



A construction project scheduling methodology considering COVID-19 pandemic measures

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ABSTRACT

Introduction: At the beginning of the COVID-19 pandemic, various social measures were taken and various sectors were affected with strict precautions and safety measurements. The construction industry, where numerous employees work together, was affected by these COVID restrictions. The pandemic period typically further delayed the construction contracts. **Methods:** This study addresses the project duration, pandemic risk, and project cost of a construction project case by using both multi-objective genetic algorithm and resource constrained project scheduling techniques, using modeling of COVID-19 infection rate. Finally, the analytic hierarchy process (AHP), a multi-objective technique, is used to obtain an optimal solution using three criteria: project duration, total cost, and pandemic risk value. **Results:** A case study is used for analyzing the outcomes of the pandemic-based modeling, the original schedule of the case study ends in 46 days. Feasible schedules are obtained with durations occurring between 61 to 199 days, the pandemic risks range from 46% to 89%, and the total cost varies from 174,669.8 Turkish Lira (TL) to 186,126.7 TL. Consequently, the most optimal-final solution is obtained Alternative 5 (0.46% pandemic risk, 199 Day (10 workers) with 185,722 TL). **Conclusion:** We conclude that the possible rate of pandemic-related delays can be obtained by using both these techniques and the infection modeling method. Using the COVID-19 infection rate modeling, duration and cost changes are calculated by considering infection risk in construction workers. **Practical Applications:** Using the COVID-19 infection rate modeling, project delays and cost overruns are determined by considering infection risk in construction workers. Optimum worker sizes and delayed construction activities are determined according to the selected solution by using the AHP technique. Expectedly, this study may help determine the construction process while preserving social distances between construction workers during pandemic situations like COVID-19.

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1. Introduction

COVID-19 forced people to find alternative solutions in every sector and to adapt to the new normal, not only in daily routines but also in every aspect of life. Timewise uncertainties of the pandemic and/or the possibility of future pandemics necessitate reviewing and updating business plans accordingly. Specifically economic, sociological, and educational difficulties need to be addressed properly. Alternative conditions and solutions need to be developed to provide continuity in the current processes, ensuring little interruption and minimal difficulties. This study provides

a framework to model possible scheduling updates to comply with measures to COVID-19 infections.

The World Health Organization (WHO) declared “coronavirus disease 2019 (COVID-19)” as a global pandemic on March 11, 2020 (Ranney et al., 2020). This disease has affected most of the sectors worldwide. It causes serious health problems, is potentially fatal, and is highly infectious. According to WHO, the COVID-19 virus spreads primarily through saliva droplets or nasal discharge when an infected person coughs or sneezes. This definition shows that the transmission of the virus depends on direct communication from person to person; indirect contact through solid objects; mucous membranes such as those of the nose, mouth, and eyes from the hands; and occurs when it passes through droplets and possibly dispersed particles between people inside a short-range (Schoen, 2020).

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Social distancing norms, masks, and self-hygiene are extremely important precautions for safety from this disease. Social distancing prevents direct contact between people and also reduces the risk of infected respiratory droplets' transmission (two main mechanisms for respiratory infection; Sun & Zhai, 2020). Social distance becomes more important for people with a high risk of serious chronic disease (Centers for Disease Control and Prevention [CDC], 2020). COVID-19 virus is considered to spread mainly from person to person, especially people who are in close contact (within about six feet) through produced respiratory droplets when an infected person coughs or sneezes (Occupational Safety and Health Administration, 2020b). To apply social or physical distance, people should be kept at least six feet apart both indoors and outdoors (CDC, 2020). And the fewer people you are in contact with, the less likely you are to be an infection risk. Carteni et al. (2021) attempted to specify convenient strategy policies in the COVID-19 crisis given the way the virus is spread through the population. This is a "game of chance" and the less close contact people have with each other, the less likely the spread of the infection (Schoen, 2020). People play a key role in preventing the spread of this disease and necessary measures, such as social distancing have to be taken. COVID-19 has a higher infection rate than seasonal flu (Biggerstaff et al., 2014; Li et al., 2020). Huynh (2020) evaluated the role of cultural viewpoints in applying social distancing rules, highlighting several strategies such as staging and applying cumulative interventions that can work well in the case of influenza pandemics.

The social distance rule looks simple and is one of the most effective ways to protect against the risk of virus exposure, including maintaining a distance of at least six feet between two people (Occupational Safety and Health Administration, 2020a). The basic principles of social distance (1–2 m or 3–6.5 ft), surface cleaning and disinfection, hand washing, and other good hygiene strategies, besides personal measures, building-related supports such as heating, ventilation, and air conditioning (HVAC) system are very important (Guo et al., 2021; Schoen, 2020). The minimum required personal area can be determined depending on the dynamical or static condition of the environment. Ntounis et al. (2020) determined the minimum area of personal space using social distances for both static conditions (i.e., people are sitting, and standing still) and dynamic (locations that people walk freely). Social distance is a personal protective gap to others in social life or outside of work. However, besides during daily life, the disease can also spread at the workplace, school, or in any other environment. Since schools and workplaces are part of the communities in which they are located, the current measures on social life should be extended to these areas (D'angelo et al., 2021). Various measures should be adopted in business life according to pandemic conditions. While planning these interventions, the interaction level of the groups within and with each other should be minimized by constituting smaller groups of employees as well as maintaining social distance (Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a). Responsible people at workplaces must take measures, considering the pandemic conditions to control the environment continuously. For instance, at the workplace, it is necessary to make sure that the workforce applies social distance and applies the relevant requirements to someone who is detected that he/she does not comply with such practices (Reizen & Johnson, 2020). Measures should be taken not only during the work but also at all the meetings. In this context, physical contact and the number of participants at meetings should be limited; crowded meetings should not be organized; attention should be paid to maintaining social distance in meetings; meetings should be held online or via conference call as much as possible and working environments should be revised to pay attention to social distance (Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a). Employers should explore policies and practices

such as flexible workplaces (e.g., working from home) and flexible working hours (e.g., gradual shifts) to increase the physical distance between employees and between employees and others (Occupational Safety and Health Administration, 2020b). Workstations should be adjusted or repositioned and partitions should be set up to create more distances between employees (Occupational Safety and Health Administration, 2020a). Considering the pandemic measures, rearranging the seating places in common resting areas and gradually arranging the breaks help maintain the distances between workers (Occupational Safety and Health Administration, 2020a). Awareness should be generated among the employees for rearrangement of their working style adapting to pandemic conditions. In most cases, systematic rearrangements and precautions by the managers are insufficient to protect against the pandemic. Moreover, workers need to comply with every measurement. In this backdrop, it is extremely important to convey employees' self-compliance with social distance and to reinforce this awareness (The Calgary Construction Association, 2020). Continuous and planned supervision is required after the necessary precautions are taken and the employees are informed, especially on social distance-wearing mask-hygiene. It is important to carry out regular inspections in employee areas to verify that employees are practising physical distance; it is the best way to see if they are working under pandemic conditions (The Calgary Construction Association, 2020).

The construction industry has an important point in terms of both the number of its employees and its share in the national economy. The COVID-19 pandemic currently has a significant impact on the construction industry, as on any other industry (Helm & Bröcker, 2020). The slowdown of the construction industry due to pandemic situations now affects the economy of the countries negatively, resulting in rising unemployment rates. For example, a study on the potential impact of COVID-19 on construction workers reported that the workforce from a construction project could decrease by 30% to 90% due to the spread of COVID-19 (Araya, 2021). Projects were stopped or delayed due to COVID-19 in the United States (ENR, 2020). This has created the possibility of a loss of workforce or discontinued construction projects to affect the economy negatively. Therefore, even under pandemic conditions, construction projects need to be continued as possible. This study is about how to prepare and adopt a work plan and work environment that is compatible with pandemic conditions, especially maintaining the social distance norms in construction workplaces.

2. Research background

In times of pandemics, life can not be as same as that in normal days. We have to continuously deal with new constraints, and this way of life is called the "new normal." In the new normal life, construction sites will also be significantly different from the previous ones (LoBue & Lua-Valencia, 2020). Interactions between construction workers are also important, as the spread of COVID-19 is often driven by human interactions (Araya, 2021). As in every field, minimizing the number of employees or working teams is important in preventing the spread of the virus in the construction sector. Even during "normal" periods, employers have certain obligations related to the health and safety of their employees (LoBue & Lua-Valencia, 2020). In this pandemic period, this responsibility becomes even more important. First, it is necessary to attempt to mitigate the risk by observing social distance to complete the work in a safer way (Construction Scotland, 2020). The risk of virus contamination becomes a priority in occupational safety analyses. To mitigate this risk, several factors are needed to be considered, such as the number of construction workers allowed at the construction

site, the method of these workers to perform their jobs, and the methodology of project managers for estimating the project's workforce (Araya, 2021). In this process, to stop the spread of the virus, the social distance between workers must be redesigned by planning with a lesser workforce at the construction site (Alenezi, 2020).

During this pandemic period, various news on the transmission of the virus at construction sites were reported (Bousquin, 2020). Although construction sites present unique challenges, some companies took measures such as wearing masks and gloves to contain virus spread (Schoen, 2020). However, these measures were considered to be insufficient. Examples include reports of 19 workers who tested positive for COVID-19 and a surge in the number of COVID-19 cases in Austin construction workers and their families in Texas, despite a series of precautions being implemented at a construction site in Maine (LoBue & Lua-Valencia, 2020). If effective measures are not taken at the construction site, news about such virus transmission may continue to appear. In this context, the workforce on construction sites will be affected, and the way construction workers are managed will likely change (Araya, 2021), although these changes and measures will cause slowdown and additional costs. Considering the negative impact of the current COVID-19 pandemic on human life, especially with regard to the lethality rate, the extra costs resulting from the measures adopted should be acceptable.

The importance of social distance and social distance during work has been mentioned in the previous paragraphs. The methodology of social distance to be adopted at the construction site environment was given by compiling and evaluating the sources obtained from various countries' legislatures. These methodologies recommended materials regarding social distance in construction sites that are listed below:

- Practice social distancing while maintaining at least six feet distance from others (Administration, 2020; Centers For Disease Control and Protection, 2021; Parvini, 2020; Public Works Los Angeles County, 2020; The Calgary Construction Association, 2020)
- Maintaining the distance and preventing clutter by making transition markings by the social distance rule (Administration, 2020; Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a; Sağlık Bakanlığı, 2020).
- Reviewing the working methods and orders by considering the social distance rule and making arrangements in accordance with this rule (Parvini, 2020; Sağlık Bakanlığı, 2020).
- Planning and monitoring the interaction of employees with each other during working periods, including breaks and meal breaks, in a way to maintain social distance (Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a; Public Works Los Angeles County, 2020; Sağlık Bakanlığı, 2020)
- Planning to minimize the number of employees at the same time in the work area and to ensure the social distance between employees, and if possible, preferring methods such as rotation or remote work (Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a; Parvini, 2020; Public Works Los Angeles County, 2020; Sağlık Bakanlığı, 2020).
- Keeping the number of people in the office as low as possible (Parvini, 2020; Sağlık Bakanlığı, 2020).
- Arrangement in the dining hall so that the distance between the tables and chairs is at least 1.5 meters (preferably 2 meters). And ensuring that there is at least 1-meter distance between the employees in case of eating in a place other than the cafeteria, preventing them from sharing their meals, and providing food to the employees if possible (Sağlık Bakanlığı, 2020).

- Placement of beds or bunk beds in dormitories by diluting 1.5–2 meters apart. And taking measures to maintain social distance at the entrance and exit of the changing areas (Sağlık Bakanlığı, 2020).
- Ensuring that going to and from the changing rooms is done gradually to reduce the intensity. Determining the number of people to maintain social distance according to the size of the locker area (Sağlık Bakanlığı, 2020).
- For the side by side washbasins, some of them should be closed to use as one full and one empty to maintain social distance and prevent contact (Sağlık Bakanlığı, 2020).
- Do not allow any size gathering and provide a minimum distance of 6 feet when two or more people need to meet. If the process requires / no alternative, provide appropriate personal protective equipment (PPE), limit the interaction to the minimum time required to perform the assigned task, and comply to the maximum extent (Public Works Los Angeles County, 2020)
- If possible, limit the number of workers in small work areas such as construction site lifts, trailers and vehicles, and areas under construction (Centers For Disease Control and Protection, 2021).
- Keep shortest possible face-to-face meetings; Create protocols for virtual meetings as opposed to face-to-face meetings or let people step up the break time to reduce the density in break rooms (Administration, 2020; LoBue & Lua-Valencia, 2020; Public Works Los Angeles County, 2020).
- Consider how to develop a new workplace culture that keeps employee morale strong, even when you give up physical intimacy between colleagues in public areas (Public Works Los Angeles County, 2020).
- Social distance should be provided in the form of sitting in areas where there is a high risk of epidemics, such as working and resting, dining halls, employees' breaks and meal breaks, social facilities, and transportation should be arranged so that this seating arrangement is provided (Aile Çalışma ve Sosyal Güvenlik Bakanlığı, 2020a, 2020b; Chamber of Architects-Istanbul Branch, 2020).
- Daily disinfection of public areas will be provided (Chamber of Architects-Istanbul Branch, 2020).
- Consider the health and safety of those on the field, especially in the light of social distancing measures (Cox et al., 2020).

In an article, a disaster recovery model is developed that can be used in cases such as the COVID-19 epidemic in the construction industry, the following advice are also recommended to give priority to work tasks; having a communication plan (e.g., for employees, customers, vendors, public and media); having prevention strategies; having an emergency response checklist; identifying potential threats, vulnerabilities and risks; periodically backing up data both online and off-site; performing routine testing of disaster probabilities; arranging for off-site work, and being insured (Sihombing, 2020). The pandemic process has negatively affected construction projects. Few construction companies had to stop their project due to the pandemic, causing various delays. Alenezi (2020) compiled the main causes of delays in construction projects in Kuwait during COVID-19, the 17 delay factors collected from the literature review emerged as delay in payments to the contractor, delay in the approval of the completed work, and delay in giving instructions by consultants. Lack of coordination and lack of execution of the works are the main reasons for these delays. Effective measures to be taken while taking pandemic measures should be evaluated from every angle and deficiencies or issues to be developed should be addressed holistically. This study aims

to decrease such delays by showing that construction projects can also be continued under pandemic conditions.

3. Case study and description of its network and activities

In this study, a case study is borrowed from Stumpf's (2000) delay analysis study for the construction of a house with a garage. Some minimal additions are made to the base case study such as approximated quantities are calculated assuming that the flat area of the structure is 150 square meters on a 225 square meter land. And the land is supposed a worker area, since each worker may travel all over the land to acquire equipment and materials and also have a break in the area. Man-hour values and unit prices are taken from various local resources such as (Akçali, 2020; Kuruoğlu & Bayoğlu, 2001). And international resources and standards (CSI, 2020; Page, 1977) are used to standardize the given activity names in a simple case. Table 1 lists the activity names, activities' relationships, and other required data for constituting a schedule. Besides, indirect costs have to be assigned to include general costs such as electricity, water usage, and security services. This project's indirect cost is considered as 5% of the total cost of the project (Bilir & Güranlı, 2015).

There are 21 activities defined in the schedule. Activities 18–21 are specifically processed for the garage section. The remaining activities are the main building-related activities. In Akçali's (2020) study, the equipment and their usages and the amounts of materials are elaborated. Besides, the minimum number of workers are included in the analyses with their hourly costs and time spendings. In the case of the number of workers is fall behind that limit, the activity is not feasible within reasonable limits. Table 1 shows the information on 21 activities, as well as the minimum and the maximum number of workers. Four exception activities include no labor limit ranges. For instance, excavation activity includes only one excavator and its labor size is not adjusted during the optimization analysis.

3.1. Worker capacity calculation

Determination of the total worker number in the workplace is a key challenge. Before the COVID-19 pandemic, there is no generally known legal regulation for limiting the worker number in a construction place. After coining the term "social distance", some legal regulations were proposed and entered into effect for limiting

between workers with varying distances (Centers for Disease Control and Prevention, 2020; Occupational Safety and Health Administration, 2020a; Parvini, 2020; Public Works Los Angeles Country, 2020; The Calgary Construction Association, 2020).

Finally, there is a geometrical problem appears for determining worker numbers with given social distances. In this study, a Monte-Carlo simulation technique is applied for determining worker limits by assuming different social distance parameters that are applied at construction places. The main principle is the workers are spreading randomly with preserving the social distance. Fig. 1 shows four different cases for determining the labor limits for different social distances in 15*15 meters field.

In Fig. 1, four sample graphics show random worker locations in a field under the assumption of different social distance variables. Each graphics' x-y axes represent the width and length of the working space respectively. Circle centers represent worker locations and the diameters represent the social distance lengths. The main principle of locating the circles, filling the field with a maximum number of randomly-located circles without each circle intersecting with other ones. After there is no available space for the next circle placement, the filling process is completed and the total circles in the field are calculated. This process is iterated 25 times to generate the average value for each social distance. Fig. 2 shows these average worker-count with changing of social distance. It also shows the maximum possible number of workers to be used in scheduling procedures. This procedure can be detailed into smaller scales and different geometries.

The equation that gives the maximum number of workers on the area was obtained from the curve fitting process shown in Fig. 2.

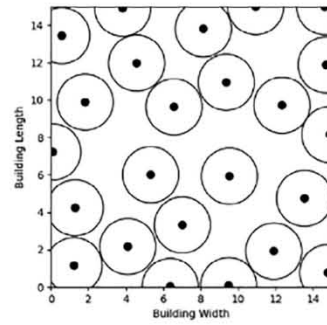
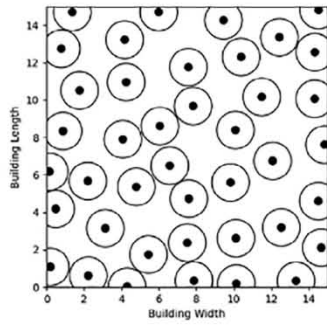
3.2. Infection risk calculation

After the COVID-19 pandemic has erupted, there are various studies appeared that model pandemic infections in processing facilities and their effect on production rate. In the construction case, there is a lack of modeling infections and their effects. Before the COVID-19, there are various pandemic and infection modeling was proposed (Riley et al., 1978; Wells, 1955). In this study, the pandemic risk modeling of Sun and Zhai's (2020) study is applied. Equation (1) shows the modeling of pandemic risk.

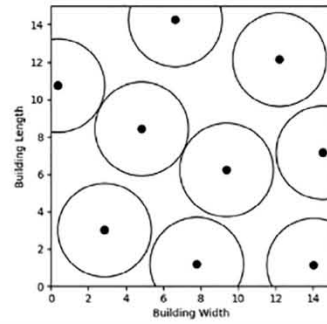
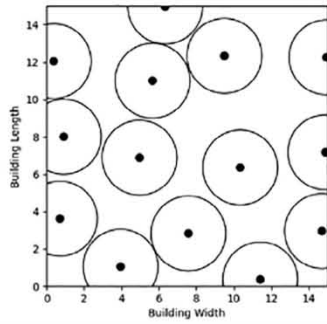
$$P_i = C/S = 1 - \exp(-P_d * (B * q * p * t) / (Q * E_z / N)) \tag{1}$$

Table 1
Activities and their essential values.

ID	Names	Predecessor	Quantity	Manhour	Worker Hour Cost (TL)	Material Unit Cost (TL)	Min. Worker	Max. Worker
1	Excavation	–	45.00	0.30	227.00	0.00	1	1
2	Concrete Forming	1	10.00	3.50	18.45	8.72	3	5
3	Reinforcement Bars	2	2.68	115.00	18.45	2827.12	4	15
4	Concrete Finishing	3	30.00	9.37	18.45	181.52	2	15
5	Brick Masonry	4	200.00	2.01	18.45	25.26	2	7
6	Roof Framing	5	10.00	40.00	18.45	1519.61	2	25
7	Clay Roof Tiles	6	101.98	0.60	18.45	75.20	2	10
8	Select Finishes	–	40.00	1.00	18.45	0.00	1	1
9	Interior Plaster	15	360.00	2.07	18.45	3.37	3	10
10	Exterior Plaster	15	195.00	2.07	18.45	3.37	3	10
11	Wood Windows	9,10	264.00	0.40	18.45	3.55	2	5
12	Wall Tiling	14	45.00	3.49	18.45	83.85	2	20
13	Floor Tiling	14	135.00	4.70	18.45	25.38	2	20
14	Interior Painting	11	450.00	1.00	18.45	4.32	2	20
15	Temporary Scaffolding	7,8	214.50	0.56	18.45	4.68	2	10
16	Clean-Up	12,13,21	150.00	1.00	18.45	1.00	1	6
17	Delivery Garage Doors	–	1.00	1.00	18.45	5000.00	1	1
18	Brick Masonry-Garage	4	100.00	2.01	18.45	25.26	2	10
19	Roof Framing-Garage	18	5.00	40.00	18.45	1519.61	2	10
20	Clay Roof Tiles-Garage	19	50.99	0.60	18.45	75.20	2	10
21	Garage Doors	17,20	1.00	30.00	30.00	0.00	5	5



(a) Social distance equals to 2 meters (b) Social distance equals to 3 meters



(c) Social distance equals to 4 meters (d) Social distance equals to 5 meters

Fig. 1. Random worker locations with different social distances.

P_1 value equals to the probability of infection risk, C and S parameters are the number of infected and susceptible cases. P_d is the social distance index that depends on social distances between workers. B is the initial infection rate that is taken as % 10. q denotes quantum generation rate in this context, quantum is defined as the number of required droplets for infecting other individuals (Wells, 1934). And the quantum generation rate can be obtained with only reverse calculations (Furuya et al., 2009). In that study, it is taken as 0.238 quantum/s from (Sun & Zhai, 2020). p is susceptible individuals' pulmonary ventilation rate. The pulmonary ventilation rate depends on the effort of susceptible individuals. It can be taken 0.3 m³/h when an individual make

indoor activity. The parameter t is the period that the group worked together. Q is ventilation rate of working space that calculated as 2.625 m³/s by assuming the air in the working space is cycled 12 times in one hour. the E_z parameter is the ventilation coefficient of the workplace taken as 1. N is the number of passengers and/or occupants. However in this case it can be defined as total workers in the place.

The P_d parameter depends on social distances between workers and can be obtained from the data given in Fig. 2. In this case, the input is the total worker number in the specified area, and the output is the average distance between workers. Fig. 3 is an inverse graph of Fig. 2 and gives the value of average social distances

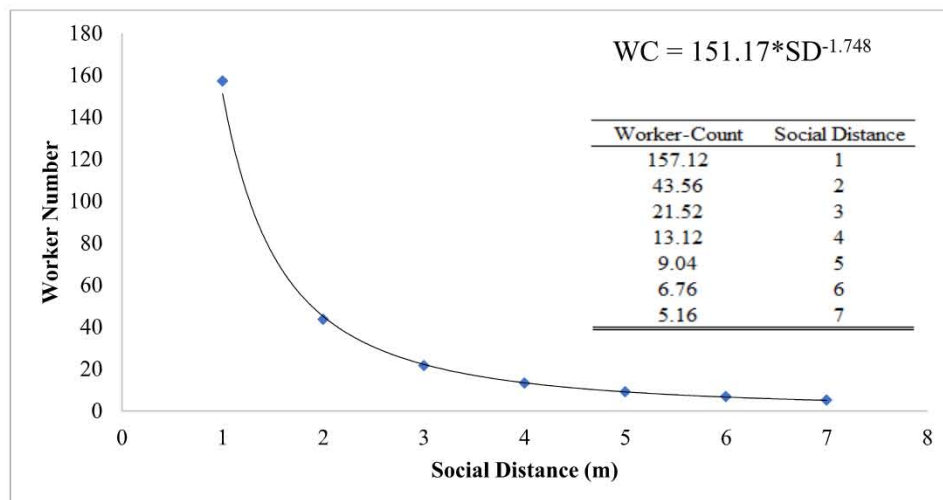


Fig. 2. The upper limit of worker numbers with changing of social distances.

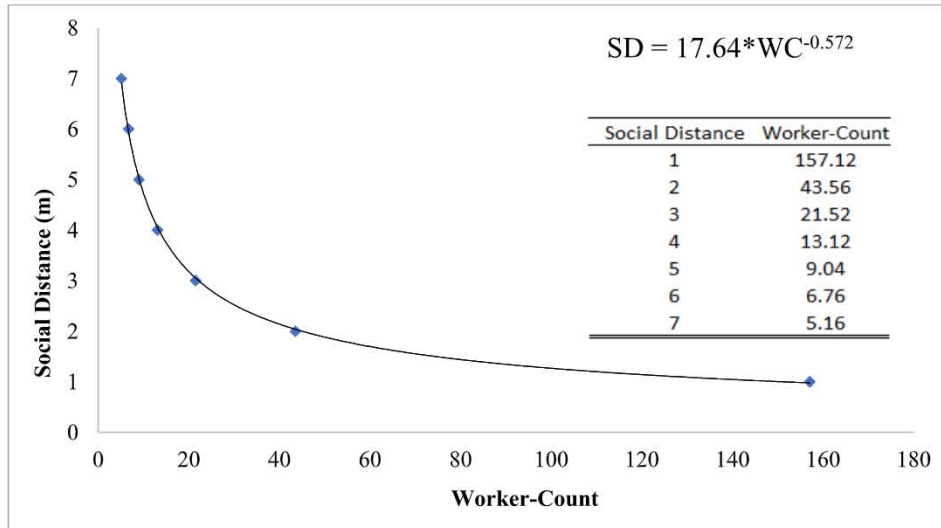


Fig. 3. Average social distance values depending on the worker number.

between workers depending on the number of workers in the space.

Depending on the construction step, the number of workers is variable during the construction. And for each day, the crew size is estimated to obtain average social distances between workers. The social distance parameter can be easily obtained from the results of the aforesaid Monte-Carlo simulation technique. After social distances are obtained from the worker number, P_d can be calculated by using Eq. (2) which was obtained with empirical modeling by Sun and Zhai (2020).

$$P_d = (-18.19 * \ln(d) + 43.276) / 100 \tag{2}$$

In Eq. (2), d denotes the social distance parameter that depends on the worker number as shown in Fig. 3. Obtaining P_d depends on the geometry of working area.

3.3. Problem formulation

This study aims to find scheduling solutions with minimizing project duration, project cost, and the probability of infection risk. Pandemic-oriented precautions are the main constraints of scheduling. Especially, due to regal regulations, the number of construction labor-size is limited, and this situation results in project delays. This study offers a methodology that possible pandemic-oriented delays are determined and minimized. The schedule in Table 1 is made without any pandemic-oriented constraints to constitute a baseline schedule for determining forthcoming delays. In the pandemic case, the worker constraints are determined and defined inside the methodology. For each day, the pandemic risk probability is calculated using Equation (1). And equation 3 is used to calculate the probability of infection risk that occurred at least one day during the project. T is the delayed project duration, i represents each day in the project. And finally P_{ii} is pandemic risk probability that calculated from Eq. (1).

$$Pandemie Risk = 1 - \prod_{i=1}^T (1 - P_{ii}) \tag{3}$$

The project cost is calculated by summing up each day's daily direct and indirect costs. Direct costs are strictly related to construction tasks and can be classified into labor and material costs. Hourly labor costs for activities are given in Table 1, daily expenditures for workers depend on the daily employment period and

daily total worker allocation. The material costs are the cost of material consumptions on activities. It is assumed that each days' processing speeds are constant. After the activity durations are obtained from manhours and worker numbers, each days' material costs are equal to the division of total material costs for an activity and the activity duration.

The project duration is calculated by conducting resource-constrained project scheduling (RCPSP) procedures with considering labor limits throughout the project. There are two kinds of labor limits that are defined for the scheduling. The first one is the overall worker limit which is the total worker allowance in the construction place. The second one is the labor limits that are defined for each activity as shown in Table 1. Random integer values between those limits are generated during the optimization analysis.

3.4. The use of resource-constrained project scheduling concept

During the scheduling of the project, labor-related constraints, such as total worker demands can be larger than total labor supplies to the project. In such a case, some activities have to be postponed to keep the daily worker demands under limits. Under these circumstances, the postponed activities are waited to start till one of the active activities ended. By using RCPSP procedures, the algorithm selects the initiated and postponed activities. There are various heuristic and deterministic methodologies that were proposed to schedule resource-constrained projects (Brucker et al., 1999; Klein, 1999). Fig. 4 shows the network and initial steps of extension of the concerned schedule by using RCPSP procedures. In the network, activities are shown by their numbers, resource requirements, and durations. There is one type of resource used in the project. The resource supply equals four units per day. The first and the last activities are dummy activities. In the schemes of the initial steps, this resource level is shown with a dashed horizontal line. These four steps represent the first four activity arrangements to re-schedule to conduct the project within this resource limit. Normally, activities 2, 3, 8, and 9 may start at the beginning of the project. However, as seen in step 4, activity 8 was postponed. As a result, the project duration is increased to 22 days from 18 days.

Within heuristic and meta-heuristic algorithms, the proximity of activities is used to sort the activities by their importance. In

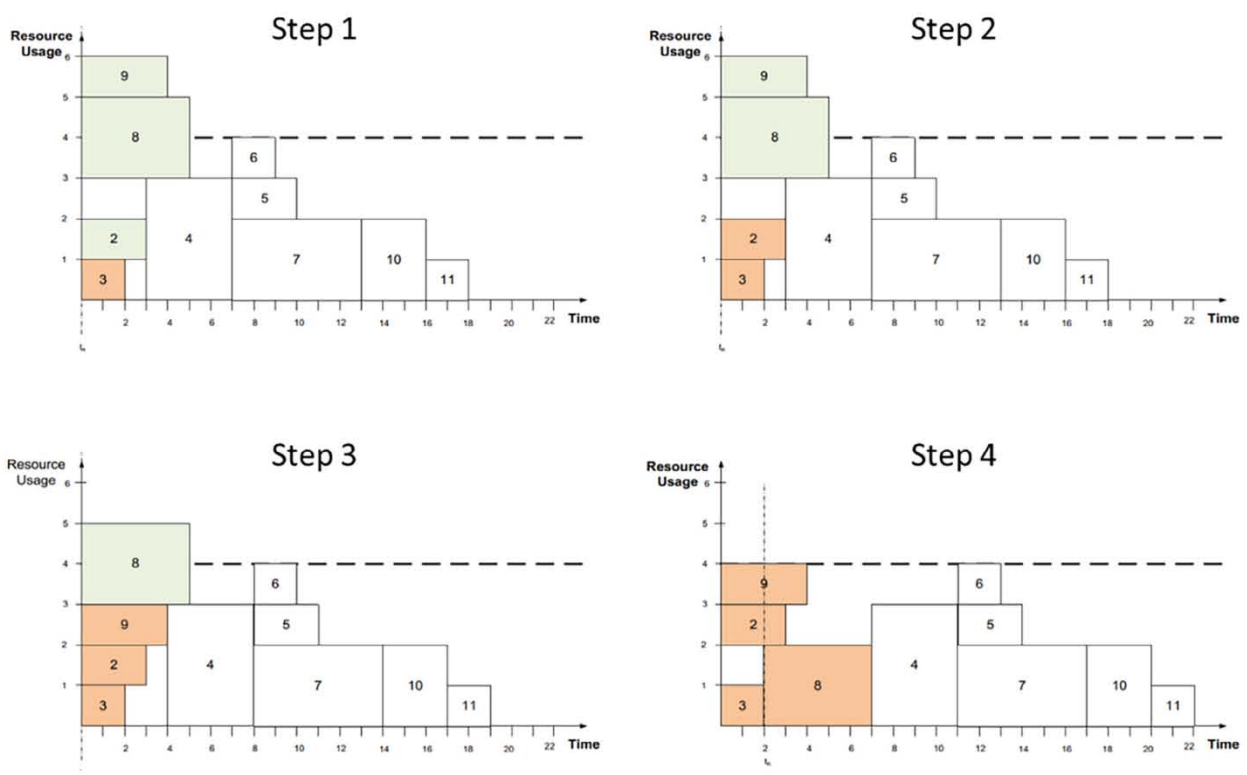
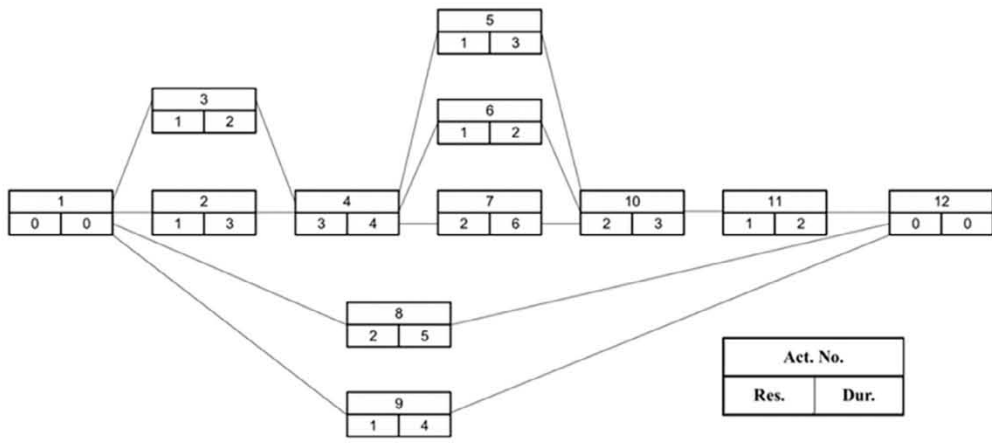


Fig. 4. The first parallel scheduling steps for a sample network (Source: Klein, 1999).

heuristic rules, various heuristic rules are proposed to use schedules' parameters (e.g., activities' late starts or total floats). When a conflict between activities occurs, the activities with higher proximities are selected to be initiated (e.g., activities with larger late start values or smaller total floats). In meta-heuristic algorithms, optimum proximities are searched to minimize total delayed project duration. Fastness and simplicity are the main advantages of heuristic algorithms is. Heuristic algorithms can show lower performance than meta-heuristic algorithms.

Serial and parallel scheduling schemes are frequently along with heuristic and metaheuristic algorithms. These schemes are extensively explained by Kolisch (1996). Various studies have been compared heuristic rules and these scheduling schemes (Klein, 1999; Kolisch, 1996; Schirmer, 2001). From these studies, the parallel scheduling scheme shows better performance than the serial

scheduling scheme. Hence, this study applies the parallel scheduling scheme to handle resource constraints.

In this study, the genetic algorithm is used to search for optimum solutions. The fitness function calculates project duration (using RCPS techniques), total cost (summing up daily cost values day by day), and the infection risk probability (using equations (1), 2, and 3). The network of the schedule and other data from Table 1 is static that does not vary throughout the analysis. There is one input vector that has to be defined and includes a proximity vector (used for resource constraint project scheduling) and worker numbers (used for generating activity durations). In this case, there are 21 activities so that, 21 proximity values and 21 worker size variables are required to constitute the fitness function's input vector. The vector includes 42 variables. The output of the fitness function includes three variables. Genetic algorithm searched solutions to

minimize each of these three outputs at the same time. A multi-objective genetic algorithm is a type of algorithm to minimize these objectives at the same time.

3.5. Multi-objective genetic algorithm

The genetic algorithm is a widely used meta-heuristic algorithm that mimics natural evolutions by computationally acquiring its' definitions and mechanisms. Population, member, gene, offspring are the adopted terms and genetic algorithm's basic definitions. Cross-over and mutation mechanisms are the two main mechanisms in nature as well as the most two important operations in genetic algorithms. By using the cross-over operation, a new offspring is produced by merging two parents' genes. Mutation operation is used for randomly changing the genetic structure of individuals. By using the mutation operation, the diversity of the population increases.

The concept of the genetic algorithm was coined by John Holland (1975). After more than a decade, this algorithm is preferred for various engineering applications (Goldberg, 2006). The algorithm was modified by adding various features. Deb et al. (2002) developed an upgraded algorithm and named NSGA-II in multi-objective solutions. In this study, MATLAB's genetic algorithm toolbox is used to perform multi-objective optimization.

The Pareto-Front is an important concept in multi-objective algorithms. Fig. 5 shows a sample Pareto front plot of a two-objective optimization. The two objectives are contradictory variables that one of them increases while the other one decreases. And also, there is a trade-off between solutions that emerged.

The main outcome of multi-objective algorithms is >1 optimum solution may occur. Pareto-front is a subset of the population that includes the best solutions which have the best scores in all objectives. One of them must be selected to operate in the practice optimization analysis.

Fig. 6 shows a flowchart of generic multi-objective genetic algorithm cycles. Initially, the population is generated with random numbers. Then based on these numbers, initial fitness values are calculated. Then, the loop of the algorithm starts. To terminate the loop, several termination criteria, including maximum computing time and converging of the optimum values are defined. Generating Pareto front, conducting cross-over, and mutation operation are three main steps during the computation. Each cycle in the loop represents a generation, cross-over operation is conducted on superior members to generate the successor member for the next generation. After the mutation operation fitness values are determined for the new members.

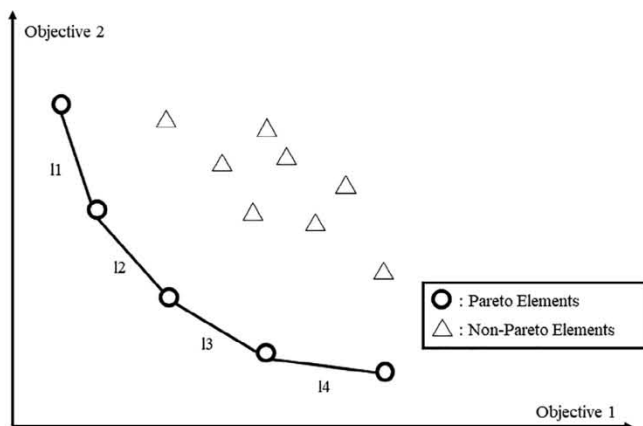


Fig. 5. A sample Pareto Front for Two Objectives.

3.6. Multi-criteria decision making analysis

The optimization provides us a set of optimal solutions; however, only one solution is needed to arrange the schedule by using it. One of the multiple criteria decision-making methods can be used to obtain the optimal-final value within this set. There are three objectives in the optimization. And in multi-criteria decision-making methods, decision-makers (experts in their fields) use the objectives as criteria and alternatives as Pareto-front solutions in accordance with the structure to be solved. Then, we aimed to find the most optimal solution among more than one criterion. In other words, we can specify Multi-Criteria Decision Making (MCDM) as a tool in which the best choice is determined based on the criteria set. In this study, Analytical Hierarchy Process (AHP), which is a multi-criteria decision-making method, is used. Decision-makers can also make decisions by using another MCDM method or using more than one criterion decision-making method at the same time.

The AHP method was developed by Saaty in the 1970s to assist in the decision-making process. The application of the method consists of several stages. The steps of the AHP method with their adaptation to this study are given as follows (Saaty, 1990; Saaty & Kearns, 1985).

- Determination of purpose: In this study, an optimum schedule is obtained within the Pareto set.
- Determining the hierarchical structure in terms of understandability and ease of application (The objectives of the optimizations are the criteria of the AHP method).
- Making binary comparisons for each of the lower levels by experts using Table 2 (a pairwise comparison is built for whole objectives).
- Calculation of priority points (synthesis-normalization). Hierarchical synthesis is used according to the weights of the criteria.
- Calculation of the consistency value (CR). The consistency index is calculated after all pairwise comparisons are made. The consistency ratio (CR) is calculated with the help of the equations in (4) and (5). CI stands for consistency index and RI stands for randomness indicator, λ_{max} stands for the eigenvector, and n stands for the matrix size.

$$CI = (\lambda_{max} - n) / (n - 1) \tag{4}$$

$$CR = CI / RI \tag{5}$$

The acceptability is checked by taking the appropriate value in Table 3 and the CI consistency ratio (CR). It is accepted if the CR does not >0.10. If it is >0.10, a discrepancy occurs, and judgments are reviewed and adjusted to obtain a consistent matrix.

- Determination of the priority values according to the CR value is generated. At this stage, the priority value of each alternative is given separately with the sum of the products of the weight value of each criterion and the importance of the alternatives according to the criteria.

4. Analysis and the results

Table 1 provides the complete data. First, a schedule is made without effects of pandemical outcomes. The baseline schedule is shown in Table 6. The project duration equals 46 days. To approach this duration, the project's worker size is considered as maximum labor limits given in Table 1. Activity durations are calculated by using these man-hours and maximum labor limits. The early start and early finish values are calculated by forward-scheduling, programmed in MATLAB software.

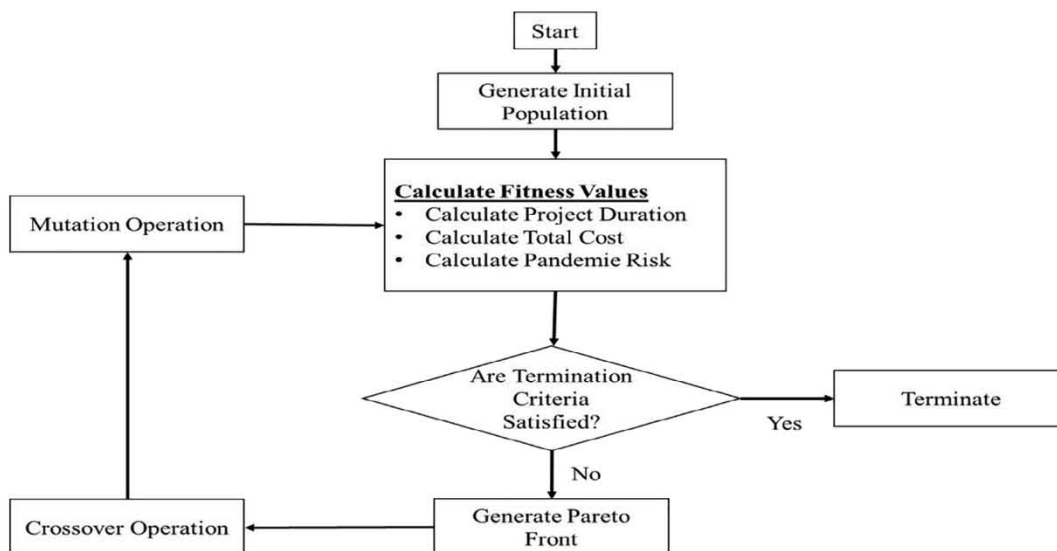


Fig. 6. Flowchart of a Generic Multi-Objective GA.

Table 2
The scale of Relative Importance (Saaty & Kearns, 1985).

Important value	Definition	Explanation
1	Equally preferred	Two activities contribute equally to the objective.
3	Moderately preferred	Experience and judgment slightly favor one activity over another.
5	Strongly preferred	Experience and judgment strongly favor one activity over another.
7	Very strongly preferred	Activity is strongly favored and its dominance is demonstrated in practice.
9	Extremely preferred	The evidence favoring one activity over another is of the highest possible order of affirmation.
2, 4, 6, 8,	Intermediate values between the two adjacent judgments	When compromise is needed.

Table 3
Random consistency (RI) (Saaty & Kearns, 1985).

Size of matrix	1	2	3	4	5	6	7	8	9	10
Random consistency	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

For the analysis, four different worker limits are supposed. These limits are 10, 15, 20, and 25 workers. With using those four limits, four different optimization runs are conducted. And four different sets of optimization results are obtained. The important point is maximum workers in Table 1 have to be equalized to the project’s maximum limit because excessive activity’s labor limit to the maximum labour limit of the project is not allowed. Besides, the minimum limit has to be equal to or lower than the maximum limits. If a project’s labor limit equals 10, the whole of activities’ maximum worker number has to be <10. Otherwise, these individual activities may not execute due to the regulated labor limits. For instance, although in Table 1, the “Reinforcement Bars-Foundation” activity’s maximum labor size was given as 15, it needs to be reduced to 10 to execute this activity.

A three-objective multi-objective genetic algorithm is applied for searching for optimum solutions within each of these scenarios. After the optimization, a tri-axial Pareto front is obtained. Fig. 7 shows the four graphs of these scenarios of the different labor limits.

105 optimum solutions appeared in each Pareto Front of 10, 15, 20, and 25 worker-limits. The results of optimum solutions are

plotted on four different graphs. Fig. 7 exhibits four 3-D Pareto front plots on the three axes for different labor limits. Each point represents different projects that have different project durations, pandemic risks, and project costs. From these results, the optimum project durations differ from 61 to 199 days, the pandemic risks differ from 46% to 89% and the total cost differs from 174,669.8 TL to 186,126.7 TL. To compare all of these conditions, the projection of the Pareto front on project cost and pandemic risk axes is given in Fig. 8.

In this study, three criteria were determined as pandemic risk, time, and cost. Since there are three criteria, the RI value was taken as 0.58 (Table 3). Alternatives were taken from the Pareto set. The Pareto set consists of 105 values, but not all values have been selected because some values are close to each other. Five alternatives were selected based on equally spaced risk percentages (Table 4). Since there are five alternatives, the RI value was taken as 1.12 (Table 3) for analyzing alternatives. The information for these alternatives and the specified criteria are given in following Table 4.

After this analysis, Alternative 5 was revealed as the most optimal-final solution. Depending on the high fatality rate of the

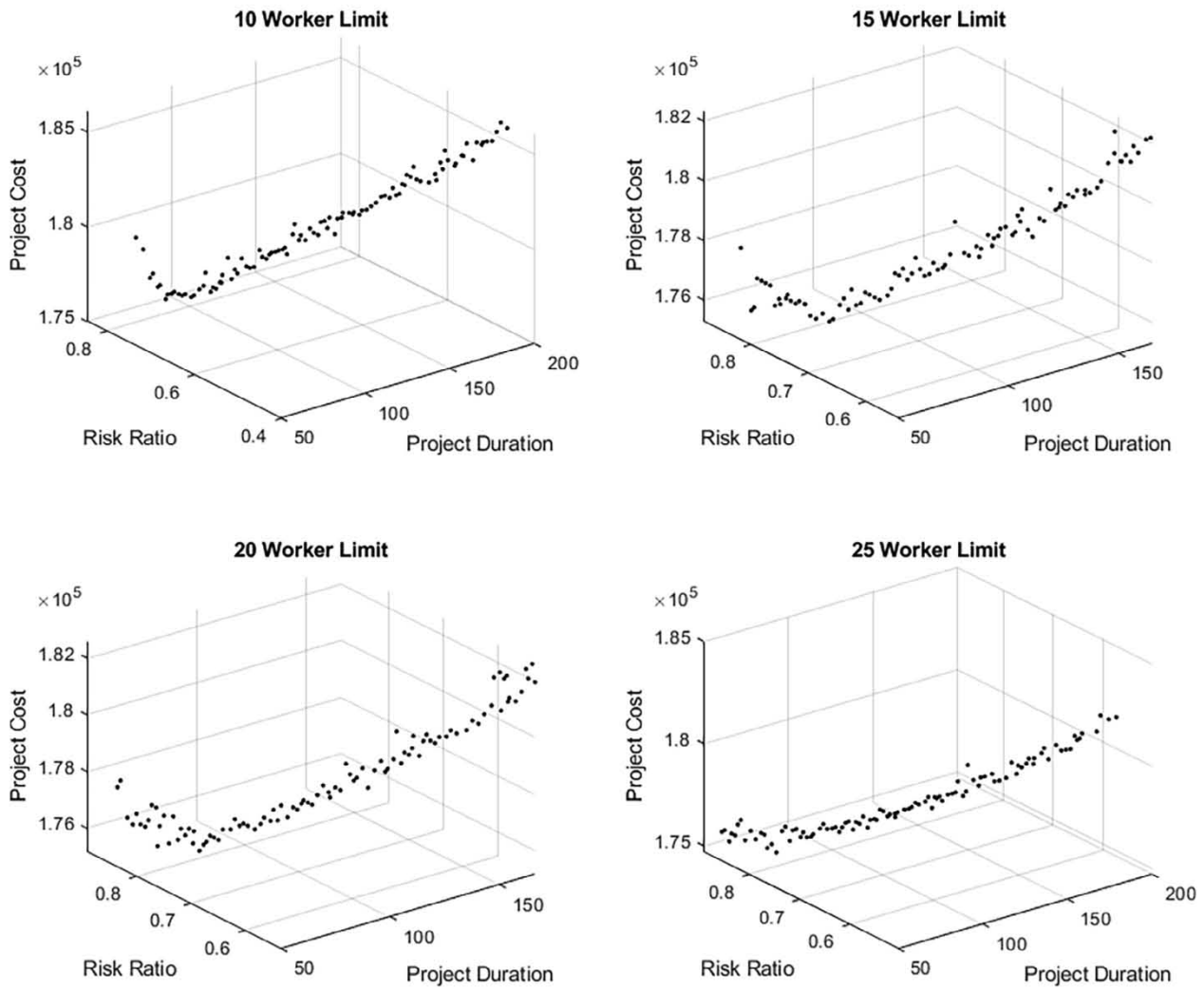


Fig. 7. Pareto results of different labor limits.

COVID-19 pandemic, pandemic risk values' level of importance is considered as the highest value by decision-makers. In case another pandemic with a lower fatality risk occurs, the weight of the pandemic-risk parameter can be decreased. Resultantly, a different optimum schedule can be obtained. Table 5 shows an ordering of selected alternatives from equally spaced risk percentages.

Table 6 shows the start and end times of the activities of Alternative 5. Table 6 also shows its comparison with the pandemic situation. The schedule is extended due to not only activity extensions but also limits of total workers affect extra delays in the construction project. Table 6 demonstrates that the starting times of activities 10, 15, and 18 can be seen as postponed. For

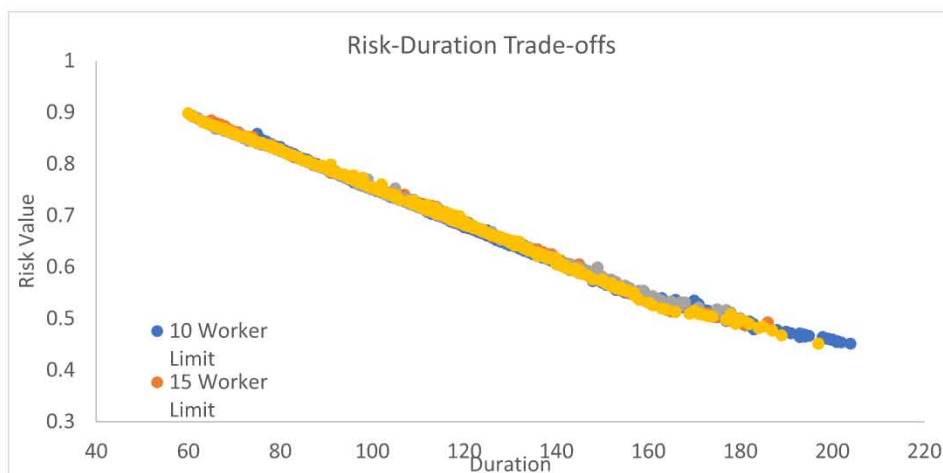


Fig. 8. Comparison of four worker condition's Pareto Front projections.

Table 4
Alternatives for AHP Classification.

Alternatives	Risk (%)	Duration (Day)	Cost (Turkish Lira)	Cost Difference
Alternative 1	0.86	70 (25 worker)	175,562.4	+0 TL
Alternative 2	0.76	98 (20 worker)	176,272.2	+709.72 TL
Alternative 3	0.66	125 (15 worker)	178,522.2	+2,959.715
Alternative 4	0.56	156 (10 worker)	181,991.1	+6,428.63 TL
Alternative 5	0.46	199 (10 worker)	185,722	+10,159.56 TL

Table 5
AHP Results.

Criteria	Level of importance	Ranking
Risk	0.648	1
Duration	0.122	3
Cost	0.230	2
Consistency ratio: 0.006 (CR < 0,1)		
Risk Criterion	Level of importance	Ranking
Alternative 1	0.062	5
Alternative 2	0.099	4
Alternative 3	0.161	3
Alternative 4	0.262	2
Alternative 5	0.416	1
Consistency ratio: 0,026 (CR < 0,1)		
Duration Criterion	Level of importance	Ranking
Alternative 1	0.412	1
Alternative 2	0.258	2
Alternative 3	0.159	3
Alternative 4	0.109	4
Alternative 5	0.062	5
Consistency ratio: 0,056 (CR < 0,1)		
Cost Criterion	Level of importance	Ranking
Alternative 1	0.337	1
Alternative 2	0.258	2
Alternative 3	0.182	3
Alternative 4	0.127	4
Alternative 5	0.095	5
Consistency ratio: 0,024 (CR < 0,1)		
Decision	Level of importance	Ranking
Alternative 1	0.168	3
Alternative 2	0.155	5
Alternative 3	0.166	4
Alternative 4	0.212	2
Alternative 5	0.299	1

instance, according to the network of the schedule, activities 9 and 10 should be started at the same time; however, activity 10 is started on the 121 st day which is in the pandemic case.

Table 6
Baseline schedule without pandemic effects.

Activity name	Duration	Early start	Early finish	Duration in pandemic	Start day in Pandemic	Finish day in pandemic
Excavation	2	0	2	2	0	2
Concrete Forming	1	2	3	2	2	4
Reinforcement Bars	3	3	6	10	4	14
Concrete Finishing	3	6	9	9	14	23
Brick Masonry	8	9	17	26	23	49
Roof Framing	2	17	19	25	49	74
Clay Roof Tiles	1	19	20	2	74	76
Select Finishes	5	0	5	5	0	5
Interior Plaster	10	22	32	32	89	121
Exterior Plaster	6	22	28	7	121	128
Wood Windows	3	32	35	5	128	133
Wall Tiling	1	38	39	5	152	157
Floor Tiling	4	38	42	40	152	192
Interior Painting	3	35	38	19	133	152
Temporary Scaffolding	2	20	22	3	86	89
Clean-Up	4	42	46	7	192	199
Delivery Garage Doors	1	0	1	1	0	1
Brick Masonry-Garage	3	9	12	3	76	79
Roof Framing-Garage	3	12	15	5	79	84
Clay Roof Tiles-Garage	1	15	16	1	84	85
Garage Doors	1	16	17	1	85	86

5. Conclusion

Resource-constrained project scheduling and multi-objective genetic algorithms are extensively employed in construction management studies. After the eruption of COVID-19, a need has arisen to model the labor limits and their effect on project results. Various studies are conducted to model COVID-19 spreading in various social areas (e.g., Sun & Zhai, 2020). By using these infection modeling and resource-constrained project scheduling techniques, alternative schedules are searched that satisfy the possible safety requirements.

This study complies with current models on infection spreading and also optimization and decision-making techniques to find optimum resource allocation and scheduling alternatives. So that this study fills a gap that modeling the effects of the COVID-19 pandemic on construction projects. This study can be a reference regarding how construction workers can work in compliance with social distance in the event of a pandemic caused by infectious diseases such as COVID-19. Continuing the construction works with fewer workers during the pandemic period results in extending the duration of the construction. However, a significant decrease in the transmission rate of a virus such as COVID-19 with a high probability of death or serious illness will tolerate this long period. The serious adverse health effects of a person will not be as important as the extension of the construction period. At the same time, if an incident occurs among workers during construction, construction activities will cease. Workers will remain in quarantine for a certain period. Therefore, the construction period will be prolonged. The compensation of employees or employees who are seriously affected by the virus is also undesirable for the employer. The safe working of employees will be in favor of both the workers and the employer.

Current studies in the field of the construction industry are trying to comply with today's technology. Building information modeling has become very popular in recent years. In the case of safety procedures, construction companies develop safety plans and there are various studies have been made about integrating BIM with safety plans. It is recommended to take into account the results of this study in researches on occupational safety in Building Information Modeling. A monitoring framework can be developed which aims to determine possible risk situations related to the pandemic factors in such projects that project safety plans are integrated with the building information modeling. And to prevent possible infection spreads in that kind of project, managers, and planners can develop necessary plannings and prepare reports for their specific necessary measurements.

The decision-maker can decide among 420 alternative schedules according to her/his priorities. To obtain an optimal solution, AHP has been applied in multi-criteria decision-making methods. In the current study, criteria were determined as contamination risk, duration, and cost. Other criteria such as quality, general job security were not considered in this study. In future studies, a decision can be made by modeling the construction process with different techniques (e.g., Building Information Modeling, Simulation) and applying decision-making techniques considering additional criteria.

Moreover, concerning safety and health work, the significance of the interhuman transmitted virus factor is emphasized and the importance of designing safer construction areas is observed. We highlight that designing safer construction areas will positively affect the construction sector. Since, as in this pandemic event, this step helps decrease the unfinished construction projects' number due to the possibility of pandemic infections.

This study takes into account the project duration, pandemic risk, and project cost factors, and evaluates the related outputs data. Owing to the other factors (e.g, quality, construction safety, environmental factor, productivity and satisfaction) that are not included in the scope of this study, no detailed evaluation is made about these factors. It is suggested to extensively investigate these factors and evaluate them in pairwise relationships. In future studies, it will positively affect the current literature. Another limitation is the case study includes a residential project construction. However, in industrial applications, this study can easily adapt to different types of construction projects (like dams, hospitals, school constructions) to oversee the effects of pandemics and necessary take precautions.

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