction planning has been mainly related with the CPM, most other aspects of the construction need have been left untouched (Kelsey, Winch, & Penn, 2001). Although, previous researches integrate drawing tolls with scheduling tools, there are limitations. Difficulty of planning work flow and spatial configuration is limitation of integration of CPM with 2D drawings. Also, integration of LoB and 2D drawings is relatively unknown method and it has limited support to plan the spatial configuration of an activity (Jongeling & Olofsson, 2007). Thus, there is gap to manage spatial configuration.

Space management is one of the important aspects which are ignored. Unplanned site layout, often cause the conflicts. Nowadays, these conflicts are solved by project managers on the site when they occur. Quality of solution depends on the problem-solving ability of project managers.

The following aspects are the gaps in construction management:

- Congestions and conflicts are major cause of productivity and material loss. A proper space planning is required for overcome these conflicts and congestions
- There are several space planning models and movement patters but they are not connected with new planning methods.
- The integration between resource plan, space plan and schedule are essential for improving planning approaches.

- There are a few researches about the loss of material and workforce for material movement.
- There is a gap between the capabilities of visualizing information and its use.

# CHAPTER 3

# METHODOLOGY

In the previous part of the thesis, the current issues on site management, site layout, construction planning, scheduling tools, 4D BIM, and robotics have been presented. The previous researches about site planning and management, and the problems in construction site were presented. The most important reasons for these problems are the spatial conflicts and how to arrange the facilities within the construction site that cause loss of time and cost. When previous studies are examined, it is seen that there are some missing parts for creating site layout. Although, recent researches are related with generic space planning and site layout, there are few researches about space planning at micro level. This study focuses on the storage areas within the construction floor layout and how the materials should be placed in these storage areas. In addition, this study also aimed to propose an autonomous storage space system by optimization tools and robots in the construction site. Optimization is uses data about material, work, and space from 4D planning tools and aims to create a material placement layout in the storage areas in the most appropriate/efficient way. It then transfers the placement information to the robots, allowing the robots to transport and place materials automatically. With this system, it is aimed to reduce the loss of time and cost. Python were used to construct optimization data. Moreover, optimization and its placement strategy were examined on a case study by comparative trials.

## 3.1. Proposed Approach

Nowadays, many modelling and planning programs are used by professionals in construction sector. 3D modelling was first introduced in the 1960s to create a three-dimensional digital visual representation of an object. It is aimed to create a realistic drawing of an object by using computer. Then, 3D modelling is integrated to

construction industry for creating visual representation of a building. Although 3D modelling and 2D drawings are considered as separate things, these concepts are interconnected in many ways. A 3D model also includes 2D drawings. 2D drawings are used to create 3D model. Also, 3D modeling can provide technical details as well as visual details. In addition to details, 3D models can provide material information which is used in building design, which is encompassed with BIM approach. 4D BIM is a process which connects 3D modelling with construction schedule, construction activities, site layout, and space relations (Figure 3.1).

*Figure 3.1.* 4D BIM

4D BIM decrease the risk due to increased team coordination and communication. It allows better communication between different parties. It is also used for construction planning, lean scheduling, safety issue identification, just in time delivery, and detecting conflicts. 4D BIM includes time-related information on lead time for building elements, installation and construction time, activity relations and the sequence of activities, information about temporary facilities, and site layout. Site layout includes the material paths between the loading areas, storage areas, and

workspaces, the paths that allow employees and workers to move between the spaces, working areas, loading areas, temporary workplaces, and site offices. The 4D model includes the location, size, and the length of time period for these areas. In addition, the 4D model shows the activity patterns, start and end date of activities, in which places to perform an activity and how much space an activity is needed to perform. Beside the activity features, 4D model includes material and workmanship information, material movement patterns, and space requirement for storage of materials.

In this research BIM is used to collect information about site layout, material features, activities and schedule. In addition, BIM can update at the end of the day work, materials used and site status. In this way, the necessary information for the algorithm to be created will be constantly updated. With this optimization system, it was found out how to place the materials in the most appropriate way by using this information. According to this information, the proposed model has been prepared.

Proposed model consists of five main stages (Figure 3.2). The first stage is the data collection stage. At this stage, the information required for the optimization is collected. Firstly, the site layout is created by collecting product model information including building elements and building space. Then, the work to be done and construction phase information is collected, where, when and what work to be done is determined. The materials required for these works and the information related to these materials are collected. Finally, the optimization stage is determined by determining the locations and sizes of the storage areas where these materials will be placed in the field. While mentioning the storage spaces it means temporary storage space on the floors of the building, not the warehouses outside of the building. In the optimization phase, a mathematical equation was created to find out how the materials should be placed within the storage areas. This equation is used to find the effort required to move a material from the storage area to the workspace to be used. The result of this equation is the fitness value. These fitness values are available for all materials and all areas where materials can be placed. Then the smallest total value of

these values is found. The settlement plan made according to this total value shows the most suitable places of the materials. Material layout plan is prepared in accordance with the information obtained as a result of optimization. This plan shows where the materials will be placed and which workspaces they will go to. This plan information is transferred to the transportation robots to be used in the field. Using this information, the robots place the materials where they need to be stored and move them to the workspaces when they need to be used. After the transportation process is completed, information is transferred to the update system. In addition, the process and construction space information of the works performed in the field are updated. Then, the current information is collected and the steps are repeated. In this way, the time and cost required to transport the materials are minimized. In addition, by creating an autonomous transport system, the transport operations are carried out uninterruptedly and in accordance with the work schedule. Therefore, material waiting times are reduced and the productivity is increased.

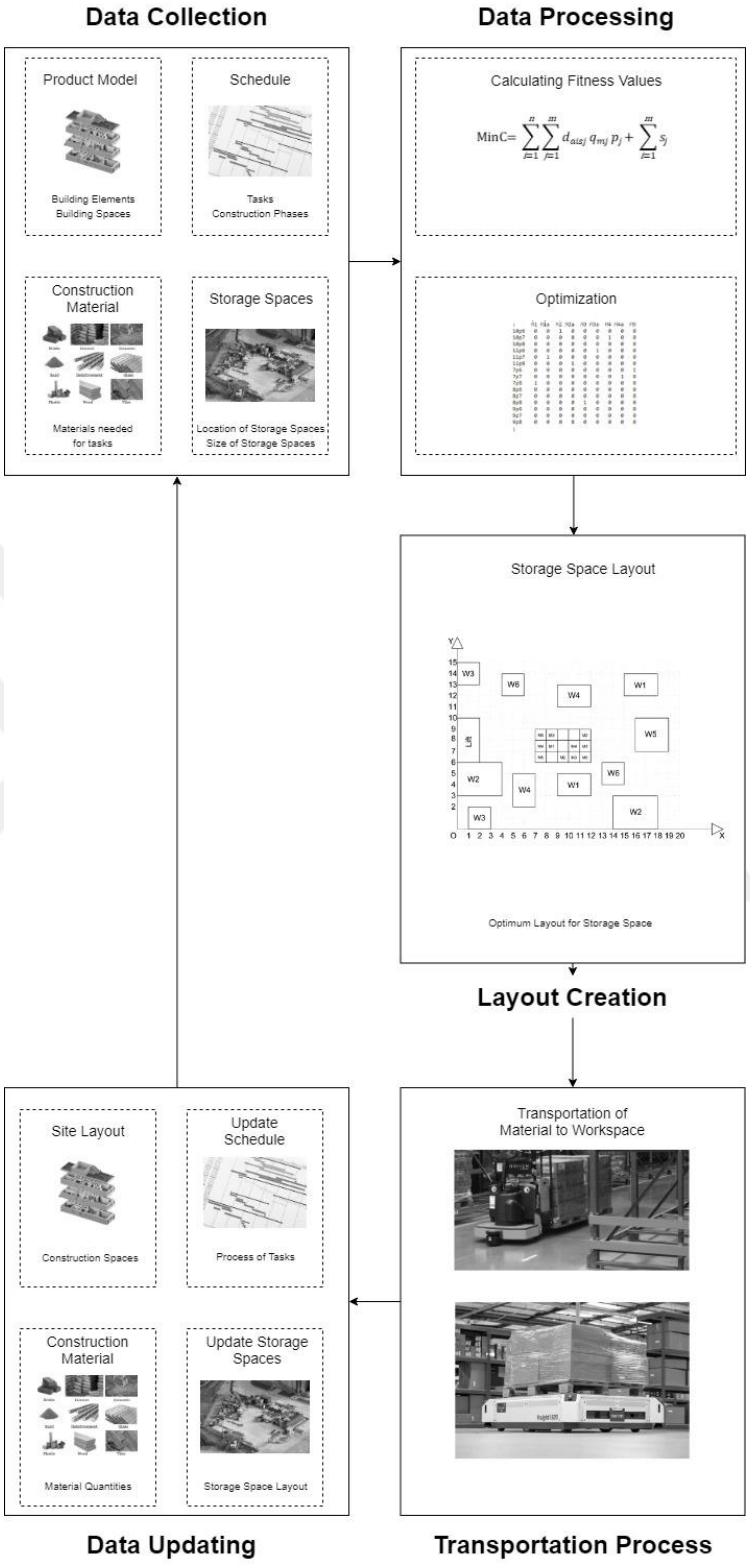


*Figure 3.2.* Proposed Approach

According to the proposed approach, the product model includes building elements and building spaces. Building elements include such as wall, floor and ceiling elements required for a construction. Building elements are indicated by volumetric data. Building space shows where these elements are located. Schedule includes the tasks which is the construction of building elements and the construction phases which includes information about when and in what order building elements should be constructed. Building elements and task combine to form the materials and equipment needed for a job. This material data gives the areas it occupies on the plan. The size of the storage areas is determined according to the area covered by the materials. In addition, schedule data and product model data combine to create workspaces. Workspaces represent the place where the building elements are to be performed and the areas required to do these works. According to the proposed model, the workspace data and storage space data are taken and the effort required to move the materials to the workspace is calculated. These data include the coordinates of the areas where the materials should be placed and the workspace areas required for performing the tasks. As a result of this process, fitness values are obtained according to all areas where all materials can be placed in storage areas. By optimizing these obtained values, the optimal total transport effort is calculated. As a result of the optimization, data is obtained on how the materials should be placed in storage areas and where they should be transported. This data is transferred to the transportation robots to be used in the construction site and transport operations are completed. At the end of these operations, the amount of materials from the warehouse areas, the progress stages of the works and the construction space status are updated at the end of the day. Operations are repeated over the updated data. In this way, a storage system is created autonomy. The data flowchart of this system is shown in Figure 3.3.

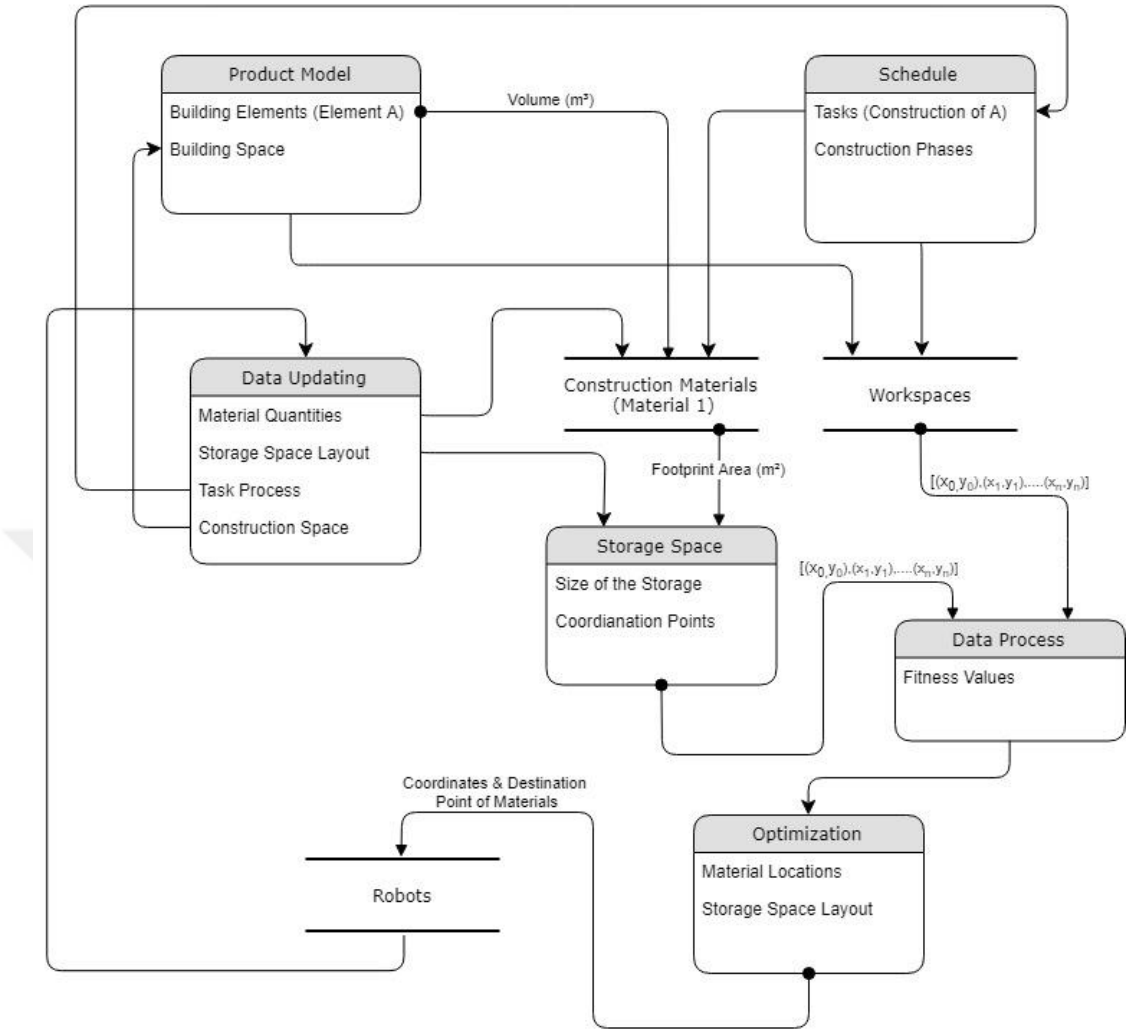


*Figure 3.3.* Data Flowchart of the Proposed Model

## 3.2. Research Materials

In this part, research materials are explained. Optimization, optimization elements, and software's which are used to calculate optimum value is explained. Process of the optimization is defined. Also, optimization is tested by using a hypothetical case study.

### 3.2.1. Optimization

Optimization is best aimed at finding the value of variables in constraints that give the best value of the criterion. In another definition, it is defined as the art of making the best decisions to accomplish certain goals or doing the best thing under certain conditions. In short, optimization is a collection of processes with the best results. The aim of the optimization is the minimize the cost and maximize the efficiency of a production. In mathematical terms, optimization can be defined briefly as minimizing or maximizing a function. An optimization algorithm is a procedure which is executed iteratively by comparing various solutions till an optimum or a satisfactory solution is found.

**Problem Formulation for Optimization**

An optimization is achieved by comparing different solutions created by using a problem knowledge. Firstly, feasibility of each problem solution is investigated. After that, an estimate of underlying objective of each solution is compared and best solution is adopted. The main purpose of the formulization is to create a mathematical model of the optimization problem. It means that, formulization is the model that allow to solve a problem by using optimization algorithm. Optimization process is shown in Figure 3.4.

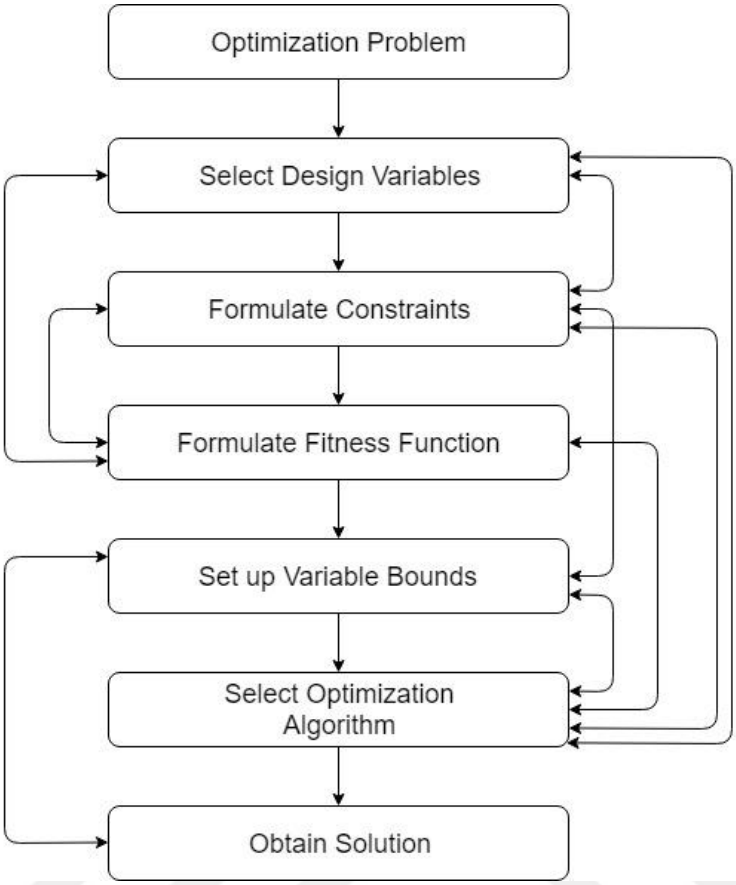


*Figure 3.4.* Optimization Process

**Design Variables**

Identifying the underlying design variables is the first step of the problem formulization of optimization. A formulization of a problem involves many design parameters which are called as design variables in optimization procedures. The first rule of the formulization is to choose minimum number of design variables as least as possible. The outcome of that optimization procedure may indicate whether to include more design variables in a revised formulation or to replace some previously considered design variables with new design variables.

**Constraints**

There are some functional relations between design variables and other design parameters. These relations represented by constraints and the number of constraints to be included in the formulation depend on the user. There are two types of constraints which are inequality and equality type constraints. Inequality constraints is the functional relations among variables are equal, smaller or greater than a resource value. Equality constraints is the functional relations which should be exactly equal to a resource value.

**Variable Bounds**

The last part of the formulation procedure is to set the minimum and the maximum bounds on each design variable. Certain optimization algorithms do not require this information. In these problems, the constraints completely surround the feasible region. Other problems require the search algorithm with in these bounds. Near optimal solution can be found in problems which have variable bounds.

### 3.2.2. Site Layout and Optimization Elements

In this chapter, site layout elements and software's used for optimization are explained.

**Site Area and Coordination System**

Site area is the area which includes constructed building and temporary facilities at a macro level. But, in this research, the site is discussed at micro level. According to this research, the building floors are accepted as site and the relation between storage areas and working areas in the floors are examined. During the site demonstration, the building and the areas within the building were assumed to be rectangular. The building area is represented by the coordinate system to determine the location of the spaces. Coordination system is a system formed by intersection of two numerical axis perpendicular to each other. The horizontal axis is called as axis of abscissa (X) and the vertical axis is called as ordinates axis (Y). The point where the two axes meet is

called origin. Accordingly, the lower left corner of the are accepted as site is designated as origin, the length of the building is indicated by X, and the width of the building is indicated by Y.

**Workspace**

Workspaces are the spaces required for to perform activities. These are short-term spaces that vary according to the characteristic of the work done. Activities can be replaced with different patterns according to the characteristic of the activities. The movement patterns of the activities are important in terms of positioning the materials required for those activities and planning the paths. In addition, there should not be more than one activity in same space due to damaging or preventing other activities. When multiple activities are in the same workspace, there may be chaos. In order to prevent this chaotic situation, schedule planning and workspace planning should be done appropriately. In this research, coordinate of the origin point of the workspaces is based to define location of workspaces. Origin points are called as $(X_{ai},Y_{ai})$. *i* indicates the number of workspaces.

**Storage Areas and Unloading Areas**

Storage areas are used for the storage of materials required for activities. These areas can be placed both inside and outside of the construction. The size of these areas varies according to material dimensions and quantities. If the storage areas are not sufficient for the materials, the materials have to be placed in different areas within construction site. As a result, there may be conflicts in the site, which can cause to material waste. It can also conflict with the activities. It may cause labor waste because they have to constantly relocate materials. There are some points to be considered when arranging storage spaces within the construction site or inside of the construction. If the storage spaces should be placed outside of the construction, they should be in a place where the vehicles can easily reach and it should be protected. If the storage spaces should be placed inside of the construction site, it should be close to lifts and access points. These areas should be located in the most recent spaces in the construction schedule.

Unloading areas are used temporarily before placing or unloading materials behind storage spaces. Also, unloading areas should be located near the access points.

In this research, the storage areas within the construction site are and how the materials should be placed in these areas are examined. The storage areas are divided into one-unit grids and the coordinates of each grid are specified separately. The origin of each grid is represented by ($X_{si}$,$Y_{si}$). *i* indicates the grid numbers.

**Distance**

Distance is the length of the space between two points. In this research, distance defines the length of the space between a workspace and storage space. The formulation of distance is:

$$D_{aisj} = \sqrt{(x_{ai} - x_{sj})^2 + (y_{ai} - y_{sj})^2} \qquad (1)$$

$D_{aisi}$ defines the distance between activity *i* and storage space j. $X_{ai}$ is the x coordinate of the activity and $Y_{ai}$ is the y coordinate of the activity. Also, $X_{sj}$ is the x coordinate of the storage space and $Y_{sj}$ is the y coordinate of the storage space. When the distance is calculated, shortest distance between two point is predicated. In this situation, there are no obstacle which can prevent the movement of materials.

**Transportation Cost and Setup Cost**

Transportation cost is the cost required to move a unit of materials form a storage area to a workspace. This cost is calculated by dividing the labor cost required to transport a unit of material by the transportation time. The total cost is obtained by multiplying the distance by the total amount of material and the cost required to move a unit of material by unit distance. The formulation of total transportation cost is formulizing as:

$$Total\ Transportation\ Cost = \sum_{i=0}^{i} D_{aisi} Q_i P_i \qquad (2)$$

$D_{aisi}$ defines the distance between activity *i* and storage space *i*, $Q_i$ defines the quantity of material, and $P_i$ defines the cost of material to move one unit of material, one-unit distance.

Setup cost is the cost required to place a material in an area. The high setup cost of a material signifies that the location of that material should not change too much.

**Fitness Function**

One of the most important issues of Lean Principles is waste of time and labor. While formulizing the fitness function, it aims to minimize the total cost and time of material transportation. In this way, it is aimed to create a more efficient construction site by reducing unnecessary transport loss in the construction site. This strategy was inspired by the lean principles. In addition, it is aimed to create a more organized storage area. Some assumptions were made when formulizing the algorithm. These are:

1. The construction site and storage space are divided into grids.
2. Size of each material to be placed is accepted as a one grid.
3. There may be more than one kind or number of materials for an activity.
4. When calculating the distance, the shortest distance has been calculated and there are no obstacles that prevents the transportation of materials.
5. While calculating the distance of workspace to storage spaces, the central coordinates of the areas were considered.

In the light of these assumptions, a fitness function was created. This fitness function gives the minimum value of the transportation cost. Formulization of the algorithm has "*n*" workspace and "*m*" storage area. Fitness formula expressed as:

Fitness (Minimum value) = (Distance x Material Quantity x Transport Cost) + Setup Cost

The mathematical representation of the fitness function is:

$$\text{MinC}= \sum_{i=1}^{n}\sum_{j=1}^{m} d_{aisj} q_{mj} p_j + \sum_{i=1}^{m} s_j \qquad (3)$$

$i = 1,2,3,\ldots\ldots,n$

$j = 1,2,3,\ldots\ldots,n$

Where C is the cost and MinC is the minimum cost. $D_{aisj}$ is the distance between activity *i* and storage area of material *j*, $q_{mj}$ is the quantity of material *j*, p*j* is the transport price of unit quantity of material needed for activity *i* of unit distance, $s_j$ is the setup cost of material *j*. Also, it is assumed that for activity *i*, the coordination of workspace is ($x_{ai}$, $y_{ai}$), and the coordination of storage areas is ($x_{sj}$, $y_{sj}$). Distance between workspace and storage areas is

$$d_{ij}= \sqrt{(x_{ai} - x_{sj})^2 + (y_{ai} - y_{sj})^2} \qquad (4)$$

For computing fitness function, two different software were used. Firstly, MATLAB software was used. Matrix Laboratory (MATLAB) is a multi-paradigm numerical computational programming language. MATLAB is an easy-to-use, fourth-generation programming language that specializes in addressing specific needs using less code and using ready-made templates. MATLAB is often used for engineering calculations, positive science, algorithm development data analysis, programming, and matrix operations. MATLAB was developed by MathWorks. MATLAB has a matrix based working system and matrix is an edited form of a set of elements (Figure 3.5).

$$A = \begin{bmatrix} a_{1,1} & a_{1,2} & . & . & . & . & a_{1,j} \\ a_{2,1} & a_{2,2} & . & . & . & . & a_{2,j} \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ . & . & . & . & . & . & . \\ a_{i,1} & a_{i,2} & . & . & . & . & a_{i,j} \end{bmatrix}$$

*Figure 3.5.* Matrix

While the MATLAB algorithm runs properly when the storage space and the number of workspaces is small, it is seen that the working time of the program is too prolonged and the problem cannot be solved as the storage area grows or the number of workspaces increases. For example, the size of the matrix established to accommodate three material in a calculation with a storage area size of 3x5 unit and three workspace area is 16008x15. The fitness value of all three values of this this matrix is calculated for the three workspace areas and the smallest value of these sums is calculated. In this example, the program was unable to calculate the optimum value. For this reason, Phyton software was used to get more accurate and faster solutions. MATLAB algorithm and its details are given in Appendix A.

### 3.2.3. Python Formulization

Python is a programming and coding language which was first created by Guido van Rossum in 1991. Python is an interpretable language, supports object-oriented programming approaches and to a certain extent, functional programming. Python is commonly used for science and engineering calculations. Python is a simpler coding language than other coding languages. Therefore, the written code is more comfortable to read. In addition, Python shows the result of the calculations step by step and the shaping of the algorithm and problem develops more efficiently. Python works with PyCharm which is an IDE (Integrated Development Environment) program. PyCharm is created by Jetbrains that can run on most operating systems. Although, PyCharm is a text editor program, it has more advantages than other text editors. PyCharm has

code recognition feature which allows faster and healthier coding. PyCharm also makes managing and editing files easier. PyCharm has three main windows which are:

- *Project Window:* This is the section where the files and the written algorithms are displayed (Figure 3.6). In this Section, folders and algorithms are saved automatically and program library and created files are managed. Also, every movement and change in PyCharm is saved. There is no “save” option.

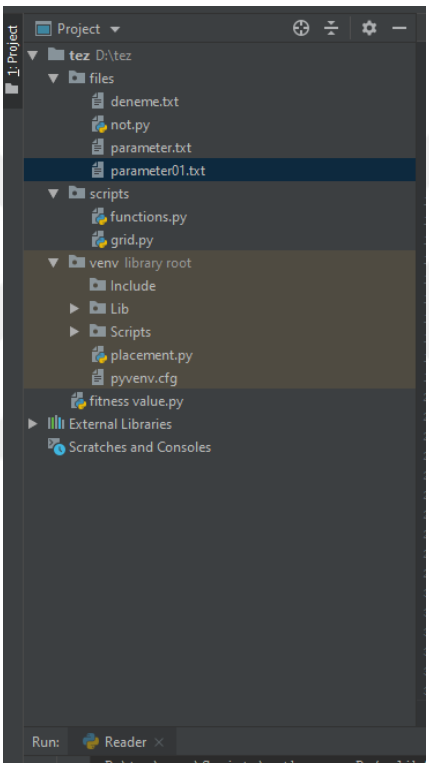


*Figure 3.6.* Python Project Window

- *Editor Window:* This is the window where coding is written (Figure 3.7). The desired algorithms or programs is written in this window. In this window, PyCharm command show links and formulas in different colors to make them more legible and easier to read and understand.

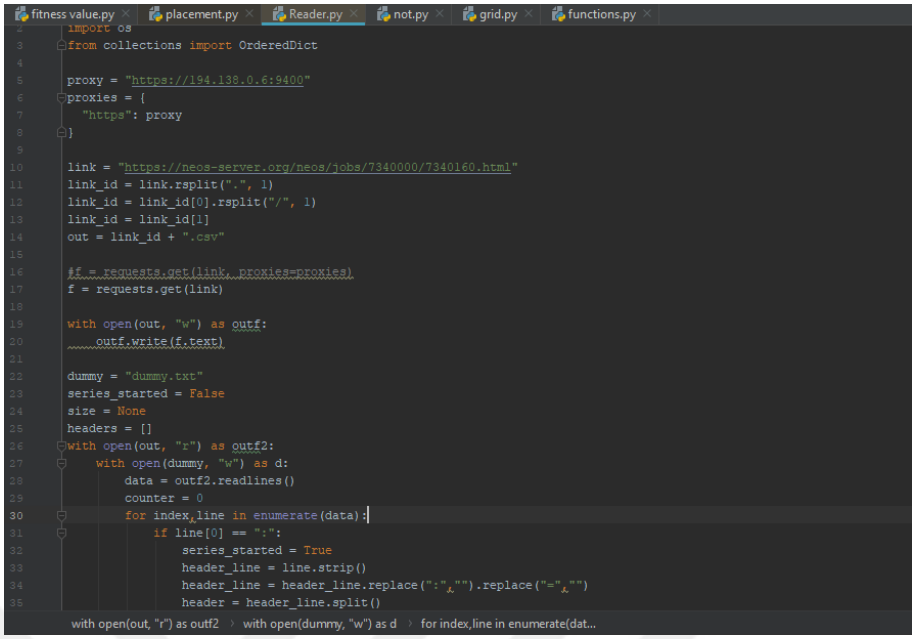


*Figure 3.7.* Python Editor Window

- *Run Window:* This is the window where the written algorithms or codes are executed. This section also shows the results that you want to display in encoding (Figure 3.8).

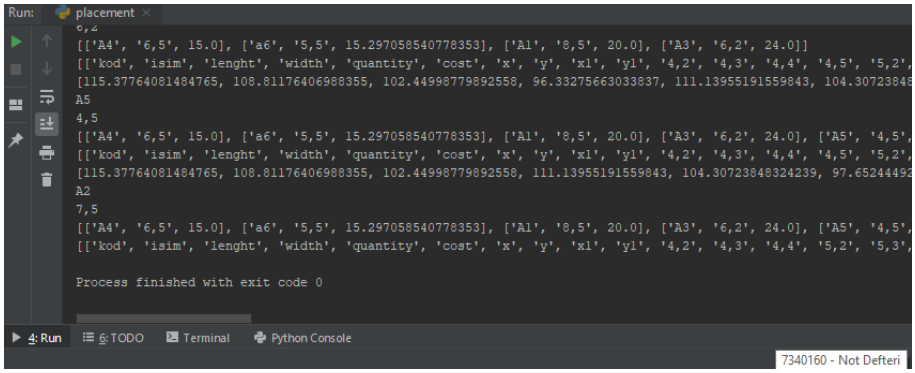


*Figure 3.8.* Python Run Window

In this research, the Phyton and PyCharm software's were used to create and solve fitness function. Material codes, material names, material information, and workspace coordinates are given as a text file into software. Then the fitness function is created by using input data and all of the fitness values were determined by using the Phyton according to coordinates of the storage area. Then, the minimum fitness value among the all obtained fitness values was found by using Gurobi Optimizer. The Gurobi Optimizer is an optimization system created by Neos Server to solve linear programming problems, mixed-integer problems, and second-order conic programming problems (SOCP). It is a mathematical optimization system which can help to solve problems by turning them into a mathematical model and finds the best solution out of lots of possibilities. In this system, data files, model files which define the problems and data, and a command file which is define the how to extract the result are loaded into a server created over the internet (Figure 3.9). Optimizer performs the optimization by taking the information in the uploaded files.

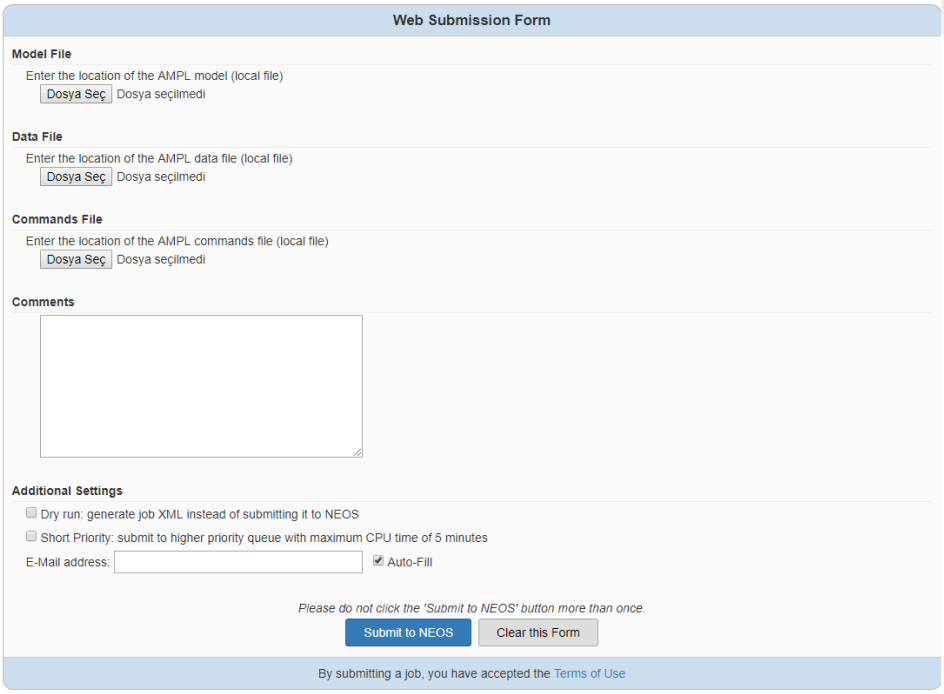


*Figure 3.9.* Gurobi Optimizer

First of all, input file is read by using Python. Input file (Figure 3.10) consists materials and workspace data. A sample model was created while coding. In this sample model, there are six different materials and setup cost, transportation cost, and coordinates of the materials are defined.  Furthermore, in the sample, the origin of the storage area is defined as (4,2) and the opposite point to origin is defined as (9,6). Accordingly, the length of the storage area is 5 unit and the width of the storage area is 4 unit. This storage area also defined in Python. The storage area is divided into grids and the coordinates of each grid are processed in the input file. There are 20 grids in total in the storage area. In the Figure X, just 6 of them are represented.

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 |
|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 10 | 5 | 0 | 0 |
| M2 | material2 | 10 | 8 | 12 | 14 | 0 | 0 |
| M3 | material3 | 40 | 6 | 6 | 1 | 0 | 0 |
| M4 | material4 | 30 | 1 | 6 | 10 | 0 | 0 |
| M5 | material5 | 10 | 12 | 2 | 10 | 0 | 0 |
| M6 | material6 | 30 | 1 | 6 | 10 | 0 | 0 |

*Figure 3.10.* Input File

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 | 4,2 | 4,3 | 4,4 | 4,5 | 5,2 | 5,3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | material1 | 2 | 5 | 10 | 5 | 0 | 0 | | | | | | |
| M2 | material2 | 1 | 8 | 12 | 14 | 0 | 0 | | | | | | |
| M3 | material3 | 4 | 6 | 6 | 1 | 0 | 0 | | | | | | |
| M4 | material4 | 3 | 1 | 6 | 10 | 0 | 0 | | | | | | |
| M5 | material5 | 1 | 12 | 2 | 10 | 0 | 0 | | | | | | |
| M6 | material6 | 3 | 1 | 6 | 10 | 0 | 0 | | | | | | |

*Figure 3.11.* Processed Coordinates into Input File

After the storage area is divided into grids, the workspace coordinates (Figure 3.12) specified in the input file are converted to “(x,y)” form for converting the input data to mathematical expressions.

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 |
|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 10 | 5 | 0 | 0 |
| M2 | material2 | 10 | 8 | 12 | 14 | 0 | 0 |
| M3 | material3 | 40 | 6 | 6 | 1 | 0 | 0 |
| M4 | material4 | 30 | 1 | 6 | 10 | 0 | 0 |
| M5 | material5 | 10 | 12 | 2 | 10 | 0 | 0 |
| M6 | material6 | 30 | 1 | 6 | 10 | 0 | 0 |

*Figure 3.12.* Workspace Coordinates

After that, the fitness function is created and all fitness values are found (Figure 3.13). The output of the fitness function is used as an input for Gurobi Optimizor. The fitness values, coordinates and destinations are defined.

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 | 4,2 | 4,3 | 4,4 | 4,5 | 5,2 | 5,3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | material1 | 2 | 5 | 10 | 5 | 0 | 0 | 35,54 | 33,62 | 32,41 | 32,00 | 31,15 | 28,93 |
| M2 | material2 | 1 | 8 | 12 | 14 | 0 | 0 | 116,38 | 109,81 | 103,45 | 97,33 | 112,14 | 105,31 |
| M3 | material3 | 4 | 6 | 6 | 1 | 0 | 0 | 17,42 | 20,97 | 25,63 | 30,83 | 12,49 | 17,42 |
| M4 | material4 | 3 | 1 | 6 | 10 | 0 | 0 | 11,25 | 10,28 | 9,32 | 8,39 | 11,06 | 10,07 |
| M5 | material5 | 1 | 12 | 2 | 10 | 0 | 0 | 99,95 | 88,36 | 76,89 | 65,62 | 103,53 | 92,39 |
| M6 | material6 | 3 | 1 | 6 | 10 | 0 | 0 | 11,25 | 10,28 | 9,32 | 8,39 | 11,06 | 10,07 |

*Figure 3.13.* Output File

Then, a model file was created which explains how to optimize the data in the data file. In the model file, the minimum value of the total of fitness values was calculated such that each material is sent to one point and no more than one material can be placed in the same point. At the optimum value found according to this algorithm, the point where the material will go is indicated as “1”, the other points are indicated as “0”. In the algorithm, it is defined that the sum of the values in the material row should be 1, while the values in the storage areas column should be less than 1 or equal to 1. Thus, the options where a material goes to more than one places or more than one material goes to one place are eliminated. Data and model files are loaded into the

Gurobi Optimizer into the NEOS Solver for optimization. The results obtained from the sample model is shown in the Figure 3.14.

```
Gurobi 8.1.0: threads=4
Gurobi 8.1.0: optimal solution; objective 310.6921995
2 simplex iterations
Trans [*,*] (tr)
:    M1  M2  M3  M4  M5  M6    :=
4p2   0   0   0   0   0   0
4p3   0   0   0   0   0   0
4p4   0   0   0   0   0   0
4p5   0   0   0   0   1   0
5p2   0   0   0   0   0   0
5p3   0   0   0   0   0   0
5p4   0   0   0   0   0   0
5p5   0   0   0   1   0   0
6p2   0   0   1   0   0   0
6p3   0   0   0   0   0   0
6p4   0   0   0   0   0   0
6p5   0   0   0   0   0   1
7p2   0   0   0   0   0   0
7p3   0   0   0   0   0   0
7p4   0   0   0   0   0   0
7p5   0   0   0   0   0   0
8p2   0   0   0   0   0   0
8p3   0   0   0   0   0   0
8p4   1   0   0   0   0   0
8p5   0   1   0   0   0   0
;
```

*Figure 3.14.* Optimization Results

### 3.2.4. Case Study

In this study, a hypothetical case was created to check the optimization and written codes and to determine the contribution of this system. Some assumptions were made while preparing the case. Firstly, it is assumed that one material will be sent to each work area. Secondly, it is assumed that the materials size is a unit size. The prepared case consists of three different stages. While there are three different activities in the first stage of the case (W1, W2, W3), each of these activities is carried out in two different workspaces. In other words, there are six workspaces in total. Six materials will be placed in these areas. These materials consist of two pieces of M1, two pieces of M2 and two pieces of M3.

In the second step of the case, two new activities were added to the activities to be done in first stage which are W4 and W5. W4 is carried out in two different workspaces and W5 is carried out in a single workspace. In other words, three new activity areas have been added. In the second stage, three materials will be placed on the storage area. These materials are two pieces of M4 and one piece of M5. In addition, when the material is placed in the second stage, it is considered that the materials placed in the first stage are in the current position. If the materials placed in the first stage need to be relocated again, these displacement costs will also be considered. In third stage, two W6 activities were added on the layout plan prepared in second stage and the locations of the previously mentioned activity areas were changed. In this case, it was examined how to re-arrange the previously placed materials and how to place the newly added two M6 materials. This three-stage case was first placed according to the FIFO method, with the first placed material goes out first. Material fitness value was calculated. Secondly, the material was placed using the optimization and codes. Fitness value was calculated according to storage placement created by function. Thirdly, this three-stage case was solved by people from different occupations through a questionnaire that allows manual solution space. The fitness value of each of the survey results was calculated and the average fitness value is taken as a base value.

**Stage 1**

There are three different activities in the first stage of the case. These activities are named W1, W2 and W3. All three activities have two workspaces. In other words, there are six activity areas in total. Of these activities, W1 activity covers an area of 2x3 units, W2 activity covers an area of 3x4 units, and W3 activity covers an area of 2x2 units (Figure 3.15).

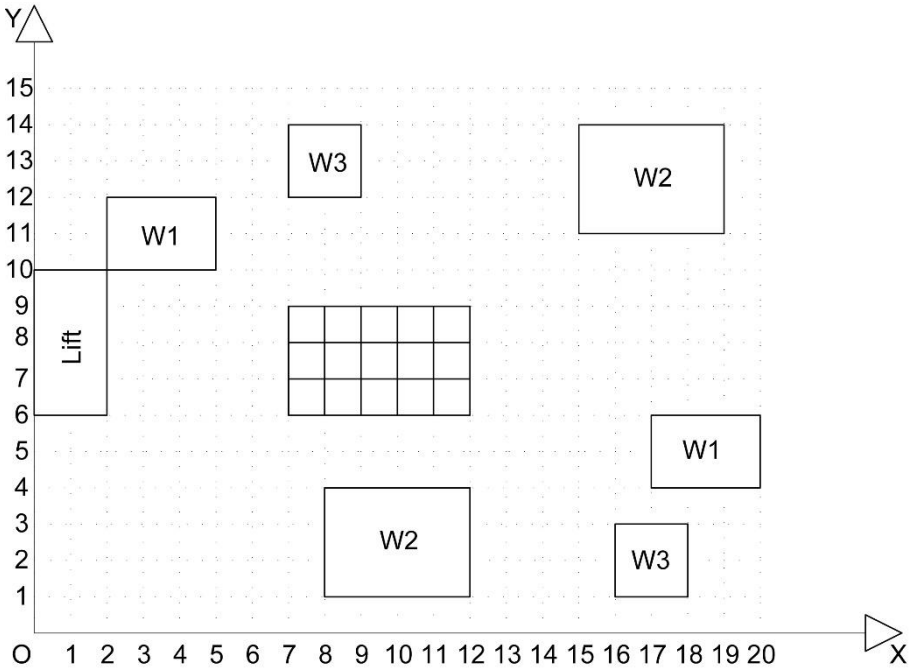


*Figure 3.15.* Site Layout of First Stage

Each activity needs one material which size is 1x1 unit. These materials will be placed in a storage area of 3x5 units. M1 material transportation cost 5 and setup cost 20, M2 material transportation cost 8 and setup cost 10, M3 material transportation cost 20 and setup cost 40 (Table 3.1).

Table 3.1. *Material Information in First Stage*

| | M1 | M2 | M3 |
|---|---|---|---|
| Transportation Cost | 5 | 8 | 20 |
| Setup Cost | 20 | 10 | 40 |

**FIFO Placement**

According to this method, the first incoming material is prepared by placing the material at the end of the storage area in order not to obstruct the passage area of the materials to be placed later. According to this, the settlement plan is shown in Figure

3.16. According to this settlement, fitness values of the materials were calculated and total fitness value was found. The following formula was used to calculate the fitness value.

$$Total\ Transportation\ Cost = \sum_{i=0}^{i} D_{wimi}\, TC_i + SC_i \qquad (5)$$

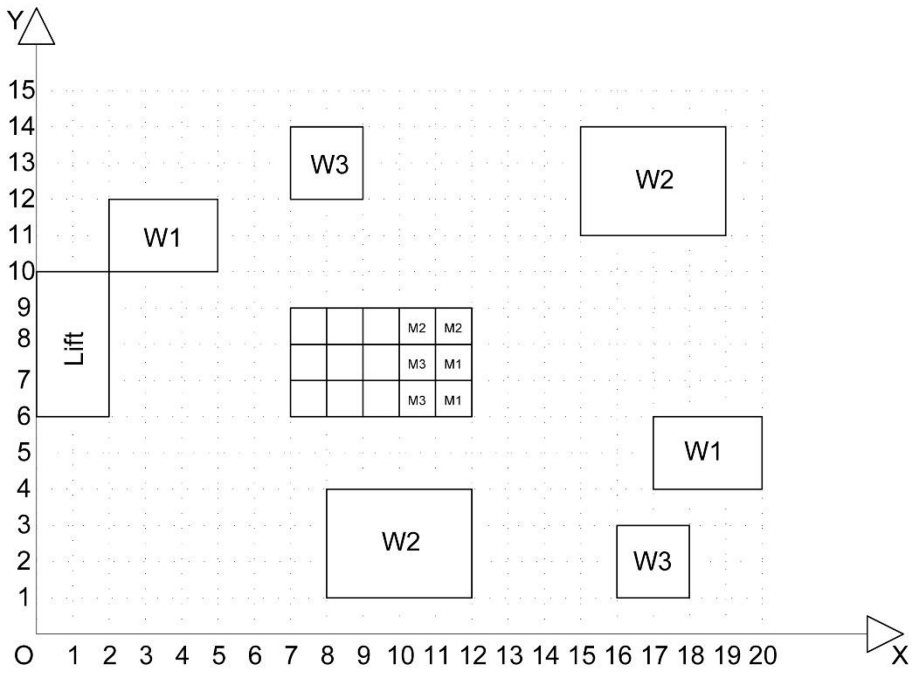


*Figure 3.16.* Storage Area Layout According to FIFO Method in First Stage

According to the layout plan, the distance of the two M1 materials to the two W1 workspace is calculated and the smallest of the total value is taken as a fitness value. Accordingly, the distance of the M1 material in the coordinate of (11,6) to the W1 workspace in the coordinate of (18.5,5) and the W1 workspace in the (3.5,11) area were calculated and fitness values were found. At the same time, the distance of the

M1 material in the coordinate of (11,7) to the both workspaces were calculated and the fitness value was found. According to these calculations;

M1 (11,6) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-6)^2}$ = 7.5663729

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.56637297 x 5 + 20 = 57.8318648

M1 (11,6) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-11)^2+(11-6)^2}$ = 9.0138781

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 9.01387818 x 5 + 20 = 65.0693909

M1 (11,7) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-7)^2}$ = 7.7620873

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.76208734 x 5 + 20 = 58.8104367

M1 (11,7) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-11)^2+(11-7)^2}$ = 8.50

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 8.50 x 5 + 20 = 62.50

There are two different fitness values for the M1 material. According to the first fitness value, M1 (11,6) material goes to the W1 (18.5.5) workspace and M1 (11,7) material goes to the W1 (3.5,11) workspace. According to second fitness value, M1 (11,6) material goes to the W1 (3.5,11) workspace and M1 (11.7) material is goes to the W1 (18.5.5) workspace. Fitness value was calculated by taking the smallest sum of these results in order to give correct results of fitness value. The first option of the fitness value is calculated as 120.4318648, while the second option is 123.8798276. So, the fitness value is taken as 120.4318648.

The same calculations were made for two M2 materials. That is distance of the M2 (11,8) and M2 (10,8) materials to the workspaces are calculated as separately. According to these calculations:

M2 (11,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-11)^2 + (12.5-8)^2}$ = 7.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.5 x 8 + 10 = 70

M2 (11,8) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(10-11)^2 + (2.5-8)^2}$ = 5.5901699

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 5.59016994 x 8 + 10 = 54.7213595

M2 (10,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-10)^2 + (12.5-8)^2}$ = 8.3216584

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 8.32165848 x 8 + 10 = 76.5732679

M2 (10,8) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(10-10)^2 + (2.5-8)^2}$ = 5.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 5.5 x 8 + 10 = 54

There are two different fitness values for the M2 material. According to the first fitness value, M2 (11,8) material goes to the W2 (17,12.5) workspace and M2 (10,8) material goes to the W2 (10,2.5) workspace. According to second fitness value, M2 (11,8) material goes to the W2 (10,2.5) workspace and M2 (10,8) material is goes to the W2 (17,12.5) workspace. The fitness value was calculated by taking the smallest sum of these results in order to give correct results of fitness value. The first option of the fitness value is calculated as 124, while the second option is 131.2946274. So, the fitness value is taken as 124.

Finally, the same calculations were made for two M3 materials. That is, the distance of the material M3 in the coordinate (10,6) to both the W3 (17,2) workspace and the W3 (8,13) workspace and the distance of the material M3 in the coordinate (10,7) to the W3 (17,2) workspace and the W3 (8,13) workspace is found to calculate fitness value. According to these calculations:

M3 (10,6) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-10)^2 + (2-6)^2}$ = 8.0622577

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 8.06225774 x 20 + 40 = 201.2451549

M3 (10,6) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-10)^2 + (13-6)^2}$ = 7.2801098

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 7.28010988 x 20 + 40 = 185.6021977

M3 (10,7) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-10)^2 + (2-7)^2}$ = 8.6023252

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 8.60232526 x 20 + 40 = 212.0465053

M3 (10,7) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-10)^2 + (13-7)^2}$ = 6.3245553

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 6.32455532 x 20 + 40 = 166.4911064

There are two different fitness values for the M3 material. According to the first fitness value, M3 (10,6) material goes to the W3 (17,2) workspace and M3 (10,7) material goes to the W3 (8,13) workspace. According to second fitness value, M3 (10,6) material goes to the W3 (8,13) workspace and M3 (10,7) material is goes to the W3 (17,2) workspace. The fitness value was calculated by taking the smallest sum of these results in order to give correct results of fitness value. The first option of the fitness value is calculated as 367.7362613, while the second option is 397.6487031. So, the

fitness value is taken as 367.7362613. According to these results, the total fitness value is calculated as 612.1681262.

**Optimization Placement**

In the first stage of the case, workspace coordinates and material information were entered into the input file according to the layout plan. There are six materials in total in the input file. Set_cost indicates the setup cost of the materials, trans_cost indicates the transportation cost of the materials, and columns X and Y indicate the coordinates of the workspaces. Center points of the workspace coordinates is taken for calculation (Figure 3.17).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 |
|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 3,50 | 11,00 | 0 | 0 |
| M1a | material1 | 20 | 5 | 18,50 | 5,00 | 0 | 0 |
| M2 | material2 | 10 | 8 | 10,00 | 2,50 | 0 | 0 |
| M2a | material2 | 10 | 8 | 17,00 | 12,50 | 0 | 0 |
| M3 | material3 | 40 | 20 | 8,00 | 13,00 | 0 | 0 |
| M3a | material3 | 40 | 20 | 17,00 | 2,00 | 0 | 0 |

*Figure 3.17.* Input Data for Optimization in First Stage

Then, the storage space is defined to algorithm created in Python. After the input file and storage area were introduced to the program, the function was run. The function calculated the distance of all materials to all the grids within the storage area and calculated the all fitness values. Python gives these fitness values as an output file (Figure 3.18).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 | 7,6 | 7,7 | 7,8 | 8,6 | 8,7 | 8,8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 3,5 | 11 | 0 | 0 | 50,5163890 | 46,5753645 | 43,0488611 | 53,6340601 | 50,1039864 | 47,0416346 |
| M1a | material1 | 20 | 5 | 18,5 | 5 | 0 | 0 | 77,7169819 | 78,3630876 | 79,4243216 | 72,7375578 | 73,4438958 | 74,6008242 |
| M2 | material2 | 10 | 8 | 10 | 2,5 | 0 | 0 | 46,8781778 | 53,2666153 | 60,1198563 | 42,2490310 | 49,3954312 | 56,8187996 |
| M2a | material2 | 10 | 8 | 17 | 12,5 | 0 | 0 | 105,4148835 | 101,3016977 | 97,7268488 | 98,8144132 | 94,3800924 | 90,4984472 |
| M3 | material3 | 40 | 20 | 8 | 13 | 0 | 0 | 181,4213562 | 161,6552506 | 141,9803903 | 180,0000000 | 160,0000000 | 140,0000000 |
| M3a | material3 | 40 | 20 | 17 | 2 | 0 | 0 | 255,4065923 | 263,6067977 | 273,2380758 | 236,9771560 | 245,9126028 | 256,3330765 |

| kod | 9,6 | 9,7 | 9,8 | 10,6 | 10,7 | 10,8 | 11,6 | 11,7 | 11,8 |
|---|---|---|---|---|---|---|---|---|---|
| M1 | 57,1651719 | 54,0036763 | 51,3249102 | 61,0030487 | 58,1608438 | 55,7945527 | 65,0693909 | 62,5000000 | 60,3887361 |
| M1a | 67,7624329 | 68,5412196 | 69,8121471 | 62,7931069 | 63,6606230 | 65,0693909 | 57,8318649 | 58,8104367 | 60,3887361 |
| M2 | 39,1204396 | 46,8781778 | 54,7213595 | 38,0000000 | 46,0000000 | 54,0000000 | 39,1204396 | 46,8781778 | 54,7213595 |
| M2a | 92,4621125 | 87,6659514 | 83,4302390 | 86,4198927 | 81,2179753 | 76,5732679 | 80,7672241 | 75,1152824 | 70,0000000 |
| M3 | 181,4213562 | 161,6552506 | 141,9803903 | 185,6021978 | 166,4911064 | 147,7032961 | 192,3154621 | 174,1640786 | 156,6190379 |
| M3a | 218,8854382 | 228,6796226 | 240,0000000 | 201,2451550 | 212,0465053 | 224,3908891 | 184,2220510 | 196,2049935 | 209,7056275 |

*Figure 3.18.* Fitness Values in First Stage

This output file is loaded into the Neos Solver optimization program as a “data” file. Then, the “run” and “model” files described in the previous sections are loaded together with the “data” file. Neos Solver reads the loaded files and gives an output file that describes the sequence in which the optimal value occurs (Figure 3.19).

```
:      M1 M1a  M2 M2a  M3 M3a
10p6    0   0   1   0   0   0
10p7    0   0   0   0   0   0
10p8    0   0   0   0   0   0
11p6    0   0   0   0   0   1
11p7    0   1   0   0   0   0
11p8    0   0   0   1   0   0
7p6     0   0   0   0   0   0
7p7     0   0   0   0   0   0
7p8     1   0   0   0   0   0
8p6     0   0   0   0   0   0
8p7     0   0   0   0   0   0
8p8     0   0   0   0   1   0
9p6     0   0   0   0   0   0
9p7     0   0   0   0   0   0
9p8     0   0   0   0   0   0
;
```

*Figure 3.19.* Neos Solver Output File in First Stage

In the output file, “1” sections indicate areas where the materials should be placed. It also shows the optimum fitness value, the number of variables and constraints, and the number of calculations performed according to this layout (Figure 3.20).

```
90 variables, all linear
21 constraints, all linear; 180 nonzeros
        6 equality constraints
        15 inequality constraints
1 linear objective; 90 nonzeros.

Gurobi 8.1.0: threads=4
Gurobi 8.1.0: optimal solution; objective 534.0813489
```

*Figure 3.20.* Neos Solver Output File in First Stage

There are 21 constraints in total. 6 of them are called equality. These constraints symbolize materials. 15 of the constraints are called inequality and symbolize the coordinates of the storage area. Each material has 15 fitness values. Optimization collects these values by selecting a fitness value from each material. This process continues until all possible total values are calculated. Then, it finds the smallest value among these values and prepares the layout according to the smallest fitness value. Optimum fitness value is 534.0813489 according to optimization and algorithm solution. The layout plan prepared according to this fitness value is shown in Figure 3.21.

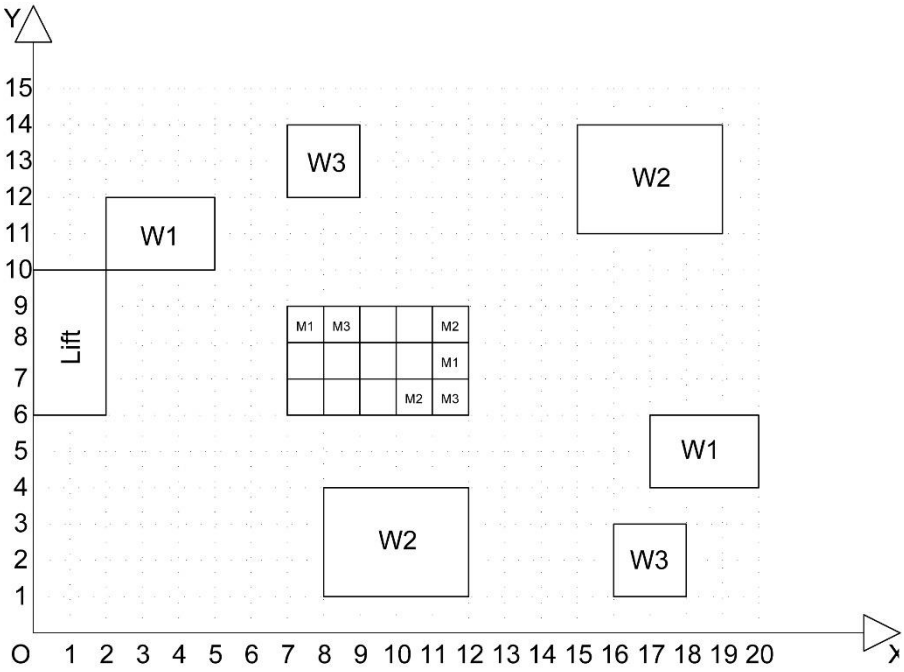


*Figure 3.21.* Storage Area Layout According to Optimization in First Stage

**Survey Placement**

The case study was prepared in three stages for people from different professions. Material information was given in the case and materials were requested to be placed in storage areas. Among the results, two surveys were explained and the other surveys were given in the appendix. When compared with other methods, the average fitness value of the survey results was taken into consideration. In the first stage of the survey, fitness values were calculated using the following formula.

$$Total\ Transportation\ Cost = \sum_{i=0}^{i} D_{wimi}\, TC_i + SC_i \qquad (6)$$

Two of the surveys were shown in Figure 3.22 and Figure 3.23. These calculations are performed is shown through these two examples.

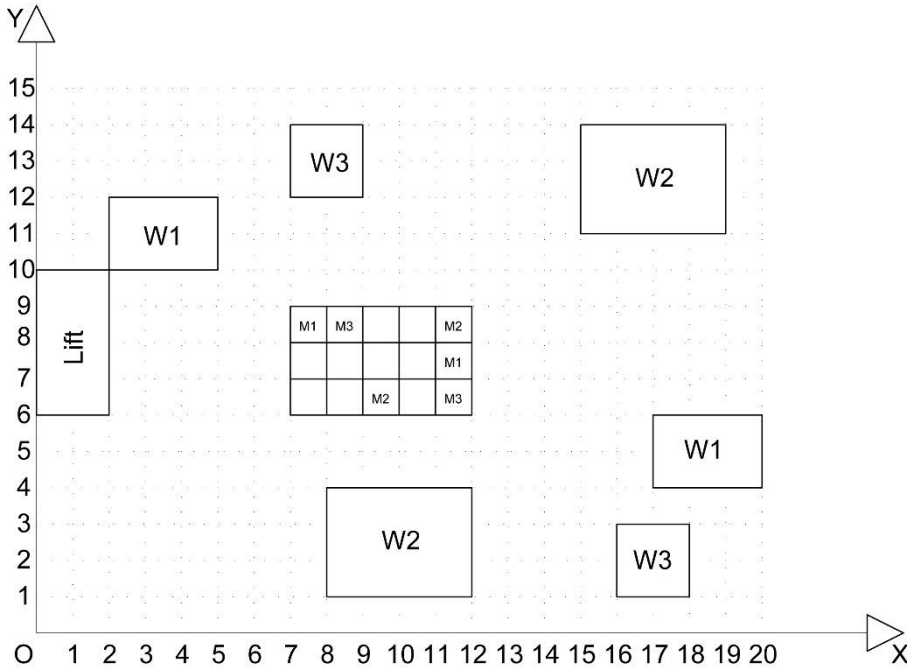


*Figure 3.22.* Storage Layout Plan According to Survey 1 in First Stage

M1 (7,8) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-7)^2+(11-8)^2}$ = 4.6097722

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 4.6097722 x 5 + 20 = 43.0488611

M1 (11,7) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-7)^2}$ = 7.7620873

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.7620873 x 5 + 20 = 58.8104367

M2 (9,6) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(10-9)^2+(2.5-6)^2}$ = 3.6400549

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 3.6400549 x 8 + 10 = 39.1204395

M2 (11,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-11)^2 + (12.5-8)^2}$ = 7.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.5 x 8 + 10 = 70

M3 (8,8) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-8)^2 + (13-8)^2}$ = 5

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 5 x 20 + 40 = 140

M3 (11,6) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-11)^2 + (2-6)^2}$ = 7.2111025

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 7.2111025 x 20 + 40 = 184.2220510

Total Fitness Value is 535.2017883.

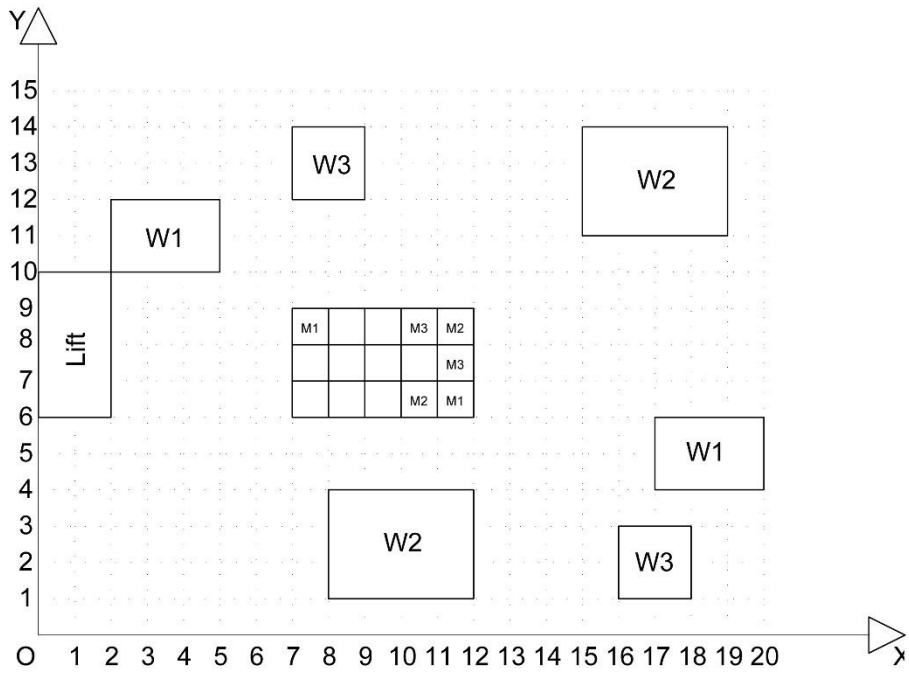


*Figure 3.23.* Storage Layout Plan According to Survey 5 in First Stage

M1 (7,8) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-7)^2+(11-8)^2}$ = 4.6097722

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 4.6097722 x 5 + 20 = 43.0488611

M1 (11,6) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-6)^2}$ = 7.5663729

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.5663729 x 5 + 20 = 57.8318648

M2 (10,6) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(10-10)^2+(2.5-6)^2}$ = 3.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 3.5 x 8 + 10 = 38

M2 (11,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-11)^2+(12.5-8)^2}$ = 7.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.5 x 8 + 10 = 70

M3 (10,8) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-10)^2+(13-8)^2}$ = 5.3851648

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 5.3851648 x 20 + 40 = 147.7032961

M3 (11,7) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-11)^2+(2-7)^2}$ = 7.8102496

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 7.8102496 x 20 + 40 = 196.2049935

Total Fitness Value is 552.7890155.

Other survey results are calculated as the survey results mentioned above. The fitness values obtained as a result of this are indicated in Table 3.2.

Table 3.2. *Survey Results in First Stage*

| | First Stage |
|---|---|
| Survey 1 | 535.2017883 |
| Survey 2 | 535.2017883 |
| Survey 3 | 534.0813489 |
| Survey 4 | 534.0813489 |
| Survey 5 | 552.7890155 |
| Survey 6 | 534.0813489 |
| Survey 7 | 535.2017883 |
| Survey 8 | 535.2017883 |
| Survey 9 | 537.1821785 |
| Survey 10 | 538.3303797 |
| Survey 11 | 534.0813489 |
| Survey 12 | 535.2017883 |
| Survey 13 | 535.2017883 |
| Survey 14 | 535.2017883 |
| Survey 15 | 534.0813489 |
| Average Fitness Value | 536.3413890 |

**Stage 2**

In the second stage of the prepared case, two new activities were added to the work program after the placements are prepared in the first stage (Figure 3.24). Of these activities, W4 activity has two different workspaces, while W5 activity has one workspace. Accordingly, there are two M4 materials and one M5 material. The transportation cost of M4 material is 2 and the setup cost is 30, while the transportation cost of M5 material is 10 and the setup cost is 80 (Table 3.3).

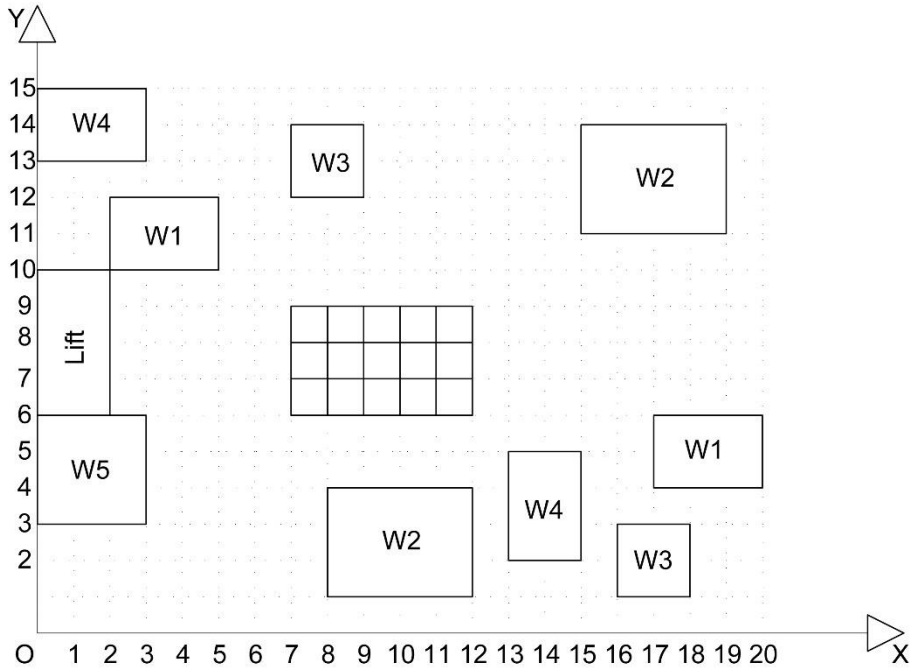


*Figure 3.24.* Site layout of the Second Stage

Table 3.3. *Material Information in Second Stage*

| | M1 | M2 | M3 | M4 | M5 |
|---|---|---|---|---|---|
| Transportation Cost | 5 | 8 | 20 | 2 | 10 |
| Setup Cost | 20 | 10 | 40 | 30 | 80 |

The placement of three new materials according to these data was done in three different ways. Firstly, layout plan was prepared according to FIFO method. Secondly, the layout plan is prepared according to the created function and software codes which is created in this research. Thirdly, the layout plan was prepared by people from different professions. Fitness values of different settlement plans were calculated and the average fitness value is taken. In this case, placement of the materials prepared in the first stage were considered as they were still in place. Previously placed materials can be relocated or new materials can be placed in empty spaces. In case of

displacement of previously placed materials, the fitness value is calculated while the amount of displacement is considered. In case of displacement of previously placed materials, the distance value is:

$$D_{aisj}=\sqrt{(x_{ai}-x_{sj})^2+(y_{ai}-y_{sj})^2}+\sqrt{(x_{osj}-x_{sj})^2+(y_{osj}-y_{sj})^2} \qquad (7)$$

$x_{osj}$ specifies the x coordinate of the material according to the placement in first stage and $y_{osj}$ specifies the y coordinate of the material according to the placement in the first stage.

**FIFO Placement**

The newly added materials above the settlement plan made in the first stage were placed as shown in Figure 3.25. The fitness value of the materials was calculated according to this location. In this settlement, the places of the previously placed materials were not changed. Accordingly, when calculating the fitness value, the fitness value of two M4 and one M5 materials was calculated and the values were added to the total fitness value found in the first stage and the new fitness value was calculated.

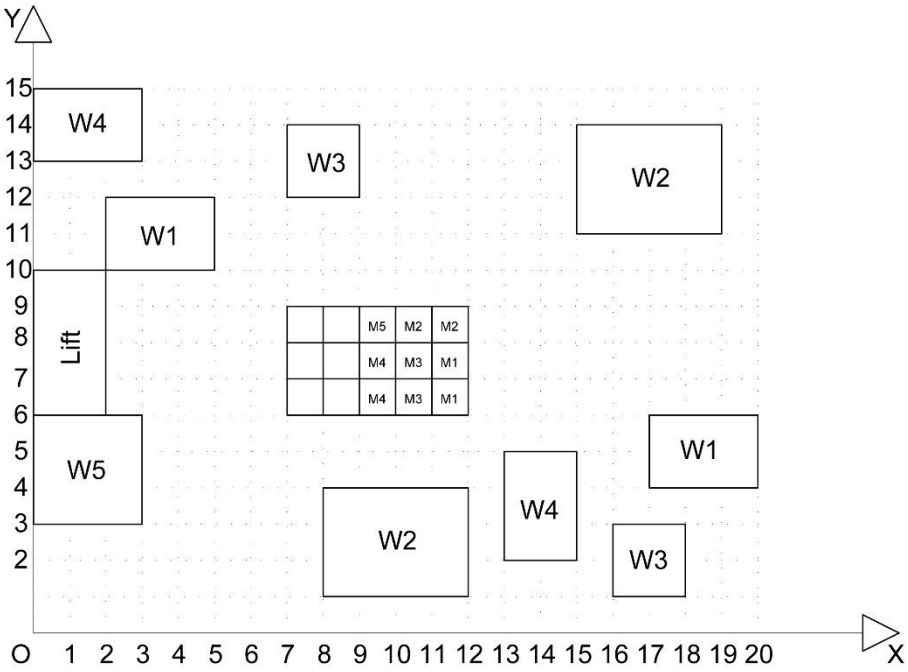


*Figure 3.25.* Storage Space Layout According to FIFO Method in Second Stage

According to the new settlement plan, the distance of two M4 materials to two W4 workspace is calculated and the smallest of the total fitness value is taken as fitness. So, the fitness values of M4 material in the coordinate (9,6) to the W4 workspace in the coordinate (14,3.5) and to the W4 workspace in the (1.5,14) area were calculated. At the same time, the distance of the M4 material in the coordinate (9,7) to both workspaces is calculated and the fitness value was found. According to these calculations;

M4 (9,6) → W4 (14,3.5)

Distance = $D_{M4W4} = \sqrt{(14-9)^2 + (3.5-6)^2}$ = 5.5901699

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 5.59016994 x 2 + 30 = 41.1803398

M4 (9,6) → W4 (1.5,14)

Distance = $D_{M4W4} = \sqrt{(1.5-9)^2 + (14-6)^2}$ = 10.9658560

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 10.96585609 x 2 + 30 = 51.9317121

M4 (9,7) → W4 (14,3.5)

Distance = $D_{M4W4} = \sqrt{(14-9)^2+(3.5-7)^2}$ = 6.1032778

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 6.10327780 x 2 + 30 = 42.2065556

M4 (9,7) → W4 (1.5,14)

Distance = $D_{M4W4} = \sqrt{(1.5-9)^2+(14-7)^2}$ = 10.2591422

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 10.25914226 x 2 + 30 = 50.5182845

There are two different fitness values for the M4 material. According to the first fitness value, M4 (9,6) material goes to the W4 (14,3.5) workspace and M4 (9,7) material goes to the W4 (1.5,14) workspace. According to second fitness value, M4 (9,6) material goes to the W4 (1.5,14) workspace and M4 (9,7) material is goes to the W4 (14,3.5) workspace. The fitness value was calculated by taking the smallest sum of these results in order to give correct results of fitness value. The first option of the fitness value is calculated as 91.6986244, while the second option is 94.1382677. So, the fitness value is taken as 91.6986244.

In addition, fitness value of the M6 was calculated by calculating the distance of M5 (9.8) material from W5 activity area (1.5.4.5). According to this:

M5 (9,8) → W5 (1.5,4.5)

Distance = $D_{M5W5} = \sqrt{(1.5-9)^2+(4.5-8)^2}$ = 8.2764726

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 8.27647267 x 10 + 80 = 162.7647267

The total fitness value in the second stage is:

612.1681262 + 91.6986244 + 162.7647267 = 866.6314773

**Optimization Placement**

In the second stage of the case, the workspace coordinates and material information of the newly added materials were entered in the input file. In addition, the coordinates where the materials previously placed in the input file are placed are written in the columns x1 and y1 (Figure 3.26).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 |
|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 3,5 | 11 | 7 | 8 |
| M1a | material1 | 20 | 5 | 18,5 | 5 | 11 | 7 |
| M2 | material2 | 10 | 8 | 10 | 2,5 | 10 | 6 |
| M2a | material2 | 10 | 8 | 17 | 12,5 | 11 | 8 |
| M3 | material3 | 40 | 20 | 8 | 13 | 8 | 8 |
| M3a | material3 | 40 | 20 | 17 | 2 | 11 | 6 |
| M4 | material4 | 30 | 2 | 14 | 3,5 | 0 | 0 |
| M4a | material4 | 30 | 2 | 1,5 | 14 | 0 | 0 |
| M5 | material5 | 80 | 10 | 1,5 | 4,5 | 0 | 0 |

*Figure 3.26.* Input Data for Optimization in Second Stage

A new distance formula is defined in the coding system, which was previously created in Python. This formula is designed to consider the displacement distance if the previously placed materials are displaced. Newly created formula is:

distance2 = math.sqrt ((location_array[i][0] – xkordinati)**2 + (location_array[i][1] – ykordinati)**2) + math.sqrt ((location_array[i][0] – x1kordinati)**2 + (location_array[i][1] – y1kordinati)**2)

The algorithm uses the new distance formula for calculating the new fitness value for previously placed materials and uses the previously defined distance formula when calculating the fitness value of a newly added material.

According to this information, the input file is read to Python program and the function is run. As a result of the fitness function, the distance and fitness values of all materials

to each storage area were calculated. Python gave the result of the calculations as an output file (Figure 3.27).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 | 7,6 | 7,7 | 7,8 | 8,6 | 8,7 | 8,8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 3,5 | 11 | 7 | 8 | 60,5163890 | 51,5753645 | 43,0488611 | 64,8144000 | 57,1750543 | 52,0416346 |
| M1a | material1 | 20 | 5 | 18,5 | 5 | 11 | 7 | 98,3325100 | 98,3630876 | 100,0398497 | 88,5489461 | 88,4438958 | 90,4122125 |
| M2 | material2 | 10 | 8 | 10 | 2,5 | 10 | 6 | 70,8781778 | 78,5648366 | 88,9642665 | 58,2490310 | 67,2839750 | 79,4462166 |
| M2a | material2 | 10 | 8 | 17 | 12,5 | 11 | 8 | 141,1919712 | 134,2865427 | 129,7268488 | 127,6588234 | 119,6783137 | 114,4984472 |
| M3 | material3 | 40 | 20 | 8 | 13 | 8 | 8 | 226,1427158 | 189,9395219 | 161,9803903 | 220,0000000 | 180,0000000 | 140,0000000 |
| M3a | material3 | 40 | 20 | 17 | 2 | 11 | 6 | 335,4065923 | 346,0689103 | 362,6807949 | 296,9771560 | 309,1581560 | 328,4441020 |
| M4 | material4 | 30 | 2 | 14 | 3,5 | 0 | 0 | 44,8660687 | 45,6524758 | 46,6433170 | 43,0000000 | 43,8924440 | 45,0000000 |
| M4a | material4 | 30 | 2 | 1,5 | 14 | 0 | 0 | 49,4164878 | 47,8044938 | 46,2788206 | 50,6155281 | 49,1049732 | 47,6918060 |
| M5 | material5 | 80 | 10 | 1,5 | 4,5 | 0 | 0 | 137,0087713 | 140,4152299 | 145,1920241 | 146,7083203 | 149,6419414 | 153,8241153 |

| kod | 9,6 | 9,7 | 9,8 | 10,6 | 10,7 | 10,8 | 11,6 | 11,7 | 11,8 |
|---|---|---|---|---|---|---|---|---|---|
| M1 | 71,3073075 | 65,1840162 | 61,3249102 | 79,0308050 | 73,9722321 | 70,7945527 | 87,4300707 | 83,1155281 | 80,3887361 |
| M1a | 78,9427728 | 78,5412196 | 80,9924870 | 69,8641747 | 68,6606230 | 72,1404588 | 62,8318649 | 58,8104367 | 65,3887361 |
| M2 | 47,1204396 | 58,1918863 | 72,6099034 | 38,0000000 | 54,0000000 | 70,0000000 | 47,1204396 | 58,1918863 | 72,6099034 |
| M2a | 115,0895295 | 105,5544952 | 99,4302390 | 104,3084365 | 92,5316838 | 84,5732679 | 96,7672241 | 83,1152824 | 70,0000000 |
| M3 | 226,1427158 | 189,9395219 | 161,9803903 | 242,1707403 | 211,2124660 | 187,7032961 | 264,4264876 | 237,4096319 | 216,6190379 |
| M3a | 258,8854382 | 273,4009822 | 296,5685425 | 221,2451550 | 240,3307766 | 269,1122487 | 184,2220510 | 216,2049935 | 249,7056275 |
| M4 | 41,1803399 | 42,2065556 | 43,4536240 | 39,4339811 | 40,6301458 | 42,0415946 | 37,8102497 | 39,2195445 | 40,8166538 |
| M4a | 51,9317122 | 50,5182845 | 49,2093727 | 53,3452351 | 52,0227155 | 50,8086520 | 54,8394847 | 53,6008474 | 52,4722051 |
| M5 | 156,4852927 | 159,0569415 | 162,7647268 | 166,3133825 | 168,6002257 | 171,9238816 | 176,1769203 | 178,2344135 | 181,2422837 |

*Figure 3.27.* Fitness Values in Second Stage

This output file is loaded into the Neos Solver optimization program as a “data” file. Then, the “run” and “model” files described in the previous sections are loaded together with the “data” file. Neos Solver reads the loaded files and outputs an output file that describes the sequence in which the optimal value occurs (Figure 3.28).

```
:      M1 M1a  M2 M2a  M3 M3a  M4 M4a  M5
10p6    0   0   1   0   0   0   0   0   0
10p7    0   0   0   0   0   0   1   0   0
10p8    0   0   0   0   0   0   0   0   0
11p6    0   0   0   0   0   1   0   0   0
11p7    0   1   0   0   0   0   0   0   0
11p8    0   0   0   1   0   0   0   0   0
7p6     0   0   0   0   0   0   0   0   1
7p7     0   0   0   0   0   0   0   1   0
7p8     1   0   0   0   0   0   0   0   0
8p6     0   0   0   0   0   0   0   0   0
8p7     0   0   0   0   0   0   0   0   0
8p8     0   0   0   0   1   0   0   0   0
9p6     0   0   0   0   0   0   0   0   0
9p7     0   0   0   0   0   0   0   0   0
9p8     0   0   0   0   0   0   0   0   0
;
```

*Figure 3.28.* Neos Solver Output File in Second Stage

There are 24 constraints in total. 9 of them are called equality. These constraints symbolize materials. 15 of the constraints are called inequality and symbolize the coordinates of the storage area (Figure 3.29). Each material has 15 fitness values. Optimization collects these values by selecting a fitness value from each material. This process continues until all possible total values are output. Then, it finds the smallest value among these values and prepares the layout according to the smallest degree. According to the optimization and algorithm solution, the optimum fitness value is 759.5247598. The layout plan prepared according to this fitness value is shown in Figure 3.30.

```
135 variables, all linear
24 constraints, all linear; 270 nonzeros
        9 equality constraints
        15 inequality constraints
1 linear objective; 135 nonzeros.

Gurobi 8.1.0: threads=4
Gurobi 8.1.0: optimal solution; objective 759.5247598
```

*Figure 3.29.* Neos Solver Output File in Second Stage

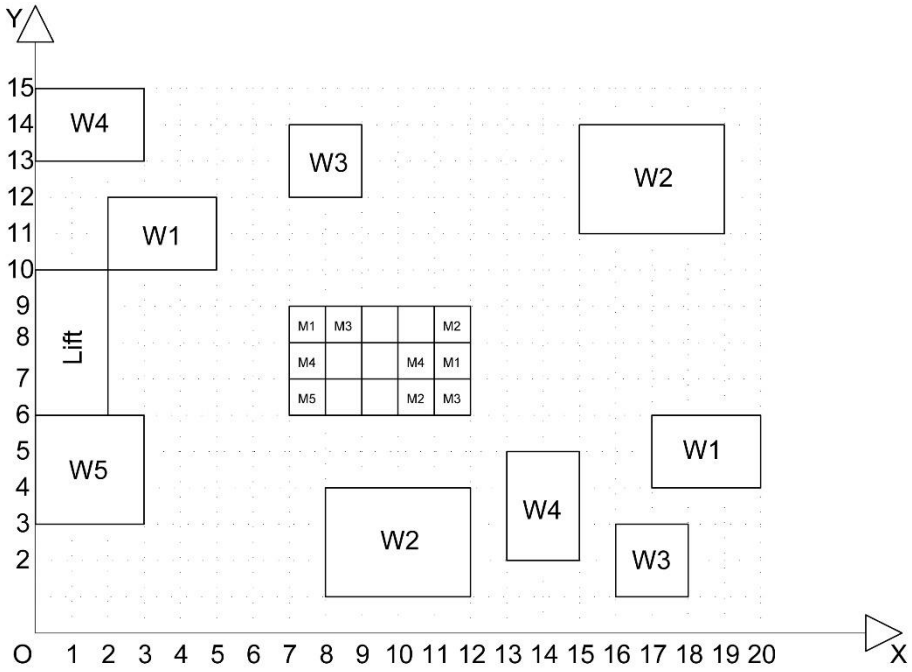


*Figure 3.30.* Storage Space Layout According to Optimization in Second Stage

**Survey Placement**

In the second stage of the survey, people were asked to place the newly added materials, considering the layout they had previously prepared. Fitness values were calculated according to the data obtained from the layout plans. If there has been a change in the location of previously placed materials, this change is also considered in the distance. According to the surveys, the layout plans in the second stage are given in Figure 3.31 and Figure 3.32.

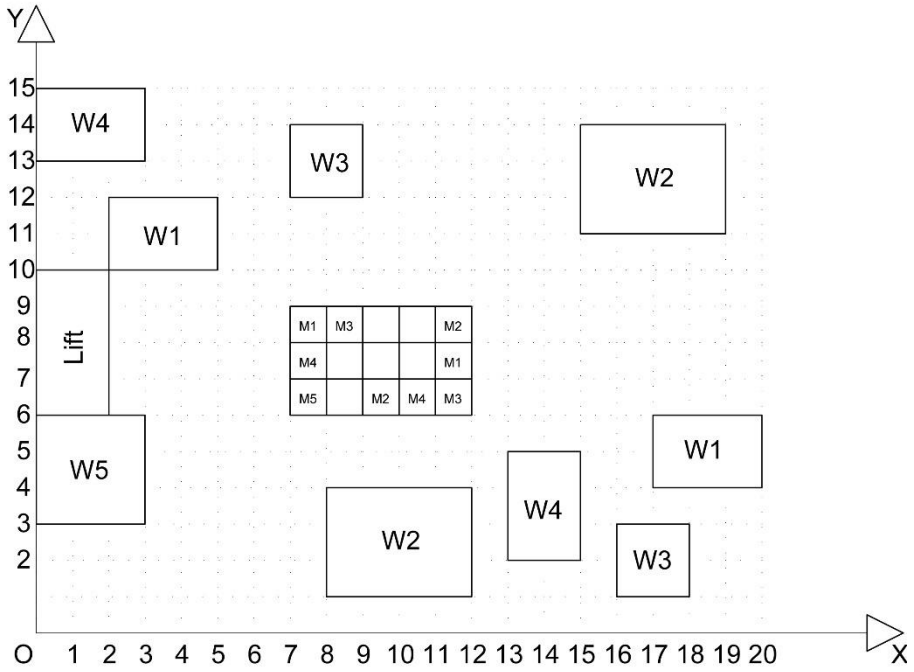


*Figure 3.31.* Storage Layout Plan According to Survey 1 in Second Stage

M1 (7,8) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-7)^2+(11-8)^2}$ = 4.6097722

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 4.6097722 x 5 + 20 = 43.0488611

M1 (11,7) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-7)^2}$ = 7.7620873

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.7620873 x 5 + 20 = 58.8104367

M2 (9,6) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(10-9)^2+(2.5-6)^2}$ = 3.6400549

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 3.6400549 x 8 + 10 = 39.1204395

M2 (11,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-11)^2 + (12.5-8)^2}$ = 7.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.5 x 8 + 10 = 70

M3 (8,8) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-8)^2 + (13-8)^2}$ = 5

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 5 x 20 + 40 = 140

M3 (11,6) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-11)^2 + (2-6)^2}$ = 7.2111025

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 7.2111025 x 20 + 40 = 184.2220510

M4 (7,7) → W4 (1.5,14)

Distance = $D_{M4W4} = \sqrt{(1.5-7)^2 + (14-7)^2}$ = 8.9022469

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 8.9022469 x 2 + 30 = 47.8044938

M4 (10,6) → W4 (14,3.5)

Distance = $D_{M4W4} = \sqrt{(14-10)^2 + (3.5-6)^2}$ = 4.7169905

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 4.7169905 x 2 + 30 = 39.4339811

M5 (7,6) → W5 (1.5,4.5)

Distance = $D_{M5W5} = \sqrt{(1.5-7)^2 + (4.5-6)^2}$ = 5.7008771

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 5.7008771 x 10 + 80 = 137.0087712

Total fitness value is 759.4490344.

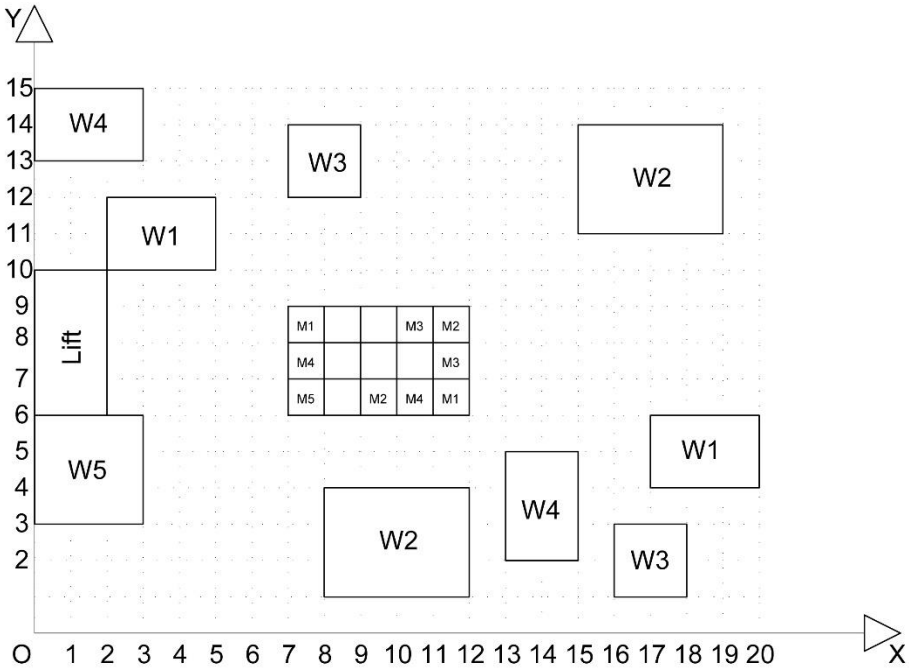


*Figure 3.32.* Storage Layout Plan According to Survey 5 in Second Stage

M1 (7,8) → W1 (3.5,11)

Distance = $D_{M1W1} = \sqrt{(3.5-7)^2+(11-8)^2}$ = 4.6097722

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 4.6097722 x 5 + 20 = 43.0488611

M1 (11,6) → W1 (18.5,5)

Distance = $D_{M1W1} = \sqrt{(18.5-11)^2+(5-6)^2}$ = 7.5663729

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 7.5663729 x 5 + 20 = 57.8318648

M2 (10,6) → M2 (9,6) → W2 (10,2.5)

Distance = $D_{M2W2} = \sqrt{(9-10)^2+(6-6)^2} + \sqrt{(10-9)^2+(2.5-6)^2}$ = 3.6400549

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 3.6400549 x 8 + 10 = 39.1204395

M2 (11,8) → W2 (17,12.5)

Distance = $D_{M2W2} = \sqrt{(17-11)^2 + (12.5-8)^2}$ = 7.5

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.5 x 8 + 10 = 70

M3 (10,8) → W3 (8,13)

Distance = $D_{M3W3} = \sqrt{(8-10)^2 + (13-8)^2}$ = 5.3851648

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 5.3851648 x 20 + 40 = 147.7032961

M3 (11,7) → W3 (17,2)

Distance = $D_{M3W3} = \sqrt{(17-11)^2 + (2-7)^2}$ = 7.8102496

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 7.8102496 x 20 + 40 = 196.2049935

M4 (7,7) → W4 (1.5,14)

Distance = $D_{M4W4} = \sqrt{(1.5-7)^2 + (14-7)^2}$ = 8.9022469

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 8.9022469 x 2 + 30 = 47.8044938

M4 (10,6) → W4 (14,3.5)

Distance = $D_{M4W4} = \sqrt{(14-10)^2 + (3.5-6)^2}$ = 4.7169905

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 4.7169905 x 2 + 30 = 39.4339811

M5 (7,6) → W5 (1.5,4.5)

Distance = $D_{M5W5} = \sqrt{(1.5-7)^2 + (4.5-6)^2}$ = 5.7008771

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 5.7008771 x 10 + 80 = 137.0087712

Total fitness value is 778.1567011.

Other survey results are calculated as the survey results mentioned above. The fitness values obtained as a result of this are indicated in Table 3.4.

Table 3.4. *Survey Results in Second Stage*

| | Second Stage |
|---|---|
| Survey 1 | 759.4490344 |
| Survey 2 | 830.2234184 |
| Survey 3 | 758,4235204 |
| Survey 4 | 774.4498645 |
| Survey 5 | 778.1567011 |
| Survey 6 | 767.4490344 |
| Survey 7 | 770.5776259 |
| Survey 8 | 772.0495539 |
| Survey 9 | 765.5024785 |
| Survey 10 | 762.5776259 |
| Survey 11 | 789.3167369 |
| Survey 12 | 770.4721819 |
| Survey 13 | 761.9456785 |
| Survey 14 | 766.4498645 |
| Survey 15 | 760.0749539 |
| Average Fitness Value | 772.4745515 |

**Stage 3**

In the third stage of the case, a new activity (W6) was added. The W6 activity has two different workspaces and one M6 material is required for each area (Figure 3.33). The transportation cost of M6 material is 30 and the setup cost is 15 (Table 3.5).

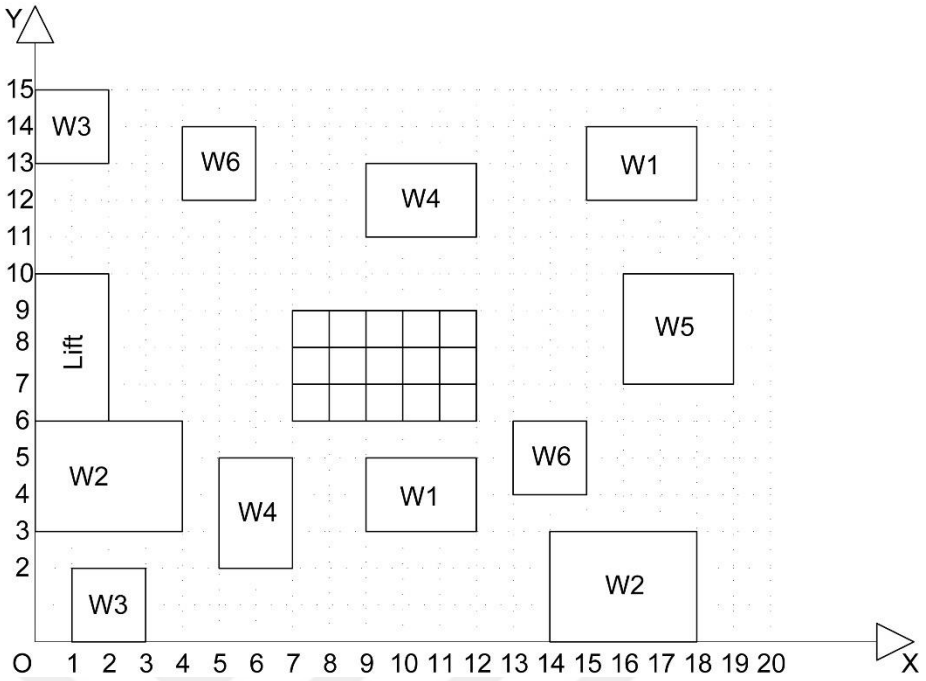


*Figure 3.33.* Site Layout of Third Stage

Table 3.5. *Material Information in Third Stage*

| | M1 | M2 | M3 | M4 | M5 | M6 |
|---|---|---|---|---|---|---|
| Transportation Cost | 5 | 8 | 20 | 2 | 10 | 30 |
| Setup Cost | 20 | 10 | 40 | 30 | 80 | 15 |

In addition, the workspace of the materials specified in the second stage have changed. Accordingly, a new storage layout is required. When planning the storage layout for third stage of the case, the materials in the layout plan made in second stage should be considered as they were still in place. In this case, the location of the previously placed materials may change or the placement of the new materials can be made by keeping the location of the previously placed materials constant. In case of relocation of materials, the fitness value will be calculated with the fitness formula given in second stage. The placement of the newly added two materials were done in three different

ways. Firstly, the layout plan was prepared according to FIFO method. Secondly, the layout plan was prepared according to the optimization and software codes. Finally, the layout plan was prepared by people from different professionals. Fitness values of different settlement plans were calculated and average fitness value is taken a fitness.

**FIFO Placement**

The newly added materials were placed in the layout plan as shown in Figure 3.34. In this layout, the places of the previously placed materials have not been changed again. The fitness value of the materials was calculated according to this location. Accordingly, fitness value was calculated by calculating the distance of two M6 materials to both W6 work areas. The smallest sum of the fitness value is taken as a fitness. In addition, the total fitness value was calculated by recalculating the previously calculated fitness values as the workspaces were relocated.

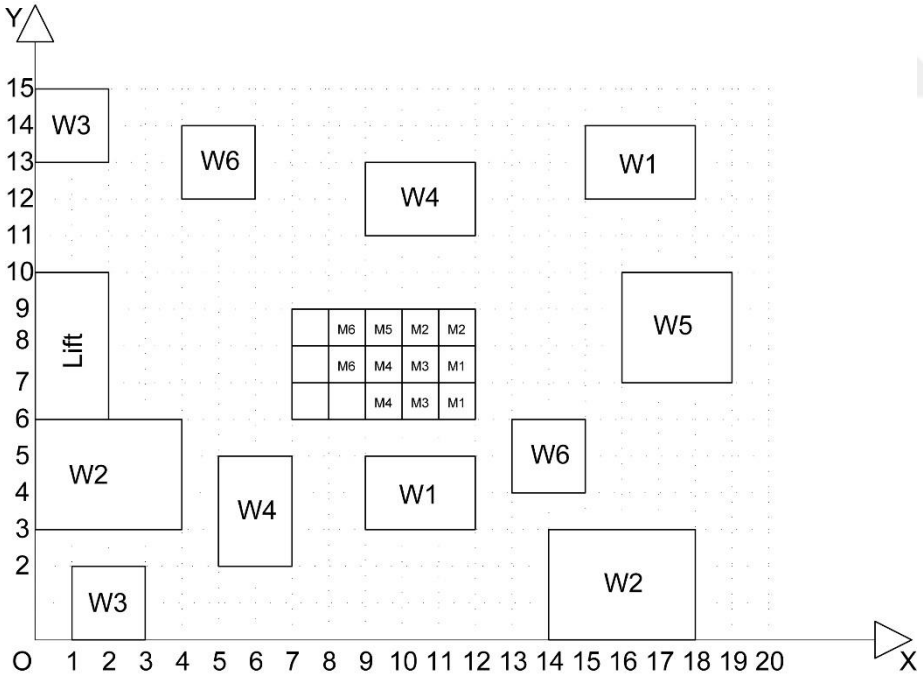


*Figure 3.34.* Storage Space Layout According to FIFO Method in Third Stage

The fitness values of the M6 material in the (8,7) coordinate to the W6 workspace in the (14,5) coordinate and to the W6 workspace in the (5,13) area were calculated. At the same time, the fitness value of the material M6 in the coordinate (8,8) was calculated by calculating the distance to both workspaces. According to these calculations;

M6 (8,7) → W6 (14,5)

Distance = $D_{M6W6} = \sqrt{(14-8)^2 + (5-7)^2}$ = 6.3245553

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 6.32455532 x 30 + 15 = 204.7366596

M6 (8,7) → W6 (5,13)

Distance = $D_{M6W6} = \sqrt{(5-8)^2 + (13-7)^2}$ = 6.7082039

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 6.70820393 x 30 + 15 = 216.2461179

M6 (8,8) → W6 (14,5)

Distance = $D_{M6W6} = \sqrt{(14-8)^2 + (5-8)^2}$ = 6.7082039

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 6.70820393 x 30 + 15 = 216.2461179

M6 (8,8) → W6 (5,13)

Distance = $D_{M6W6} = \sqrt{(5-8)^2 + (13-8)^2}$ = 5.83095189

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 5.83095189 x 30 + 15 = 189,9285567

There are two different fitness values for the M6 material. According to the first fitness value, M6 (8,7) material goes to the W6 (14,5) workspace and M6 (8,8) material goes to the W6 (5,13) workspace. According to second fitness value, M6 (8,7) material goes to the W6 (5,13) workspace and M6 (8,8) material is goes to the W6 (14,5) workspace. The fitness value was calculated by taking the smallest sum of these results in order to give correct results of fitness value. The first option of the fitness value is

calculated as 394.6652163, while the second option is 432.4922358. So, the fitness value is taken as 394.6652163.

In addition, since the coordination of the workspaces are change, the fitness values of previously placed materials were recalculated. According to new calculations:

M1 (11,6) → W1 (10.5,4)

Distance = $D_{M1W1} = \sqrt{(10.5-11)^2+(4-6)^2}$ = 2.0615528

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 2.06155281 x 5 + 20 = 30.3077640

M1 (11,7) → W1 (16.5,13)

Distance = $D_{M1W1} = \sqrt{(16.5-11)^2+(13-7)^2}$ = 8.1394102

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 8.13941029 x 5 + 20 = 60.6970514

M2 (11,8) → W2 (16,1.5)

Distance = $D_{M2W2} = \sqrt{(16-11)^2+(1.5-8)^2}$ = 8.2006097

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 8.20060973 x 8 + 10 = 75.6048778

M2 (10,8) → W2 (2,4.5)

Distance = $D_{M2W2} = \sqrt{(2-10)^2+(4.5-8)^2}$ = 8.7321246

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 8.7321246 x 8 + 10 = 79.8569968

M3 (10,6) → W3 (2,1)

Distance = $D_{M3W3} = \sqrt{(2-10)^2+(1-6)^2}$ = 9.4339811

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 9.4339811 x 20 + 40 = 228.6796220

M3 (10,7) → W3 (1,14)

Distance = $D_{M3W3} = \sqrt{(1-10)^2+(14-7)^2}$ = 11.8321596

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 11.8321596 x 20 + 40 = 276.6431920

M4 (9,6) → W4 (6,3.5)

Distance = $D_{M4W4} = \sqrt{(6-9)^2+(3.5-6)^2}$ = 3.9051248

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 3.9051248 x 2 + 30 = 37.8102497

M4 (9,7) → W4 (10.5,12)

Distance = $D_{M4W4} = \sqrt{(10.5-9)^2+(12-7)^2}$ = 5.2201532

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 5.2201532 x 2 + 30 = 40.4403064

M5 (9,8) → W5 (17.5,8.5)

Distance = $D_{M5W5} = \sqrt{(17.5-9)^2+(8.5-8)^2}$ = 8.5146931

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 8.5146931 x 10 + 80 = 165.1496310

The total fitness value is 1389.854907.

**Optimization Placements**

In the third stage of the case, the workspace coordinates and material information of the newly added M6 material were entered in the input file. In addition, the coordinates where the materials previously placed in the input file are placed are written in the columns x1 and y1. In the third stage, since the locations of the workspace areas mentioned in the previous stages were changed, the positions of these workspace areas were updated. (Figure 3.35).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 |
|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 10,5 | 4 | 7 | 8 |
| M1a | material1 | 20 | 5 | 16,5 | 13 | 11 | 7 |
| M2 | material2 | 10 | 8 | 2 | 4,5 | 10 | 6 |
| M2a | material2 | 10 | 8 | 16 | 1,5 | 11 | 8 |
| M3 | material3 | 40 | 20 | 1 | 14 | 8 | 8 |
| M3a | material3 | 40 | 20 | 2 | 1 | 11 | 6 |
| M4 | material4 | 30 | 2 | 10,5 | 12 | 10 | 7 |
| M4a | material4 | 30 | 2 | 6 | 3,5 | 7 | 7 |
| M5 | material5 | 80 | 10 | 17,5 | 8,5 | 7 | 6 |
| M6 | material6 | 15 | 30 | 5 | 13 | 0 | 0 |
| M6a | material6 | 15 | 30 | 14 | 5 | 0 | 0 |

*Figure 3.35.* Input Data for Optimization in Third Stage

The program calculates the new fitness value for previously placed materials and adds the cost of moving to the fitness values if the material is moved from its previous location to another location. When calculating the fitness value of a newly added material, it uses the firstly defined distance formula.

According to this information, the input file is read to Python program and the function is run. As a result of the fitness function, the distance and fitness values of all materials to each storage area were calculated. Python gave the result of the calculations as an output file (Figure 3.36).

| kod | isim | set_cost | trans_cost | x | y | x1 | y1 | 7,6 | 7,7 | 7,8 | 8,6 | 8,7 | 8,8 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| M1 | material1 | 20 | 5 | 10,5 | 4 | 7 | 8 | 50,1556444 | 48,0488611 | 46,5753645 | 47,1881505 | 46,5966920 | 48,5849528 |
| M1a | material1 | 20 | 5 | 16,5 | 13 | 11 | 7 | 99,6176467 | 96,1805126 | 94,2928045 | 90,8681772 | 87,0216301 | 85,1190956 |
| M2 | material2 | 10 | 8 | 2 | 4,5 | 10 | 6 | 75,7612260 | 80,0195808 | 87,6706327 | 75,4772675 | 79,8885438 | 88,1971930 |
| M2a | material2 | 10 | 8 | 16 | 1,5 | 11 | 8 | 126,2755348 | 127,3649374 | 130,8144132 | 112,2746492 | 112,9641726 | 116,4621125 |
| M3 | material3 | 40 | 20 | 1 | 14 | 8 | 8 | 284,7213595 | 252,6751604 | 229,7056275 | 292,6029163 | 257,9898987 | 224,3908891 |
| M3a | material3 | 40 | 20 | 2 | 1 | 11 | 6 | 261,4213562 | 278,6671060 | 301,4892244 | 256,2049935 | 272,9511807 | 296,5019147 |
| M4 | material4 | 30 | 2 | 10,5 | 12 | 10 | 7 | 50,2169993 | 48,2065556 | 46,9547011 | 47,4721360 | 45,1803399 | 43,9061171 |
| M4a | material4 | 30 | 2 | 6 | 3,5 | 7 | 7 | 37,3851648 | 37,2801099 | 41,2195445 | 39,2315514 | 40,0622577 | 42,6772849 |
| M5 | material5 | 80 | 10 | 17,5 | 8,5 | 7 | 6 | 187,9351657 | 196,0660172 | 205,1189802 | 188,2344135 | 190,3190559 | 197,4921677 |
| M6 | material6 | 15 | 30 | 5 | 13 | 0 | 0 | 233,4032967 | 204,7366596 | 176,5549442 | 243,4731932 | 216,2461180 | 189,9285568 |
| M6a | material6 | 15 | 30 | 14 | 5 | 0 | 0 | 227,1320344 | 233,4032967 | 243,4731932 | 197,4828759 | 204,7366596 | 216,2461180 |

| kod | 9,6 | 9,7 | 9,8 | 10,6 | 10,7 | 10,8 | 11,6 | 11,7 | 11,8 |
|---|---|---|---|---|---|---|---|---|---|
| M1 | 46,6421356 | 47,9508497 | 51,3600094 | 48,3355204 | 51,0182946 | 55,1556444 | 52,6684438 | 55,8224345 | 60,1556444 |
| M1a | 82,4760512 | 78,0234318 | 76,2497308 | 74,8335007 | 69,2295150 | 68,0741165 | 69,5112345 | 60,6970515 | 62,1651719 |
| M2 | 75,2712843 | 80,7779835 | 90,4984472 | 75,1152824 | 85,0522185 | 95,8569968 | 90,9931504 | 96,0398753 | 105,1413755 |
| M2a | 99,2006849 | 99,1065191 | 102,4198927 | 87,8885438 | 86,4289909 | 88,7672241 | 79,8144962 | 77,4642750 | 75,6048779 |
| M3 | 310,9955295 | 280,8871875 | 260,0000000 | 337,4004341 | 312,7564446 | 296,3330765 | 368,2359950 | 347,3766655 | 333,2380758 |
| M3a | 252,0465053 | 269,1122487 | 294,5584412 | 248,6796226 | 268,2842712 | 297,3242758 | 245,9126028 | 276,3330765 | 308,0350850 |
| M4 | 45,1977440 | 42,4403065 | 41,3724309 | 44,0415946 | 40,0498756 | 40,0622577 | 44,8700217 | 42,0498756 | 40,8906849 |
| M4a | 42,2823856 | 43,2195445 | 45,2887898 | 45,7585365 | 46,6301458 | 48,3661499 | 49,4265511 | 50,2065556 | 51,6998353 |
| M5 | 188,6002257 | 188,6740623 | 193,4312031 | 189,0569415 | 188,1080693 | 191,2219946 | 189,6419414 | 187,9393766 | 189,9133836 |
| M6 | 256,8677324 | 231,3330765 | 207,0937271 | 273,0697580 | 249,3074903 | 227,1320344 | 291,5863337 | 269,5584412 | 249,3074903 |
| M6a | 167,9705854 | 176,5549442 | 189,9285568 | 138,6931688 | 149,1640786 | 165,0000000 | 109,8683298 | 123,1665383 | 142,2792206 |

*Figure 3.36.* Fitness Values in Third Stage

This output file is loaded into the Neos Solver optimization program as a “data” file. Then, the “run” and “model” files described in the previous sections are loaded together with the “data” file. Neos Solver reads the loaded files and outputs an output file that describes the sequence in which the optimal value occurs (Figure 3.37).

```
:      M1 M1a  M2 M2a  M3 M3a  M4 M4a  M5  M6 M6a
10p6    0   0   0   0   0   1   0   0   0   0   0
10p7    0   0   0   0   0   0   1   0   0   0   0
10p8    0   0   0   0   0   0   0   0   0   0   0
11p6    0   0   0   0   0   0   0   0   0   0   1
11p7    0   1   0   0   0   0   0   0   0   0   0
11p8    0   0   0   1   0   0   0   0   0   0   0
7p6     0   0   0   0   0   0   0   0   1   0   0
7p7     0   0   0   0   0   0   0   1   0   0   0
7p8     0   0   0   0   0   0   0   0   0   1   0
8p6     0   0   0   0   0   0   0   0   0   0   0
8p7     1   0   0   0   0   0   0   0   0   0   0
8p8     0   0   0   0   1   0   0   0   0   0   0
9p6     0   0   1   0   0   0   0   0   0   0   0
9p7     0   0   0   0   0   0   0   0   0   0   0
9p8     0   0   0   0   0   0   0   0   0   0   0
;
```

*Figure 3.37.* Neos Solver Output Date in Third Stage

There are 26 constraints in total. 11 of them are called equality. These constraints symbolize materials. 15 of the constraints are called inequality and symbolize the coordinates of the storage area (Figure 3.38). Each material has 15 fitness values. Optimization collects these values by selecting a fitness value from each material. This process continues until all possible total values are output. Then, it finds the smallest value among these values and prepares the layout according to the smallest degree. Optimum fitness value is 1282.9288430 according to optimization and algorithm solution. The layout plan prepared according to this fitness value is shown in Figure 3.39.

```
165 variables, all linear
26 constraints, all linear; 330 nonzeros
        11 equality constraints
        15 inequality constraints
1 linear objective; 165 nonzeros.

Gurobi 8.1.0: threads=4
Gurobi 8.1.0: optimal solution; objective 1282.928843
```

*Figure 3.38.* Neos Solver Output Date in Third Stage

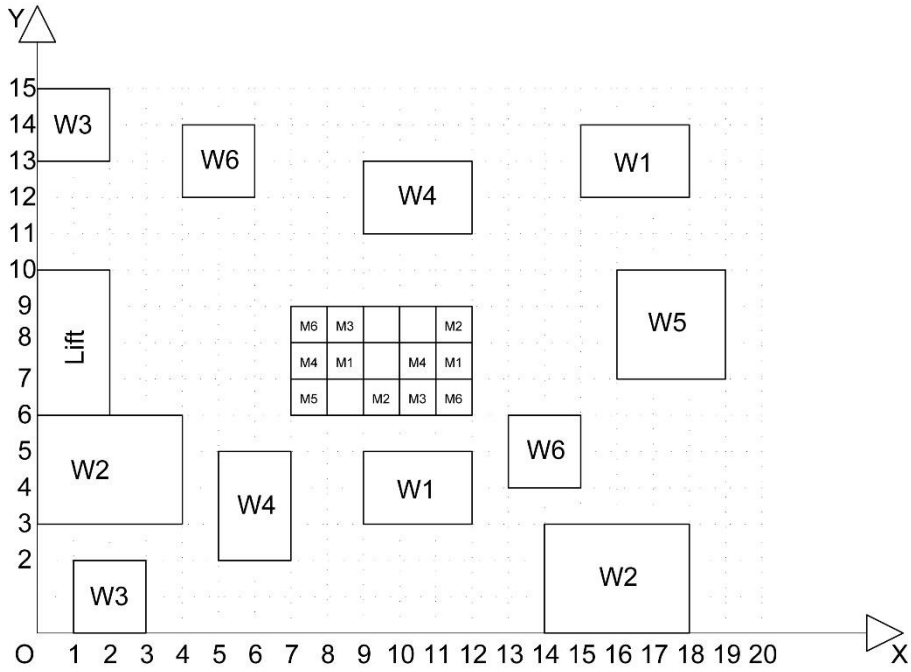


*Figure 3.39.* Storage Space Layout According to Optimization in Third Stage

Survey Placement

In the third stage of the survey, people were asked to place the newly added materials, considering the layout they had prepared earlier. It was also told that the locations of the previously mentioned workspaces have changed. According to the new site layout, materials were placed in the storage areas. Fitness values were calculated according to the data obtained from the layout plans. If there has been a change in the location of previously placed materials, this change is also considered in the distance. According to the surveys, the sequences in the second stage are given in Figure 3.40 and Figure 3.41.

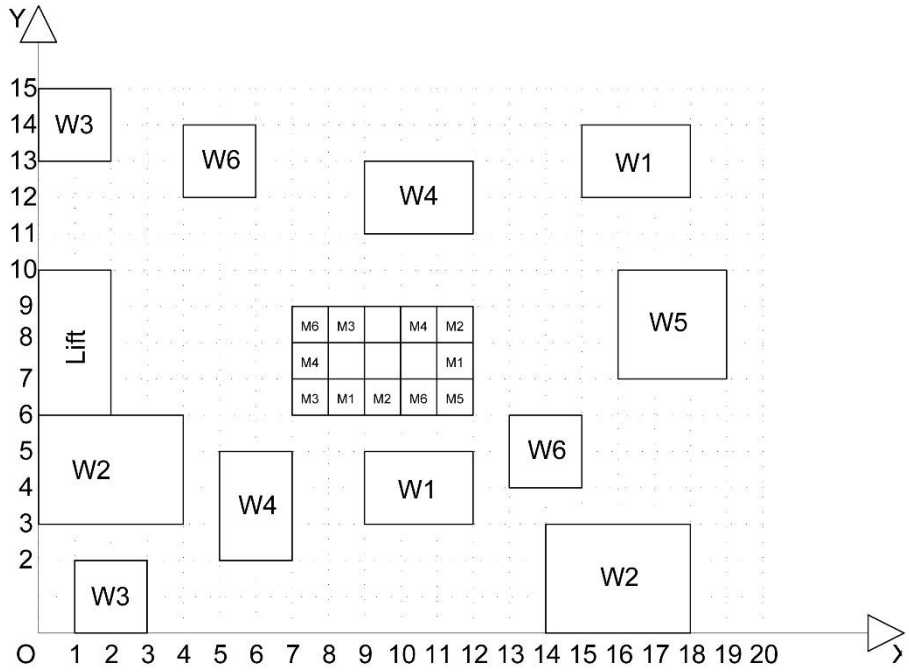


*Figure 3.40.* Storage Layout Plan According to Survey 1 in Third Stage

M1 (7,8) → M1 (8,6) → W1 (10.5,4)

Distance = $D_{M1W1}$ = $\sqrt{(8-7)^2+(6-8)^2}$ + $\sqrt{(10.5-8)^2+(4-6)^2}$ = 5.4376300

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 5.4376300 x 5 + 20 = 47.1881500

M1 (11,7) → W1 (16.5,13)

Distance = $D_{M1W1}$ = $\sqrt{(16.5-11)^2+(13-7)^2}$ = 8.1394103

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 8.1394103 x 5 + 20 = 60.6970515

M2 (9,6) → W2 (2,4.5)

Distance = $D_{M2W2}$ = $\sqrt{(2-9)^2+(4.5-6)^2}$ = 7.1589105

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 7.1589105 x 8 + 10 = 67.2712840

M2 (11,8) → W2 (16,1.5)

Distance = $D_{M2W2} = \sqrt{(16-11)^2 + (1.5-8)^2}$ = 8.2006097

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 8.2006097 x 8 + 10 = 75.6048779

M3 (8,8) → W3 (1,14)

Distance = $D_{M3W3} = \sqrt{(1-8)^2 + (14-8)^2}$ = 9.2195444

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 9.2195444 x 20 + 40 = 224.3908890

M3 (11,6) → M3 (7,6) → W3 (2,1)

Distance = $D_{M3W3} = \sqrt{(7-11)^2 + (6-6)^2} + \sqrt{(2-7)^2 + (1-6)^2}$ = 11.0710678

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 11.0710678 x 20 + 40 = 261.4213560

M4 (7,7) → W4 (6,3.5)

Distance = $D_{M4W4} = \sqrt{(6-7)^2 + (3.5-7)^2}$ = 3.6400549

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 3.6400549 x 2 + 30 = 37.2801098

M4 (10,6) → M4 (10,8) → W4 (10.5,12)

Distance = $D_{M4W4} = \sqrt{(10-10)^2 + (8-6)^2} + \sqrt{(10.5-10)^2 + (12-8)^2}$= 6.0311288

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 6.0311288 x 2 + 30 = 42.0622576

M5 (7,6) → M5 (11,6) → W5 (17.5,8.5)

Distance = $D_{M5W5} = \sqrt{(11-7)^2 + (6-6)^2} + \sqrt{(17.5-11)^2 + (8.5-6)^2}$= 10.9641941

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 10.9641941 x 10 + 80 = 189.6419410

M6 (10,6) → W6 (14,5)

Distance = $D_{M6W6} = \sqrt{(14-10)^2 + (5-6)^2}$ = 4.1231056

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 4.1231056 x 30 + 15 = 138.6931680

M6 (7,8) → W6 (5,13)

Distance = $D_{M6W6} = \sqrt{(5-7)^2 + (13-8)^2}$ = 5.3851648

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 5.3851648 x 30 + 15 = 176.5549440

Total fitness value is 1320.8060315.

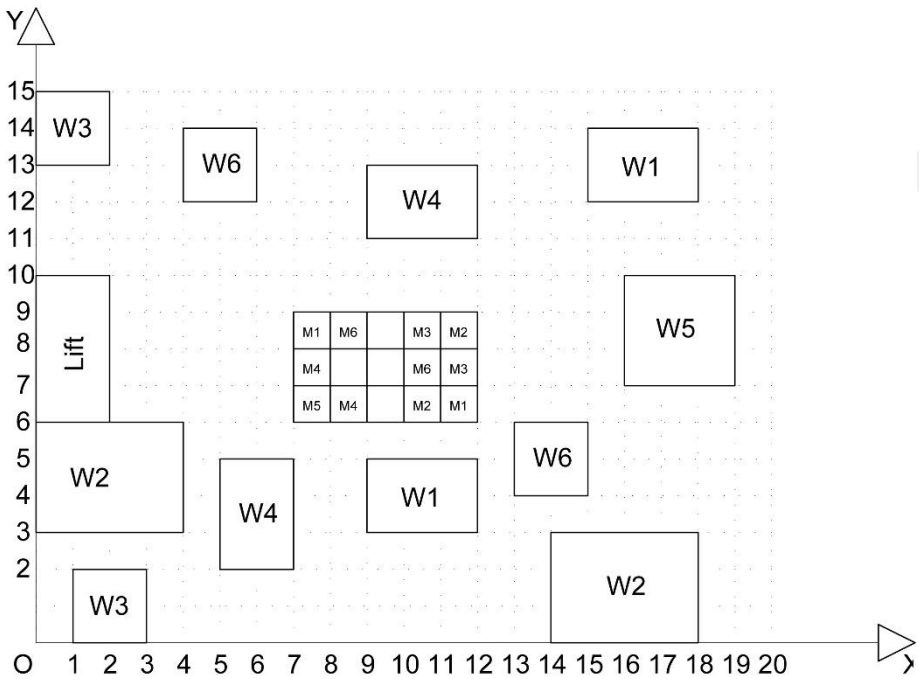


*Figure 3.41.* Storage Layout Plan According to Survey 5 in Third Stage

M1 (7,8) → W1 (16.5,13)

Distance = $D_{M1W1} = \sqrt{(16.5-7)^2+(13-8)^2}$ = 10.7364553

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 10.7364553 x 5 + 20 = 73.6772765

M1 (11,6) → W1 (10.5,4)

Distance = $D_{M1W1} = \sqrt{(10.5-11)^2+(4-6)^2}$ = 2.0615528

Fitness = $D_{M1W1}TC_{M1}+SC_{M1}$ = 2.0615528 x 5 + 20 = 30.3077640

M2 (9,6) → M2 (10,6) → W2 (2,4.5)

Distance = $D_{M2W2} = \sqrt{(10-9)^2+(6-6)^2} + \sqrt{(2-10)^2+(4.5-6)^2}$ = 9.1394103

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 9.1394103 x 8 + 10 = 83.1152824

M2 (11,8) → W2 (16,1.5)

Distance = $D_{M2W2} = \sqrt{(16-11)^2+(1.5-8)^2}$ = 8.2006097

Fitness = $D_{M2W2}TC_{M2}+SC_{M2}$ = 8.2006097 x 8 + 10 = 75.6048776

M3 (10,8) → W3 (1,14)

Distance = $D_{M3W3} = \sqrt{(1-10)^2+(14-8)^2}$ = 10.8166538

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 10.8166538 x 20 + 40 = 256.3330760

M3 (11,7) → W3 (2,1)

Distance = $D_{M3W3} = \sqrt{(2-11)^2+(1-7)^2}$ = 10.8166538

Fitness = $D_{M3W3}TC_{M3}+SC_{M3}$ = 10.8166538 x 20 + 40 = 256.3330760

M4 (7,7) → W4 (10.5,12)

Distance = $D_{M4W4} = \sqrt{(10.5-7)^2+(12-7)^2}$ = 6.1032778

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 6.1032778 x 2 + 30 = 42.2065556

M4 (10,6) → M4 (8,6) → W4 (6,3.5)

Distance = $D_{M4W4}$ = $\sqrt{(8-10)^2+(6-6)^2}$ + $\sqrt{(6-8)^2+(3.5-6)^2}$ = 5.2015621

Fitness = $D_{M4W4}TC_{M4}+SC_{M4}$ = 5.2015621 x 2 + 30 = 40.4031242

M5 (7,6) → W5 (17.5,8.5)

Distance = $D_{M5W5}$ = $\sqrt{(1.5-7)^2+(4.5-6)^2}$ = 5.7008771

Fitness = $D_{M5W5}TC_{M5}+SC_{M5}$ = 5.7008771 x 10 + 80 = 137.0087712

M6 (10,7) → W6 (14,5)

Distance = $D_{M6W6}$ = $\sqrt{(14-10)^2+(5-7)^2}$ = 4.4721359

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 4.4721359 x 30 + 15 = 149.1640770

M6 (8,8) → W6 (5,13)

Distance = $D_{M6W6}$ = $\sqrt{(5-8)^2+(13-8)^2}$ = 5.830951

Fitness = $D_{M6W6}TC_{M6}+SC_{M6}$ = 5.830951 x 30 + 15 = 189.9285568

Total fitness value is 1334.0824373.

Other survey results are calculated as the survey results mentioned above. The fitness values obtained as a result of this are indicated in Table 3.6.

Table 3.6. *Survey Results in Third Stage*

| | Third Stage |
|---|---|
| Survey 1 | 1320.8060315 |
| Survey 2 | 1343.7477555 |
| Survey 3 | 1379.8377582 |
| Survey 4 | 1351.8826699 |
| Survey 5 | 1334.0824373 |
| Survey 6 | 1351.5916971 |
| Survey 7 | 1319.7339569 |
| Survey 8 | 1361.2347675 |
| Survey 9 | 1486.5461614 |
| Survey 10 | 1338.4223079 |
| Survey 11 | 1362.6725879 |
| Survey 12 | 1320.0249297 |
| Survey 13 | 1349.8924248 |
| Survey 14 | 1344.7776060 |
| Survey 15 | 1304.6414272 |
| Average Fitness Value | 1351.3263013 |

# CHAPTER 4

# RESULTS AND DISCUSSIONS

In this section, the results and the analysis of the optimization and cases described in the previous section are explained. The three different results were compared with each other and it was determined how much benefit the optimization had.

## 4.1. Results of the First Stage

In this section, the results and the analysis of the optimization and cases described in the previous section are explained. The three different results were compared with each other and it was determined how much benefit the optimization had.

Table 4.1. *Results of the First Stage*

| | First Stage |
|---|---|
| Survey 1 | 535.2017883 |
| Survey 2 | 535.2017883 |
| Survey 3 | 534.0813489 |
| Survey 4 | 534.0813489 |
| Survey 5 | 552.7890155 |
| Survey 6 | 534.0813489 |
| Survey 7 | 535.2017883 |
| Survey 8 | 535.2017883 |
| Survey 9 | 537.1821785 |
| Survey 10 | 538.3303797 |
| Survey 11 | 534.0813489 |
| Survey 12 | 535.2017883 |
| Survey 13 | 535.2017883 |
| Survey 14 | 535.2017883 |
| Survey 15 | 534.0813489 |
| Average Survey Value | 536.3413890 |
| FIFO Method | 612.1681262 |
| Optimization | 534.0813489 |

The results were compared with each other (Figure 4.1). According to the comparisons, the FIFO method yielded the highest results, while the results of the survey were close to the optimization results. While the average value of the survey results is 536.3413890, the algorithm result is 534.0813489. According to these results, optimization provides only 0.4% contribution in case of low number of materials and works. In addition, optimization according to FIFO method contributed of 14.6%.

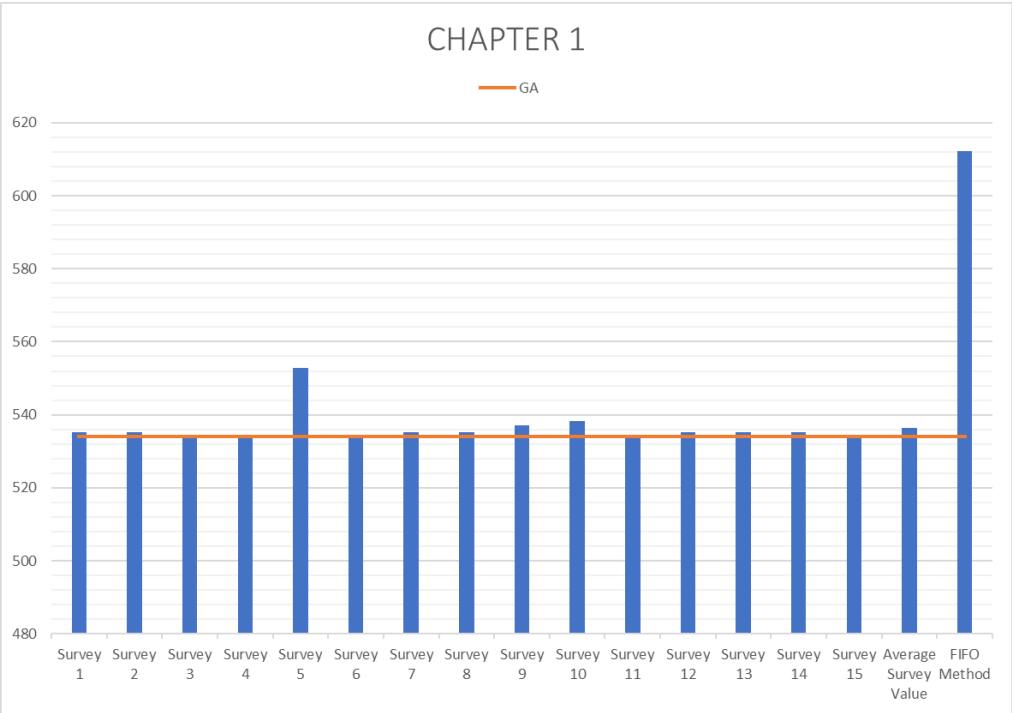


*Figure 4.1*. Comparison of the Results in First Stage

Five of the survey results were performed in the same sequence as the optimization. Also, seven of the survey results were found to be very close to the optimization solution. According to the results obtained in the first stage of the case, it was found that while the number of materials and works were low, people were able to arrange them comfortably and accurately, and the transportation costs were lower.

## 4.2. Results of the Second Stage

In the second stage of the case, the number of the materials and the number of the workspaces increased. In this case, the results of the survey were different. While the results of the survey in the first stage were very close to each other, different results were obtained in the second stage (Table 4.2).

Table 4.2. *Results of the Second Stage*

| | Second Stage |
|---|---|
| Survey 1 | 759.4490344 |
| Survey 2 | 830.2234184 |
| Survey 3 | 758,4235204 |
| Survey 4 | 774.4498645 |
| Survey 5 | 778.1567011 |
| Survey 6 | 767.4490344 |
| Survey 7 | 770.5776259 |
| Survey 8 | 772.0495539 |
| Survey 9 | 765.5024785 |
| Survey 10 | 762.5776259 |
| Survey 11 | 789.3167369 |
| Survey 12 | 770.4721819 |
| Survey 13 | 761.9456785 |
| Survey 14 | 766.4498645 |
| Survey 15 | 760.0749539 |
| Average Fitness Value | 772.4745515 |
| FIFO Method | 866.6314773 |
| Optimization | 759.5247598 |

A graph was prepared by comparing the results obtained (Figure 4.2). The sequence prepared by the FIFO method has the highest values. As can be seen in the graph, there were differences in the survey results. In addition, the difference between the average fitness value of the survey results and the fitness value of the sequence prepared using optimization was opened. While the average of the survey results is 772.4745515, the fitness value of the sequence prepared according to optimization is 759.5247598. In this case, the optimization provided a benefit of 1.4% according to survey results. In addition, the optimization provided a layer of 14.10% relative to the FIFO method.

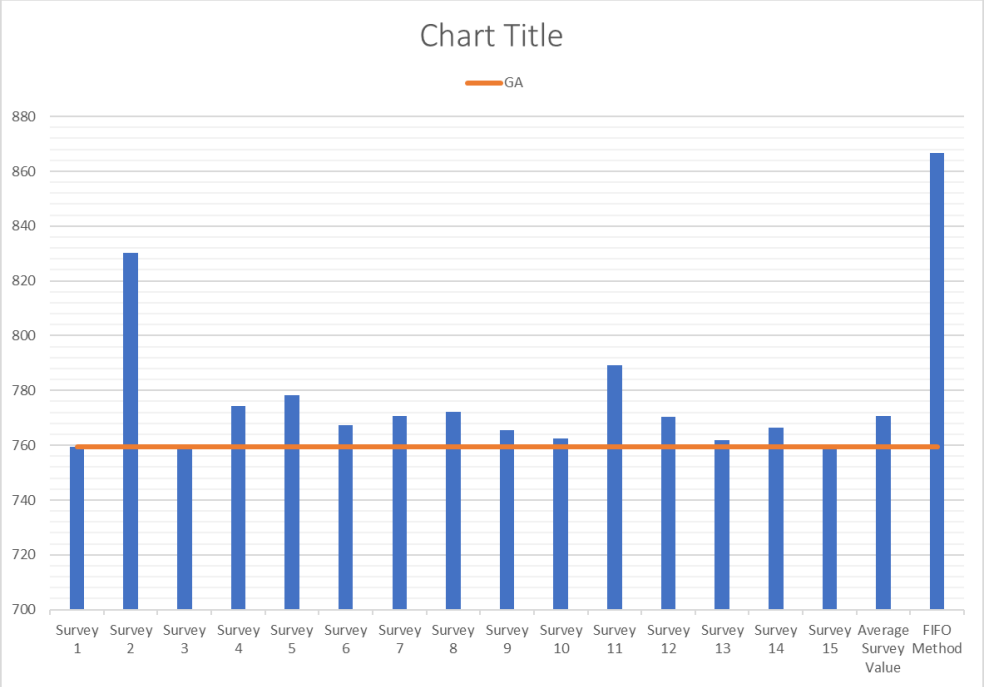


*Figure 4.2*. Comparison of the Results in Second Stage

This shows that as the number of materials increases, people find it difficult to arrange them, differences in the arrangement according to individuals and transportation costs increase. In such cases, a storage layout plan using the optimization will yield better results.

### 4.3. Results of the Third Stage

In the third stage of the case, the number of materials and the number of workspaces increased, while the locations of the previously mentioned business areas changed. In this case, the results of the survey, fitness value calculated by placement according to FIFO method and fitness value calculated by optimization placement are shown in Table 4.3.

Table 4.3. *Results of the Third Stage*

| | Third Stage |
|---|---|
| Survey 1 | 1320.8060315 |
| Survey 2 | 1343.7477555 |
| Survey 3 | 1379.8377582 |
| Survey 4 | 1351.8826699 |
| Survey 5 | 1334.0824373 |
| Survey 6 | 1351.5916971 |
| Survey 7 | 1319.7339569 |
| Survey 8 | 1361.2347675 |
| Survey 9 | 1486.5461614 |
| Survey 10 | 1338.4223079 |
| Survey 11 | 1362.6725879 |
| Survey 12 | 1320.0249297 |
| Survey 13 | 1349.8924248 |
| Survey 14 | 1344.7776060 |
| Survey 15 | 1304.6414272 |
| Average Fitness Value | 1351.3263013 |
| FIFO Method | 1389.854907 |
| Optimization | 1282.9288430 |

A graph was prepared by comparing the results obtained (Figure 4.3). In the third stage, the sequence prepared by the FIFO method is higher than the average of the survey results, while the highest value in this stage is the survey 9. Furthermore, the difference between the mean fitness value of the survey results and the fitness value of the sequence prepared using optimization was further elucidated. While the average of the survey results is 1351.3263013, the fitness value of the sequence prepared according to optimization is 1282.9288430. In this case, the optimization benefited 5.3% according to survey results. Furthermore, the optimization provided a layer of 8.3% relative to the FIFO method.

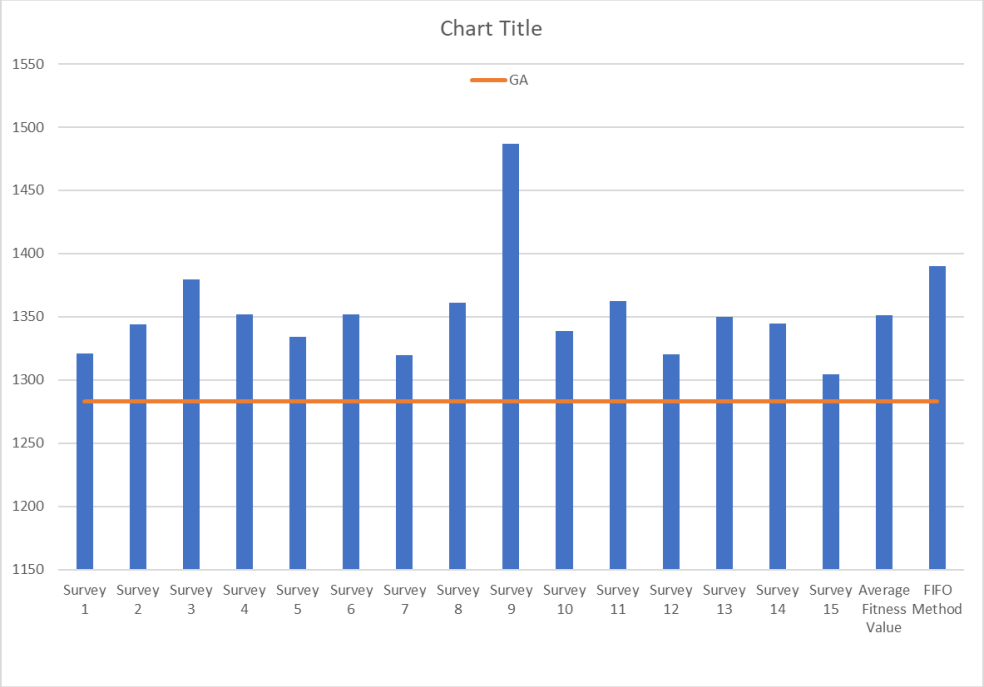


*Figure 4.3.* Comparison of the Results in Third Stage

In this case, the difference between fitness values obtained by sequencing with FIFO method and sequencing by optimization was decreased. However, according to the survey results, the benefit of the optimization increased significantly compared to previous stages. In the previous stage, it was observed that as the number of materials increased, it was difficult for people to arrange and transportation costs increased. At this stage, it has become difficult for people to find the most appropriate arrangement when the workspace areas have been moved, and transportation costs have increased significantly. In such cases, a storage layout using the optimization will significantly reduce transportation costs and lost time.

In addition, the algorithm created will act as an intermediary between the transport robots and the planning programs, enabling the robots to automatically transport the materials. In this case, the cost of transporting the material will be reduced to almost zero, thus making a 100% savings from the cost spent for material transportation. Since the robots operate in a rechargeable way, the only cost of the robots is the cost

of electricity needed to charge. This cost is negligible in the construction site environment. In an automated storage system, robots also work at night to prepare materials. In this case, it reduces the waiting period of the workers who will work in the field of work until the material arrives. In this case, the workers who will work in the workspaces do not have to wait for the material and thus, their productivity increases. An autonomous storage area to be created in this way can significantly reduce both cost and time loss on site.

In addition, due to the density of material that occurs in the storage areas when manpower is transported, efforts are made to remove the materials from those areas. As the number of materials increases, human movements are restricted and other materials need to be moved. However, since robots can pass under the pallets where the materials are placed, they can easily reach anywhere in the storage area, allowing the materials to be removed from the storage areas much faster.

# CHAPTER 5

# CONCLUSION

In this part of the research, the study is summarized. The results of the study, discussions and limitations are explained. In addition, future studies are indicated to shed light on this study.

## 5.1. Research Summary

Nowadays, with the increase of high and complex building construction projects, construction sites have shrunk and the arrangement of temporary spaces within the construction site has become important. Nowadays, these arrangements are realized by the field supervisors during the construction phase. However, when it is not planned before and there is no good reaction to the immediate problems, construction costs and construction times increase. Therefore, the arrangement of temporary spaces in the field has become important and new concepts have emerged in relation to these arrangements and wastes formed as a result of these arrangements.

The concept of lean construction is a concept that has emerged to reduce waste generated on site. According to lean principles, it is aimed to reduce waste such as material losses and unnecessary waiting times. For this purpose, studies have been carried out on the placement of temporary areas on the construction site. However, there are very few studies on the location of the storage areas on the construction site, the placement of the materials in the storage areas and the transportation of these materials to the work areas.

In addition, developing robot technology is frequently used in our daily lives. While different robots are used frequently in different sectors, the use of robots on construction sites is very rare. Many distribution and supply companies such as

Amazon provide transportation of materials by using transport robots in central warehouse areas. It is also possible to use these robots in construction sites.

In this research, it is aimed to create an autonomously managed storage area by making studies on how the materials should be placed in the storage areas and how these materials should be transported from the storage areas to the workspaces. In order to solve the distribution problem efficiently, an optimization function has been established. According to this optimization function, material placement layouts of storage areas are created by taking material information, work program and field layout from the currently used BIM models. These layout plans are transferred to the robots, where the robots place the materials according to the layout plan and carry these materials to the work areas according to the work schedules. In this way, it is aimed both to reduce material losses and to reduce the time and cost required to transport the materials.

The optimization was tested by preparing a case study. The case study was conducted in three different ways. Firstly, sequencing was performed according to FIFO method. Then the sequence was made according to the optimization. Finally, placements were made to people from different occupational groups and the results were compared.

### 5.2. Main Results and Discussions

The results and discussions are defined in this chapter.

- While the number of materials and business areas is low, the optimization prepared by the settlement provides little benefit compared to the settlements made by people. As the number of materials and business areas increase, the layout plan prepared with the optimization makes more contributions compared to the settlements prepared by people. When the locations of the business areas changed, the placement made according to the optimization made a significant contribution. In this case, it has been observed that the optimization makes the material placement better.

- The optimization creates a link between robots and BIM-based programs. Thanks to this connection, robots know when and where the materials will go and how they should be placed in storage areas. According to this information, materials are placed and transported appropriately. When robots are used, transport costs are reduced to almost zero.
- Thanks to BIM, since the activities can be monitored and planned on a daily basis, the optimization generates daily layout plans, allowing robots to move according to new plans every day. Since the robots are continuously operable devices, the transport of materials to the work sites is carried out continuously. In this case, the material of the workers is always with them and the waiting times are reduced to zero.

### 5.3. Limitation of The Study

There are some limitations in this study.

Firstly, the shortest distance between two points was calculated while calculating the distance between the storage areas and work areas in the algorithm. However, when calculating this distance, materials must be calculated considering the locations of these routes in order to be transported on the routes within the construction site.

Secondly, the higher the number of materials and the number of business areas, the higher the calculation times. In this case, Neos Solver is used to make the algorithm work faster. The information obtained as a result of the algorithm must be uploaded to Neos Solver system manually. More powerful computers are needed to make calculations faster and automatically.

Finally, the generated optimization function must provide data files that are suitable for the data required by the robots. For this reason, the algorithm must be made compatible with the programming languages used for robots.

## 5.4. Recommendation for Further Studies

The optimization developed in this study can be developed by professional software developers to create an interface between BIM and robots. In addition, according to the optimization, it is assumed that there are no objects in the construction site that prevent any wall and material transportation. In future studies, an algorithm can be created by considering these obstacles. In addition, the working performance of the algorithm was tested on a generated case. This test can also be performed using robots in a real construction site environment. In this case, the more useful the algorithm can be determined by more accurate values.

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# APPENDICES

## A. MATLAB CODING

Firstly, the input file was defined using the “xlsread” command, which is used to read the input file in MATLAB. In the “xlsread” command, first the file name and then which rows and columns selected in the file are defined. The Figure shows that “M” refers to the set of all columns and rows between the H3 and M1000 space in the input file. In addition, the storage area is defined from the read file and it is divided into one-unit grids. These grids are defined in the “P” set. Also, “rectangle” command is used to show areas visually.

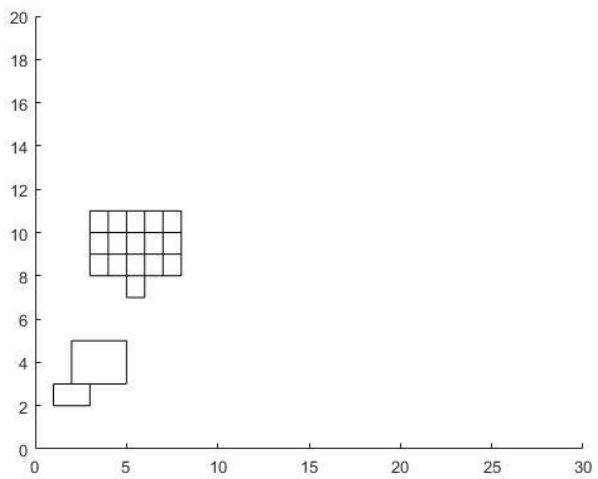
```
M = xlsread('Input','H3:M1000');
```

```
lengthM=5;          %lenght of the storage
widthM=3;           %width of the storage
xCentreM=3;         %x coordinate of the storage
yCentreM=8;         %y coordinate of the storage


satir=1;
for i=1:1:widthM
    for j=1:1:lengthM
    P(satir,:)=[xCentreM+j-1 yCentreM+i-1];
    satir=satir+1;
    end
end
sizeP = size(P);


for i=1:1:sizeP(1,1)
    rectangle('Position', [P(i,1), P(i,2), 1, 1]);

end
```

After that, workspaces were created by using workspace information obtained from the input file. These workspaces are also shown visually by using rectangle command. In the code, “j = 1: 1: sizexCentreW (1)” define that workspaces are defined from first one to last one separately.

```
xCentreW = xlsread('veri','I4:I1000')    %x coordinate of workspaces
yCentreW = xlsread('veri','J4:J1000')    %y coordinate of workspaces
lengthW = xlsread('veri','K4:K1000');    %lenght of workspaces
widthW = xlsread('veri','L4:L1000');     %width of workspaces

for j=1:1:sizexCentreW(1)

        rectangle('Position', [xCentreW(j), yCentreW(j), lengthW(j), widthW(j)])

end
```

As a result of these commands, the storage area and workspaces are defined and these areas are shown visually as output.




The set “M” and “P” was then converted to the matrix by using the “size” command. After that, by using the “recperms” command, a set containing the distance of the elements in the “P” set to workspaces was created and a permutation consisting of this set was created. In this permutation, all the possibilities that the materials can settle have been revealed. The permutation formula was used to calculate the probability of the program only as much as the number of materials, and to shorten the calculation time of the program. The fitness function was constructed by using this permutation set called “A”. “Temp” defines the fitness function. Finally, the minimum value was determined using “min” function. In this way, it was tried to determine the most suitable possibility among all placement possibilities.

```
 a(1,:) = recperms (sizeP(1),1:1:sizeP(1));
for i=1:1:factorial(sizeP(1))-1
    a(i+1,:)= recperms (sizeP(1),a(i,:));
end
mincost=99999999999;
sizeA=size(a);
for i=1:1:sizeA(1)
    temp=0;
    for j=1:1:sizeM(1)
        temp=temp+M(j,3)*distance(M(j,:),P(a(i,j),:));
    end
    if(mincost>temp)
        mincost=temp;
        minloc = a(i,:);
    end
end
```

## B. PHYTON CODING

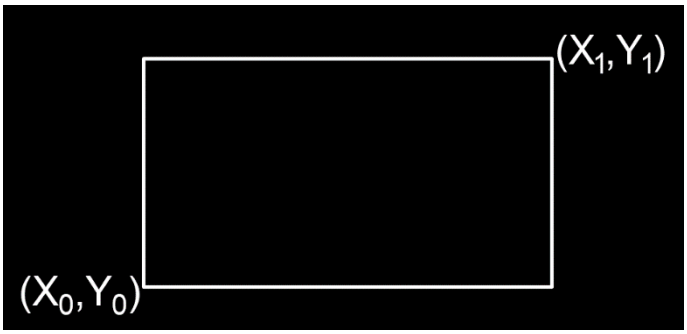
First of all, a Python file is opened in PyCharm and the functions used in the equation which is created to solve algorithm are defined. The “read_file” command is used to read the input data, the “write_file” command is used to write output data, the “read_as_list” command is used to read the data contained in the input file separately, and the “rebuild_tab_text” command is used to recreate input data as appropriate for programing language.

```python
def read_file(save_location):
    with open(save_location, 'r') as f:
        dosya = f.read()
    return dosya


def write_file(string, save_location):
    with open(save_location, 'w') as f:
        f.write(string)


def read_as_list(list_variable):
    if list_variable[len(list_variable) - 1] == '\n':
        list_variable = list_variable[0:len(list_variable) -1]
    list_variable = list_variable.split('\n')
    for i in range(0, len(list_variable)):
        list_variable[i] = list_variable[i].split('\t')
    return list_variable


def rebuild_tab_text(list_variable):
    nrow = len(list_variable)
    for i in range(0, nrow):
        list_variable[i] = '\t'.join(list_variable[i])
    list_variable = '\n'.join(list_variable)
    return list_variable
```

In addition, the “create_grid” command is used to divide the storage area into one-unit grids and calculate the coordinates of each grid separately. Four different data is entered to use “create_grid” command.

```python
def crete_grid(x0, y0, x1, y1):
    location_array = []
    for i in range(x0,x1+1):
        for j in range (y0,y1+1):
            location_array.append([i,j])
    return location_array
```

The first data is the x coordinate of origin of the storage area (x0), the second data is the y coordinate of the same point (y0), the third data is the x coordinate of the point opposite to origin (x1), and the fourth data is the y coordinate of same corner (y1).




Then, input and output files and their file locations are defined.

```
path_input00 = 'D:/tez/files/parameter.txt'
path_output00 = 'D:/tez/files/parameter01.txt'
path_input01 = 'D:/tez/files/deneme.txt'
```

Commands, input and output files, and file locations are defined, a new Python file is opened and the algorithm is started to be created. Firstly, the input file was read using the “read_as_list” command. Figure 3.25 shows the input file. The input file is defined as “data” (Figure 3.26). A sample model was created while coding. In this sample model, there are six different materials and setup cost, transportation cost, and coordinates of the materials are defined. Furthermore, in the sample, the origin of the storage area is defined as (4,2) and the opposite point to origin is defined as (9,6). Accordingly, the length of the storage area is 5 unit and the width of the storage area is 4 unit. Secondly, the material storage area is defined as “location_array”.

```
location_array = crete_grid(4, 2, 9, 6)
```

After the storage area is divided into grids, the workspace coordinates specified in the input file are converted to “(x,y)” form and the column in which these coordinates are specified in the input file is defined.

```
for i in range(0,len(location_array)):

    data[0].append(str(location_array[i][0]) + ',' + str(location_array[i][1]))
    for j in range(1,len(data)):
        xkordinati = int(data[j][6])
        ykordinati = int(data[j][7])
```

Then, the distance of the workspaces to each unit of the storage area was calculated by using the “distance” formula. In addition, transportation cost and setup cost are defined in the input file.

```
distance = math.sqrt((location_array[i][0]-xkordinati)**2 + (location_array[i][1]-ykordinati)**2)
trans_cost =int(data[j][5])
set_cost = int(data[j][4])
```

Then, the fitness function was created and this function was solved. Finally, the fitness values were recorded in the table and printed as an output file.

```
        fitness = set_cost + trans_cost*distance
        data[j].append(str(fitness))
        print(fitness)

malzeme = rebuild_tab_text(data)
write_file(malzeme, path_output00)
```