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SIMULATION, 5D VISUALIZATION AND OPTIMIZATION OF ON-SHORE WIND FARM CONSTRUCTION

by
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AN ABSTRACT OF THE THESIS OF

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For the past few decades, renewable energy, such as wind power, has been increasingly sought after as an alternative to traditional energy sources which are limited, costly and not environmental-friendly. Although Europe and North America combine for a wind power capacity of 113.6 GW, other regions and countries are far behind and still suffer from electricity shortages.

Particularly, Lebanon has been experiencing electricity cuts for the past thirty years, thus compelled to import it and use noisy and extremely unhealthy generators at very high prices with mediocre quality. The construction of a large on-shore wind farm in Lebanon could be a big step towards resolving the electricity shortage problem. However, the construction of such projects can be very challenging and complex as it offers unique challenges (e.g. challenging topography, absence of an existing road network, impact of high wind speeds, etc.). In order to address these construction complexities, this thesis presents work targeted at efficiently designing and planning the on-shore wind farm construction process, particularly for the region of Marjaayoun, Lebanon.

The solution to the electricity shortage and to the complexities of on-shore wind farm construction is described in details using a simulation model developed in AnyLogic 7.0 software, including 5D visualization (3D animation with time and cost data). The developed work illustrates the different construction stages from topographical surveying to wind turbines erection. The simulation model is tested on a case study in Marjaayoun, Lebanon and is then optimized to minimize the project's construction cost and duration by varying the resource quantities.

The results highlighted the potential of using AnyLogic 7.0 for simulating, visualizing and optimizing complex construction processes offering unique challenges such as those found when constructing on-shore wind farms.

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INTRODUCTION

1.1. Research Background

1.1.1. Overview

1.1.1.1. Wind Power

In the past few decades, renewable energy has been increasingly sought after mainly due to the diminishing quantity of fossil fuel resources and due to the traditional energy sources' negative impact on the environment [1]. Renewable energy is based on the use of natural resources such as wind, solar and hydro power. Wind power has become the leading mechanically-based source of renewable energy [2]. It is harvested through wind turbines which consist of blades connected to a rotor fixed at the top of the turbine's tower. The blades, when exposed to wind, rotate and generate electricity. Wind turbines may vary greatly in size. Small ones can be independently installed to supply energy for specific households, but the main wind power supply is generated by systems of large interconnected wind turbines called wind farms. These can be either on-shore or off-shore. The scope of this research focuses on on-shore wind farms.

The leading countries in cumulative wind power capacity are Germany, Spain and the United States (USA). In fact, Europe and North America capture 75% of the worldwide market as shown in Figure 1. In that area, Asia (excluding the Middle East) comes next with 19.4%, followed by the remaining countries, all together adding up to 4.7%, which clearly shows that several countries, specifically the Middle East, are far behind.

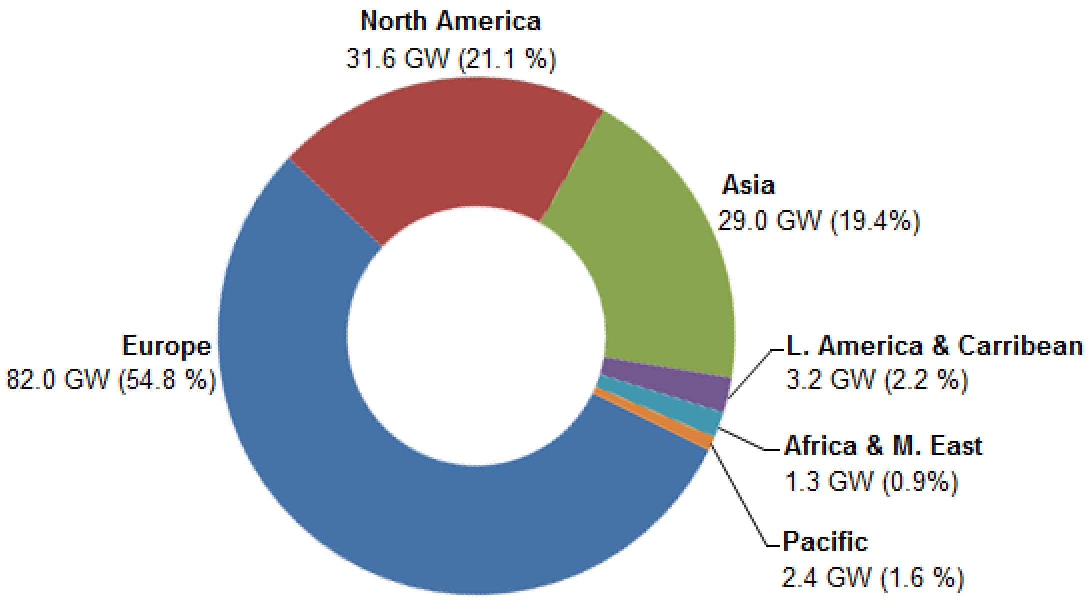


Figure 1: Total Wind Power Capacity

Despite being far behind, the geography and climate conditions in the Middle East and North Africa (MENA) are highly conducive to the development of wind energy production. As a matter of fact, a number of governments (e.g. Iran, Jordan, etc.) in the Middle East have started developing national plans for renewable energy, with Iran being the leader in that field [3]. In comparison to the MENA region, Lebanon is considered behind in terms of wind power energy. Not only is it behind in terms of wind energy, but the country has also been experiencing cuts in electricity for the past few decades, thus compelled to import it and to use unhealthy generators, at high prices and low quality. It is believed that an extensive development of wind energy can play a crucial role in resolving, or at least reducing, the electricity supply shortages currently faced. Lebanon has a set goal of reaching 12% of renewable energy by 2020 [4]. The construction of an-shore wind farm in Lebanon can be a huge step towards achieving this goal especially that several regions in that country (e.g. Marjaayoun, Dahr El Baidar and Akkar) are favorable for such projects primarily due to elevated wind speeds [4].

1.1.1.2. Simulation in Construction

The construction of a large on-shore wind farm, despite having aspects common to other types of construction projects, offers several challenges. In fact, such projects are relatively new in Lebanon. Additionally, given large site areas, site topography becomes increasingly challenging especially when it comes to earthwork. Moreover, wind farms are usually constructed in empty areas where there are generally no existing road networks. Furthermore, the site selection for such projects is mostly based on having high wind speeds. Erecting wind turbines requires the use of cranes. Such activities involving cranes and executed at high elevations become greatly challenging when subjected to high wind speeds as execution needs to be stopped when wind speed is above a certain value. These are some of the challenges faced in such projects, therefore, the construction process needs to be perfectly well planned and studied before execution.

Nowadays, the construction industry is becoming increasingly challenging due to the rising competition in the market and due to the growing complexity of projects. In order to match these complexities and to remain in the competition, many tools are continuously created and developed to find new ways to improve construction performance. One of the important additions to the construction industry has been the emergence of Building Information Modeling (BIM) which is “a digital representation of physical and functional characteristics of a facility” according to the US National Building Information Model Standard Project Committee. It is “a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition.” [5]. Instead of using traditional 2D drawings, BIM focuses more on 3D models. One of the advantages of BIM is the integration of all project information such as 2D drawings, 3D models, schedules which turn the models into 4D models (with time as the 4^{th} dimensions) and cost data which result in a 5D model (with cost as the 5^{th} dimension). Quantity take-offs and project cost calculations thus become much more easily generated. Another advantage is that BIM provides a common and shared interface for all trades and fields through which communication and collaboration becomes easier among stakeholders [5]. With the emergence of BIM, many tools are increasingly being adopted such as simulation modeling, 5D visualization, optimization, etc. Simulation modeling consists of creating a model that is the "imitation of the operation of a real-world process or system over time" [6]. It takes as input data from the model creator based on historical data and assumptions. The model itself consists of logical relationships and processes defined by the modeler. The output consists of results based on the interaction of the input data with the designed model. In many cases, it is useful to accompany a simulation model with visuals to provide the viewers with an animation of the process being simulated. Visualization can serve as a verification tool [7] and can aid viewers that are unfamiliar with simulation to understand the model. Finally, optimization consists in "the selection of a best element (with regard to some criteria) from some set of available alternatives" [8]. These three tools can be very useful in construction and are usually all applied prior to execution. In fact simulating, visualizing and optimizing construction processes can help planning teams in improving construction performance. Some of the advantages of these methods are that they allow construction companies to visualize construction processes virtually early on which can be very helpful to foresee and prevent all kinds of risks and potential problems that might arise during construction and to optimize the process before execution by minimizing costs, wastes and project duration.

1.1.2. Literature Review

Numerous previous research efforts have addressed wind farm processes and their optimization. Most of them have focused on the optimization of the design of wind farms and wind turbines to maximize their energy yield. More specifically, several models, programs and algorithms have been developed and used to optimize wind farm layout in order to maximize power generation and minimize project costs. For instance, Gonzalez et al. proposed an evolutive algorithm to optimize the wind farm layout, the goal of which is to find the optimum turbines positioning in order to maximize the present value of the yearly net cash flow [9]. Chen et al. also worked on the turbines' layout but their research included wind turbines with different hub heights and their optimization was made using a genetic algorithm to maximize power output [10]. Additionally, Zhang et al. present constraint programming and mixed integer linear programming models that incorporate non-linearity of such problems. Different wind scenarios are studied and additional constraints are taken into consideration such as landowner participation and noise constraints [11]. Chowdhury et al. worked on optimizing both layout and turbine size for a given wind turbine using constrained Particle Swarm Optimization [12]. Another approach was used by Eroglu et al. and it consists of a particle filtering approach to design the optimum layout to minimize the wake effects and to maximize power generation focusing mainly on site boundaries and turbine spacing as constraints [13]. Finally, Chen et al. used a greedy algorithm to optimize the wind farm layout [14].

Other design aspects have also been tackled as well, such as the optimization of the turbines' tower structure, blades, rotors and noise reduction in order to design the most efficient wind turbines [15, 16, 17, 18]. Negm et al. describe several optimization models for the design of typical wind turbine tower structures to maximize the system performance as a whole [15]. Similarly, other research works addressed the optimization of wind turbine blades (aerodynamic and structural). Xudong et al. developed blade design methods to maximize the energy yield of wind turbines for a given size of turbines [16]. The turbine rotors were studied as well by Fuglsang and Madsen. They present a developed numerical multi-disciplinary optimization method for the design of horizontal axis wind turbines with the objective of minimizing cost of energy [17]. A completely different aspect was also studied, which is wind turbine noise. Oerlemans et al. worked on reducing wind turbine noise by using optimized airfoils and trailing-edge serrations [18].

In addition to the design phase, the post-construction phase has also been addressed by some researchers with the aim of minimizing operations and maintenance (O&M) costs. In fact, Tian et al.'s research aimed at reducing the operation and maintenance costs of wind power generation systems [19].

Hence, a lot of research efforts sought to optimize wind farms processes by addressing several aspects related to the design phase or the O&M phase. Nonetheless, the construction of wind farms has still not been widely addressed.

This paper presents work aiming at efficiently designing, planning, and optimizing the construction process of on-shore wind farms. This is mainly achieved through the use of Discrete Event Simulation (DES) and visualization techniques which have been increasingly used in the field of construction. Martínez and Ioannou introduced a DES tool, STROBOSCOPE, to efficiently simulate construction processes and get valuable data such as utilization rates of the different resources, idleness, cost data, etc. [20]. Furthermore, Kamat and Martínez acknowledged the importance of verifying and validating simulation models created in STROBOSCOPE and thereby proposed 3D visualization as a potential solution by creating VITASCOPE [21]. Some research efforts utilized both these simulation and visualization tools to intelligently preempt in the construction process of a manmade island for an airport [22] and efficiently plan and design construction operations at airports in a way that has the least impact on airside operations [23]. Nevertheless, it is worth mentioning that few works attempted at simulating wind farm construction operations using DES. Although Byon [24] used DES to simulate and optimize wind farm O&M operations and Atef and Nassar used DES to simulate installation of turbines according to wind effects, only Nassar et al. [25] worked on simulating the wind farm construction operations using DES, in particular the STROBOSCOPE software. It focused on the selection of access road routes to reach optimal access road selection and optimize the whole process.

However, the latter research effort presented a simplified simulation model without sufficient granularity representing wind farm construction operations. The proposed study, on the other hand, offers the simulation modeling of the whole on-shore wind farm construction process from topographical survey to wind turbines installation and provide generic data (e.g. materials, resources, daily productivities, etc.) that can be adopted for any other project and easily tailored to match its scale. Additionally, this study uses AnyLogic 7 (Educational Version) [26], which has been rarely used in construction, and takes advantage of its various features to not only simulate wind farm construction processes in detail but also verify and validate their credibility by visualizing them in 3D. Furthermore, this research effort visualizes project time and cost data and thereby presents a 5D visualization model as well as uses the available optimization features to efficiently allocate resources and minimize time and cost. Therefore, this paper, modeling for a specific challenging site in Lebanon (Marjaayoun), can serve as a guide for using AnyLogic 7 for simulation, 5D visualization and optimization of not only wind farm construction operations but any other construction operation or even other processes in various fields.

1.2. Research Problem

The on-shore wind farm construction process can be very costly and challenging. In fact, it requires a lot of heavy and expensive equipment such as cranes, trucks, excavators, etc. On-shore wind farms are typically constructed in rural areas where the topography is challenging and where there are no existing road networks. A considerably big road network is essential for the construction process because of the vehicles involved in it, including trucks delivering the wind turbines to site. Additionally, sites selected for such projects are subject to high wind speeds which restrict the cranes' operation since there are wind speed limits above which such equipment cannot operate which also adds to the complexity of the construction process.

Complex construction projects are increasingly using new methods to improve construction performance. Some of these methods are simulation and visualization. These help in predicting construction performance results. They can also be used to optimize construction planning and results.

For the case of Lebanon particularly, for the past thirty years, the country has been experiencing cuts in electricity, thus compelled to import it and use noisy and extremely unhealthy generators. This happened at very high prices in contrast to a mediocre quality. Hence, an adequate solution to this shortage in electricity supply can be achieved through the use of renewable energies, in particular wind energy.

1.3. Thesis Objectives

The overall objective of this research is to efficiently plan, design, validate, and optimize the on-shore wind farm construction processes. Five specific objectives are identified in the proposed study:

- Create a generic and detailed simulation model of the whole on-shore wind farm construction process from topographical survey to wind turbine installation and provide generic data (e.g. resources, productivities, etc.) that can be used for any on-shore wind farm project
- Verify and validate (i.e. face validity) created simulation models by animating and visualizing processes in 3D
- Create a 5D visualization model by visualizing as well construction project's time and cost data
- Enhance the performance of models by optimizing project cost and minimizing project duration
- Evaluate the technical aspects of the research and the effectiveness of the designed models by assessing its performance on an actual site in the region of Marjaayoun, Lebanon

1.4. Thesis Methodology and Research Method

In order to address and achieve the above stated objectives, this thesis takes the required steps to create a simulation model that serves as a tool to meet these objectives. So the thesis methodology is mainly based on simulation modeling and visualization, in addition to a case study to test the created simulation model. As for the research method, the detailed steps taken to achieve the thesis objectives are thoroughly described below.

As a first step, the detailed on-shore wind farm construction process is fully defined including its different packages and activities. All activities are clearly defined and sequenced as per the logical relationships between them. The resources required for each activity are listed as well as the activities' respective productivities or daily outputs. The resources and daily outputs are found mainly using local and international manuals.

Once the construction process is fully detailed and defined, a discrete-event simulation (i.e. process-centric) model is developed using AnyLogic 7.0 software which is the only simulation software that includes the three types of modeling: Agent Based, System Dynamics and Discrete Event (i.e. Process-centric) [26]. The software also offers different types of experiments such as simulation, parameter variation and optimization experiments. An additional advantage is that AnyLogic allows the user to create 3D animations for the designed models and to express results in a user-friendly way. As such, the following step consists in turning the simulation model into a 5D visualization. 3D shapes are associated to the different elements of the model and cost parameters are added. The goal is to have a model that can present to the users the construction process in 3D animation, varying with time, and presenting cost data as well. Time and cost are the fourth and fifth dimension which explains the term 5D visualization.

After that, the *Optimization Experiment* is set up, also using AnyLogic 7.0. The experiment consists of defining an objective function as well as the parameters that need to be varied. In this research work, the optimization is based on resource allocation. The goal is to find the optimum resource allocation for construction to complete the project in the shortest duration at the lowest cost. Therefore, minimizing time, and mainly cost were selected as the objectives of the optimization.

The next step consists of testing the created model on a case study for a specific site in Marjaayoun, Lebanon. The latter location is favorable for such projects (i.e. wind farms) mainly because of the elevated wind speed there which is equal to approximately 7.5 m/s on yearly average [4]. The required construction quantities are calculated for all the activities ranging from topographical survey to wind turbines erection. The construction unit-costs are also found for the specific market conditions. The gathered data such as the quantities, unit-costs, etc. all serve as inputs to the simulation model. The model is then run and outputs the 5D visualization as well as the optimum resource allocation that results in a minimum duration and minimum costs. These optimum results are then be compared to other resource allocations to assess the extent to which resource allocation can affect a project’s cost and duration.

Figure 2 is a summary diagram of the research method.

Figure 2: Research Method Steps

CHAPTER 2

ON-SHORE WIND FARMS OVERALL CONSTRUCTION PROCESS

2.1. Construction Packages and Activities

The on-shore wind farm construction process is divided into six main packages which are topographical surveying, earthwork, road construction, foundation construction, electrical works and wind turbines erection.

The first package, topographical surveying, is essential because it provides all the site's points' elevations. It accurately determines the relative locations of points on the site's surface. On-shore wind farm sites typically do not have existing road networks. Moreover, large sites with wide roads are needed in order for the trucks to be able to access and move around the site to deliver the wind turbines. To that end, the second and third packages are needed which consist of earthwork and road construction. First, through earthwork, cut and fill activities are performed to prepare the road. Then the road is paved resulting in a road network. Wind turbines are huge structures subject to high wind speeds and thus require to be fixed on strong foundations, which bring in the next construction package, foundation construction. Furthermore, the ultimate goal of such projects is to generate electricity which means that there is inevitably an electrical works package which consists in linking the turbines to a substation that will be distributing electricity to households. Finally, the last construction package is wind turbine installation or erection. The turbines are delivered to site, lifted to their respective foundations and fixed to become operational.

These different packages are illustrated and shown in Figure 3.

1. Topographical Surveying

Courtesy of landform surveys (www.landform-surveys.co.uk)

2. Earthwork

Courtesy of Monroe roadways (www.monroeroadways.com)

3. Road Construction

Courtesy of Sarajevo times (www.sarajevotimes.com)

4. Foundations Construction

Courtesy of IOWA LECET (www.iowalecet.org)

5. Electrical Works

Courtesy of National Wind (www.nationalwind.org)

6. Wind Turbines Erection

Courtesy of DIERET (www.inforse.org)

Figure 3: Illustrated On-Shore Wind Farm Construction Packages

Each of these packages includes one or more activities. These activities within each construction package, as well as their relationships, are shown in Figure 4.

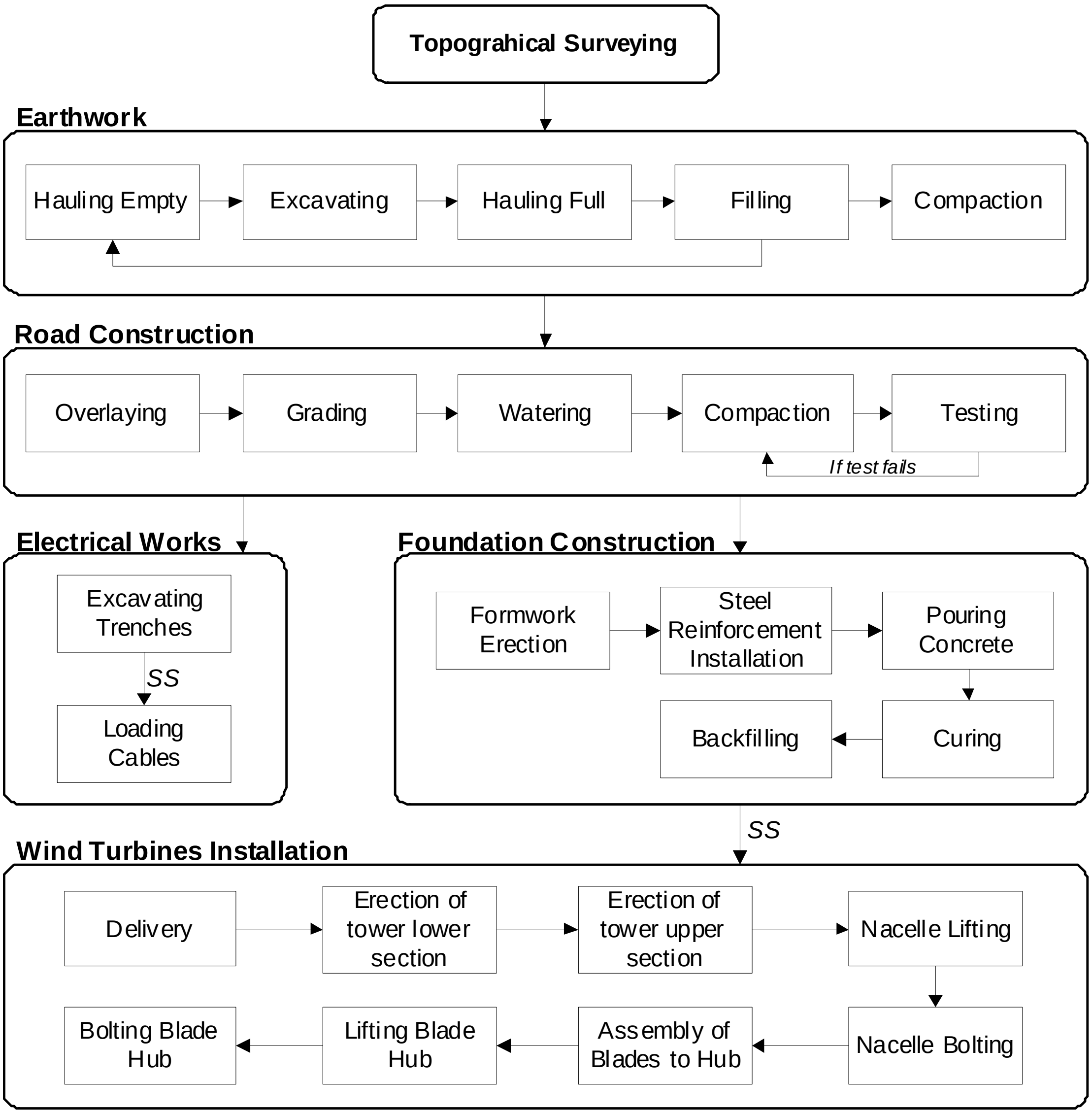


Figure 4: On-Shore Wind Farm Construction Process

In the scope of this research work, the substation construction and the connection to the electrical grid were not incorporated. Among electrical activities, only the ones interfering with the construction process were included.

2.2. Activities' Resources and Daily Outputs

In the following subsections, the above activities are defined in details and for each, daily outputs and required resources (i.e. equipment and crews) are listed. These are generic inspired from common construction practices and productivity manuals [27], and can thereby be applicable to any other site where similar construction operations are to take place and easily adjusted for project scale and location using factors.

2.2.1. Topographical Surveying

The first activity of the process is topographical surveying which consists of measuring the elevation of the site's different points. The resources needed to complete this activity are a surveying crew and one electronic level. The crew is made of one chief of party, one instrument man and one rodman. For this crew, the daily output is equal to 13355 m^2 [3.3 acres].

2.2.2. Earthworks

After surveying is finished, the earthwork package can begin. The purpose of this construction part is to perform cut and fill operations on the soil so that road construction can occur. This part includes five activities, the first of which is excavating. The resource involved in excavation is a dozer (410 HP). For this resource, the daily output is 489 bank m^3 [640 BCY]. The second activity is filling which requires a dozer (200 HP). The daily output in that case is 765 loose m^3 [1000 LCY]. In parallel to excavating and filling, hauling would be taking place as well. The resource needed for hauling is a dump truck with a 9 m^3 [12 CY] capacity and with a speed of 32 km/hour [20 MPH]. The last activity involved in earthwork is compaction which is performed on the filled soil using a sheepsfoot roller (240 HP) at a daily output of 994 m^3 [1300 ECY]. The sequencing of these activities is shown in Figure 4. In case fill volume is greater than cut volume, borrow needs to be brought to site. Loading borrow onto the trucks is done at a rate of 917 loose m^3/day [1200 LCY/day].

2.2.3. Road Construction

Once earthwork activities are done, road construction may begin. The first step of road construction, is overlaying the 30 cm aggregate base course for roadways. In order to do that, a crew made of a foreman and two laborers, a loader of capacity 1.1 m^3 [1.5 CY] and an aggregate truck are required. The daily output for this activity is 3177 m^2 [3800 SY]. The second activity consists of grading which requires a grader. The same crew mentioned above is involved for all road construction. Road grading is done at a rate of 1672 m^2/day [2000 SY/day]. Then, the road needs to be watered using a water truck at a rate of 2500 m^2/day [2990 SY/day]. Afterwards, the road is compacted using a sheepsfoot roller (240 HP) at a daily output of 990 m^3 [1500 CY]. Finally, the last activity is testing, to make sure the road segments were well compacted. Only one laborer is needed and it assumed that 20 tests can be performed every day with one laborer. Each test is performed on 30 meter road segments.

When the road construction is finished, foundation construction and electrical works may begin. For every finished foundation, a wind turbine can be installed. Most importantly, the roads are now available for all kinds of vehicles to enter the site and perform the necessary works.

2.2.4. Foundation Construction

The wind turbines will eventually be standing on reinforced concrete foundations. In order to construct these, the first activity consists of erecting the formwork by a crew of three carpenters and one laborer. The daily output of this activity is 29 m^2 CA [315 SFCA]. Then, steel reinforcement installation is performed by a crew of four rodmen at a rate of 3.6 tons/day [7200 lbs. /day]. Afterwards, concrete placing is performed. The resources required for that are a concrete crew, a concrete truck and two gas engine vibrators. The concrete crew is made of a foreman, five laborers and a cement finisher. The daily output of placing concrete is 306 m^3 [400 CY]. Then the activity of curing is performed by two laborers at a rate of 511 m^2 / day [55 CSF / day]. Finally, once the foundations are complete, they are backfilled using a dozer (200 HP) having a daily output of 810 loose m^3 [1060 LCY].

2.2.5. Electrical Works

Since the purpose of wind farms is to generate electrical power, electrical works definitely form a big part of the construction process. Indeed, an electric network connects the turbines to a substation to harvest and supply electricity. There are two main activities included in the electrical works package. The first one consists of electrical trenches excavation which requires a 1.1 m^3 [1.5 CY] excavator to perform at 363 m^3/day [475 BCY/day]. The second activity is the cable installation which requires three electricians to install 110 m [3.6 CLF] per day.

In this paper, the substation construction and the connection to grid are not included in the simulation model. The paper is only dealing with the electrical activities interfering with the construction process.

2.2.6. Wind Turbines Erection

The last construction part consists of the wind turbines installation. This process begins with the delivery of the wind turbine parts to the site using delivery trucks which move at a speed of 32 km/hour [20 MPH]. Unloading the different turbine parts is assumed to take 30 minutes per turbine. The different parts include the tower (lower and upper parts), the nacelle, the role of which is to transform the wind energy into electrical energy, the rotor, and the blades. These different parts are shown in Figure 5.

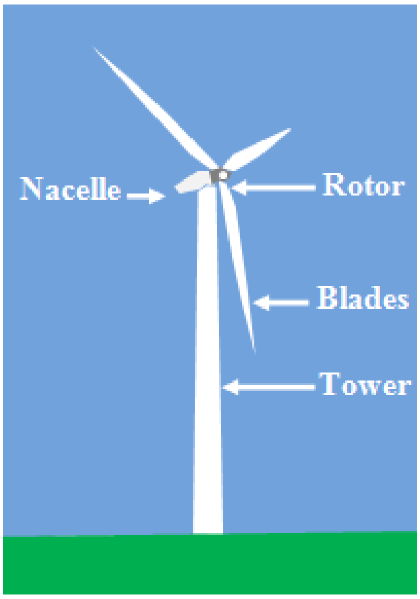


Figure 5: Typical Wind Turbine

After the delivery, the tower's lower section is erected using a secondary crane and a tower erection crew at a rate of one per day. This crew is made of one chief of party and five laborers. Then, using the main crane and that same crew, the upper part of the section is erected, also at a rate of one per day. After that, the nacelle is lifted using the main crane and bolted by a bolting crew composed of one chief of party and three laborers. Lifting one nacelle takes one and a half hour while bolting it takes up to two and a half hours. The next activity consists of the assembly of the blades to the rotor which requires a bolting crew. That activity takes three hours to be completed. Lastly, the rotor and bolted hubs are lifted using the main crane and bolted by a bolting crew to the top of the tower. These two activities take one hour and a half and two hours and a half respectively to be completed.

It is important to note that all the activities requiring the use of a main crane have a condition that needs to be satisfied in order for them to be executed. This condition is related to wind speed. In fact, if the wind speed is above 9.8 m/s [22 mph], the concerned activities need to be stopped until wind speed goes back to an allowable speed since the main crane cannot operate at wind speeds greater than 9.8 m/s [28].

2.2.7. Summary Table

On the following page, Table 1 summarizes all previously described activities with their respective resources and daily outputs given the listed resources.

Table 1: Activities' Resources and Daily Outputs

Activity	Resources	Daily Output
Topographical Surveying	▪ 1 surveying crew (1 chief of party, 1 instrument man & 1 rodman) ▪ 1 electronic level	13,355 m^2
Earthwork		
Excavating	▪ 1 dozer (410 HP)	489 bank m^3
Filling	▪ 1 dozer (200 HP)	765 loose m^3
Hauling	▪ 1 dump truck (9 m^3 capacity)	32 km/h (speed)
Compaction	▪ 1 sheepsfoot roller (240 HP)	994 m^3
Loading borrow	▪ 1 dozer (200 HP)	917 loose m^3
Road Construction		
Overlaying	▪ 1 road crew (1 foreman & 2 laborers)* ▪ 1 loader (1.1 m^3 capacity) ▪ 1 aggregate truck	3,177 m^2
Grading	▪ 1 grader	1,672 m^2
Watering	▪ 1 water truck	2,500 m^2
Road Compaction	▪ 1 sheepsfoot roller (240 HP)	990 m^3
Testing	▪ 1 laborer	20 tests

Activity	Resources	Daily Output
Foundations Construction		
Formwork Erection	▪ 1 formwork crew (3 carpenters & 1 laborer)	29 m^2 CA
Steel Reinforcement Installation	▪ 4 rodmen	3.6 tons
Concrete Placing	▪ 1 concrete crew (1 foreman, 5 laborers & 1 cement finisher) ▪ 1 concrete truck ▪ 2 gas engine vibrators	306 m^3
Curing	▪ 2 common laborers	511 m^2
Backfilling	▪ 1 dozer (200 HP)	810 loose m^3
Electrical Works		
Electrical Trenches Excavation	▪ 1 excavator (1.1 m^3 capacity)	363 m^3
Cable Installation	▪ 3 electricians	110 m
Wind Turbines Erection		
Turbines Unloading	▪ 1 delivery truck	16 turbines
Tower Lower Part Erection	▪ 1 secondary crane ▪ 1 tower erection crew (1 chief of party & 5 laborers)	1 turbine
Tower Upper Part Erection	▪ 1 main crane ▪ 1 tower erection crew (1 chief of party & 5 laborers)	1 turbine
Nacelle Lifting	▪ 1 main crane	5.3 turbines
Nacelle Bolting	▪ 1 bolting crew (1 chief of party & 3 laborers)	3.2 turbines
Blades Assembly to Rotor	▪ 1 bolting crew (1 chief of party & 3 laborers)	2.7 turbines
Lifting Rotor	▪ 1 main crane	5.3 turbines
Bolting Rotor to Tower	▪ 1 bolting crew (1 chief of party & 3 laborers)	3.2 turbines

CHAPTER 3

SIMULATION MODEL OF ON-SHORE WIND FARM CONSTRUCTION

Simulation is used to imitate real life processes, operations, situations, etc. Simulations usually happen over a period of time. The importance and benefits of simulation is that it can help predict outcomes of certain situations based on different scenarios. The flexibility of simulation is very important since the level of detail, speed of simulation, varying parameters, etc. can all be adjusted and are usually selected based on the case modeled and based on the expected and required outcomes. Simulation can be practically applied to any field with examples such as healthcare, manufacturing, marketing, construction, etc. Additionally, different types of simulation exist of which the three most important and commonly used are Discrete Event, System Dynamics and Agent Based.

In discrete event simulation, the scenario in question is modeled as a sequence of discrete events or activities. Entities arrive into the model at a certain arrival rate and go through its elements one at a time sequentially. In system dynamics the real-world processes are represented in terms of stocks, flows between these stocks, and information that determines the values of the flows [26]. Lastly, agent based modeling is an essentially decentralized and individual-centric approach. When designing an agent based model the modeler identifies the active entities, the agents (which can be people, companies, assets, vehicles, etc.), defines their behavior, puts them in a certain environment, establishes connections, and runs the simulation. The global behavior then emerges as a result of interactions of many individual behaviors [26].

AnyLogic software, which is used as part of this research, is the only tool that brings together these three modeling types within one modeling language and one model development environment. In addition to that, AnyLogic provides network based modeling which falls under the discrete event type. It is specifically designed for “space-aware” processes which involve the movement of entities and/or resources. This modeling type uses the same elements as discrete event (i.e. process-centric) simulation but also includes elements that define movement [26].

For the case of the on-shore wind farm construction process simulation, the modeling type used is the discrete event (i.e. process-centric) type in addition to network based modeling which is essential for the animation later on.

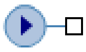
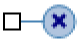
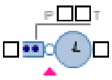
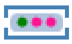
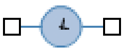
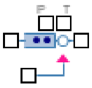
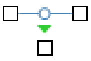
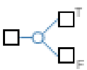
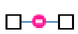
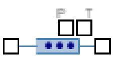
3.1. Definitions of AnyLogic 7.0 Modeling Elements

In order to explain the simulation model developed for the on-shore wind farm construction process it is important to start by defining all the elements that are used in the model. The two main libraries used are the general library and the process centric library. The elements used from each are defined in Table 2 and Table 3.

Table 2: AnyLogic General Library Elements

General Library	
event	An *event* allows the user to schedule an action to occur based on a condition or at a specific time or in a cyclic manner.
parameter	A *parameter* is used to model the characteristics of the modeled objects (e.g. speed of vehicles). Parameters are usually static and do not change during a model run.
variable	A *variable* is also used to model characteristics of a model. However, it usually varies during model execution (e.g. wind speed).
collection	A *collection* represents a group of any types of objects.

Table 3: AnyLogic Process-Centric Library Elements

Process Modeling Library	
resource type 	A *resource type* is used to define resources. It allows the user to assign to each resource an animation shape and parameters.
source 	A *source* is usually the starting point of every modeled process. It is the element that generates the entities that are going to flow through the process.
sink 	A *sink* is the last element an entity goes through. Once a process is done, entities are thrown in the sink.
service 	A *service* seizes a specific number of resources, then delays the flowing entities and then releases the seized resources.
resourcePool 	A *resource pool* is used with the service element. It is the resource needed for the specified service to be executed. When an entity is at the service element, it withdraws the resource and releases it after the delayed time.
delay 	A *delay* simply delays entities flowing through a process.
seize 	The *seize* element withdraws a certain number of resources from a specified resource pool.
release 	The *release* element returns the specified resources to their respective resource pools.
selectOutput 	The *select output* element is used when there are two alternative paths to choose from. The entity will flow through one of the ports depending on the specified condition or probability.
hold 	The *hold* element blocks the entities from flowing through the process at specific times or for specific conditions.
queue 	A *queue* is required when the next element's capacity is less than the arriving entities. Waiting entities will be stored in the queue until they can be processed.

3.2. Detailed Simulation Model

The simulation model of the construction process, using the aforementioned elements, is presented in Figure 6.

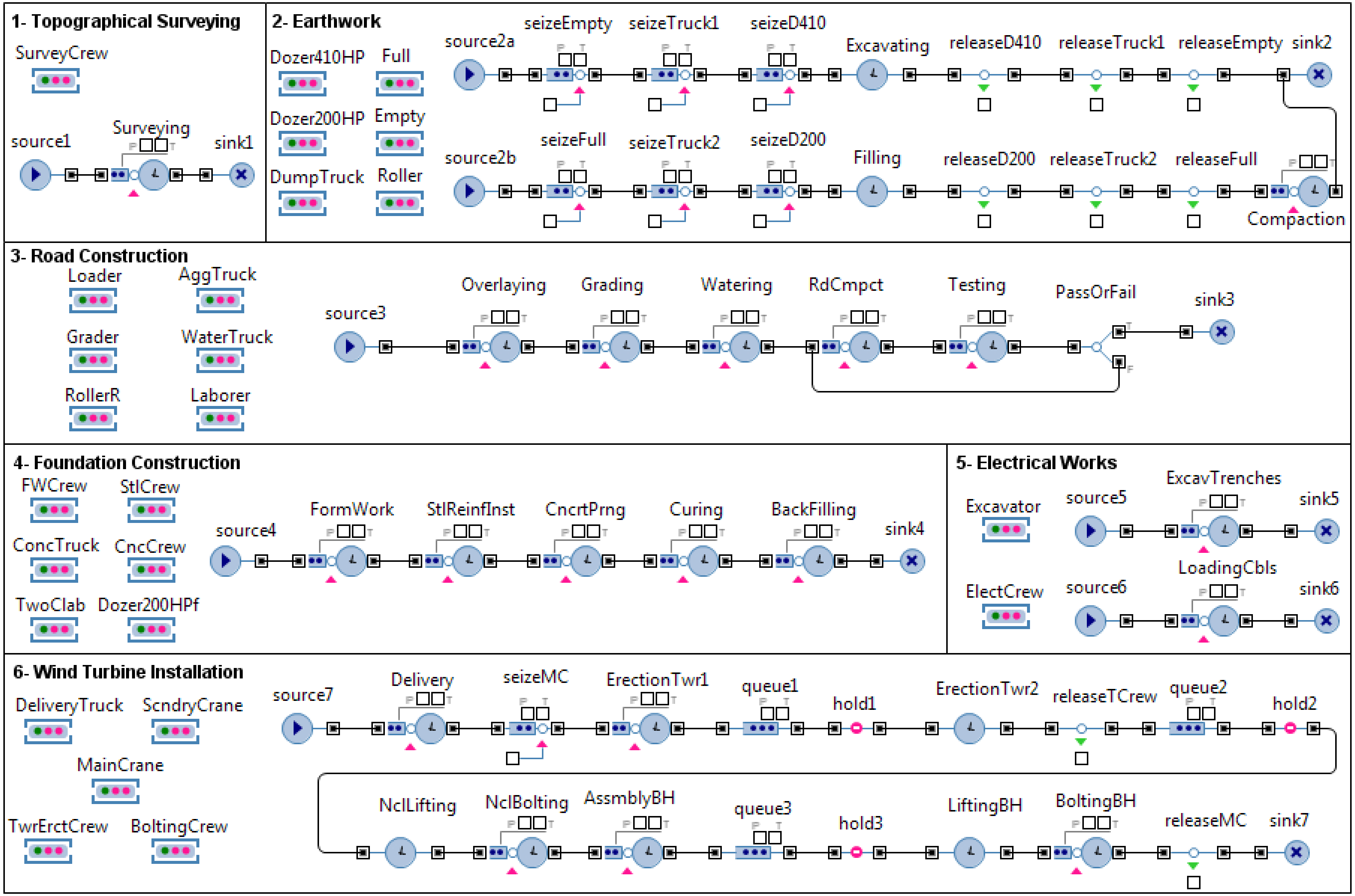


Figure 6: On-Shore Wind Farm Construction Simulation Model in AnyLogic

The model is divided into six parts matching the six construction packages. At this point, it is important to note that the model is purely of type discrete event simulation and still has no network based modeling characteristics yet. Those are developed and explained for the purpose of visualization in Chapter 4. In the following section, each package is explained respectively given that the model elements' functions have been all explained in Table 2 and in Table 3.

3.2.1. Topographical Surveying

First of all, the simplest part of the model is topographical surveying because it consists of only one activity. The model starts with a *source* which generates entities. The entities coming out of the *source* represent the parts of the site to be surveyed. Their number will depend on the case being modeled. An entity from *source1* could represent a square meter, an acre, a sub-area or any other measure of area as long as the delay time is adjusted later accordingly. The most important property of the *source* element is its arrival rate. For the activities involved in this model, the constraints on execution are not placed by the entities; instead, they are placed mainly by the resources' availability or by the activities' relationships. To that end, there is no need for a specific arrival pattern for the entities. In fact, once an activity is unconstrained, all entities can be generated and placed in the activity's queue. So, the properties selected for *source1* are arrivals defined by "interval time" where the interval time is equal to zero and where the number of arrivals is limited to a single one. The entities per arrival are equal to the amount of entities required to cover the whole site depending on what the entity is selected to represent by the modeler (e.g. 10 acres, 1 km^2, etc.). In a nutshell, these properties mean that at time zero, the selected number of entities per arrival is queued at the service called "*Surveying*". The properties of that *service* element are selected as follows: the "resource quantity" is equal to one which means that only one resource is required for the service to be executed. The "delay time" is selected based on what each entity is modeled to represent and are equal to $\frac{acres\ per\ entity}{daily\ output\ (in\ acres/time\ unit)}$. Lastly, the *ResourcePool* object is assigned to *SurveyingCrew* which is the resource pool that represents surveying crews. The number of crews it holds is one of the optimization parameters later on. The capacity of the service is set to maximum as its capacity is constrained by the available resources. The last element is the *sink*. It receives the entities after they are executed. In a nutshell, entities are generated by *source1*, they are then executed by the service *Surveying* using the resource pool *SurveyCrew* and are disposed in *sink1*.

3.2.2. Earthworks

The next construction package is earthworks and has surveying as its predecessor with a finish-to-start relationship. This relationship is modeled with the use of an *event*. The event's role is to evaluate the content of *sink1* and order an action accordingly. The code executed is as follows:

```
if(sink1.count() == X)
{
source2a.inject(Y);
source2b.inject(Z);
}
```

X represents the total number of entities to be surveyed, Y represents the number of entities to be cut and Z represents the number of entities to be filled. In the last two cases, each entity represents a volume of soil equal to the capacity of the truck. The function *inject* allows the user to inject entities into sources manually. All *source* elements aside from *source1* have entities injected to them manually. So the code means that when site surveying is complete, cut and fill operations can begin. Earthwork part of the model is the most complicated one as compared to the others. The main reason for the complexity is that the same resource, which is the dump truck, can serve different roles whether full or empty. When empty, it is a resource for the excavating activity, when full it becomes a resource for the filling activity. To differentiate between these two states, two additional resource pools are added and are called *Empty* and *Full*. The latter is initially equal to zero at the start of the model run, as all trucks are empty at the beginning. As for *Empty*, it is initially equal to the number of trucks assigned to the project. Each time an excavation occurs and a truck is filled, the resource *Full* is increased by one and the resource *Empty* is decreased by one. For this part of the model, instead of using *service* elements for the activities, *delay* elements were used, accompanied by *seize* and *release* elements. The use of three seize elements before each of the two delays (*Excavating* and *Filling*) is critical because it sets some sort of priority to the resources. It is important to note that once a resource is seized, it can only be released when it reaches a *release* element. Had the *seize*, *delay* and *release* elements been replaced by a *service* element, there would be a possibility for the model to be stuck. Let’s say for example that there is one dump truck available. As such, initially, there would be one *Empty* resource and zero *Full* resources. In the case where a service is used, there would be equal priority to all services. The truck would be seized by either *Excavating* or *Filling* with equal chances. If seized by *Filling* at first, it would have to wait for the resource *Full* to be seized as well in order to be executed, but which won’t be seized for being initially equal to zero. *Excavating* is not be able to be executed either since the truck is stuck at the filling activity. To avoid this situation, seize elements were added in a certain order to make sure that no truck is seized unless its state (empty of full) matches the one required. Then, after the delay is executed, the resources are released and entities are disposed in the sink. For the case of cutting, before the entities are disposed in the sink, one more service needs to be executed, which is compaction. This process is repeated until earthworks are completed.

A case also needs to be addressed which is the situation where cut quantities are less than fill quantities which means that borrow material must be present on site. To model this scenario, the delay time of the excavation service needs to be made dynamic, which means it changes based on the model conditions. When the quantity to be excavated is finished, the delay time is adjusted dynamically to match the daily output of the activity "filling truck with borrow material". Now similarly to the transition between packages 1 and 2, an event is added with a code to inject the required amount of entities into *source3* when *sink2* is filled.

3.2.3. Road Construction

The road construction part of the model is similar to topographical surveying with more activities placed in series. The addition here is the presence of the select output element named *PassOrFail*. Two out-ports come out of this element: one to represent the road segments that have passed the compaction test and the other to represent those who have failed the test and that need to be compacted again. In fact, for the second case, the entities are sent back to compaction where they are compacted again and tested again until they pass the test. At the end of this package, again and again, an event is executed. The difference is that this time, more than one source has entities injected in it, since it is assumed that the construction of foundations, the excavation of trenches and the installation of cables all start together. So once road construction is complete, foundation construction and electrical works begin at the same time.

3.2.4. Foundation Construction and Electrical Works

These two packages are quite straightforward given that the previous packages have been explained. A good practice for foundation construction is to consider that the entities coming out of the source correspond to foundations and not to units of works such as m^2 for formwork or m^3 for pouring. As such, the unit (i.e. foundation and not m^2 or m^3) will be consistent throughout all services. However, the delay times will need to be adjusted according to the quantities for one foundation.

3.2.5. Wind Turbines Erection

The last remaining package is the wind turbines erection. The sequence of this package is different from the others. In fact, it has a start-to-start relationship with the foundation construction package. Each time a foundation is constructed, a wind turbine may be installed on it. Elements in AnyLogic have fields in their properties called "*on enter*" and "*on exit*". These allow the user to write a code that will be executed each time an entity enters or exits the element. This is relevant to represent the relationship between foundation construction and wind turbine installation. The code executed in the "*on enter*" field of *sink4* is as follows:

```
source7.inject(1);
```

The first activity, represented by the service named *Delivery,* consists in delivering the turbines to their respective locations on site using a delivery truck, represented by a resource pool. The next element is of type "seize" and consists in seizing the main crane. The purpose for using an independent seize element is that the main crane is assumed to remain working during the process until the turbine is fully installed. The assumption is as such because it is not practical to move a main crane back and forth between turbines before each one is completed, so the main crane remains at each turbine until the latter is fully installed, and this is shown through the release element placed right before the sink. The second service after *Delivery* represents the erection of the lower part of the tower. It seizes the secondary crane as well as the tower erection crew. Once completed, only the secondary tower crane is released since the tower erection crew would still be needed for the erection of the upper part of the tower. Since the erection crew is already seized, there is no need to use a *service*, a *delay* is enough but should be followed by a *release* element to release that crew which will not be needed for the next activity. The next activities are simply services seizing their needed resources. An element used in this part of the model for the first time is the *hold* element. The reason it is used at this point, preceded by a queue, is to model the wind conditions. In fact, as previously mentioned, the main crane cannot operate in case wind speed is above 9.8 m/s [28]. So in case wind speed surpasses this value, the hold element blocks the flow of entities and places them in a queue until wind speed becomes lower than 9.8 m/s. A hold element is added before each activity that involves the use of the main crane. A variable named *WindSpeed* is created, the value of which is random within a range that varies depending on the location of the construction process that is being modeled. The following code is continuously executed along each run:

```
if(WindSpeed >= 9.8)
```

```
{hold1.setBlocked(true);
hold2.setBlocked(true);
hold3.setBlocked(true);}

if(WindSpeed < 9.8)
{hold1.setBlocked(false);
hold2.setBlocked(false);
hold3.setBlocked(false);}
```

One last event is added to model project completion. Once all the sinks include their maximum number of entities, the model is stopped.

3.3. Modeling Time and Cost

Besides modeling the different processes, modeling the overall project time and cost is deemed necessary as well. As for the delay times of every *service* and *delay*, they need to be adjusted according to what each entity represents for each activity, that is an entity representing 100 m^2 has a delay time 100 times longer than that of an entity representing 1 m^2.

Obtaining thereby overall time data is achieved by setting conditions to control the disposal of *Entities* into *Sink* elements. For example, to compute surveying activity time, the code below is used, where N represents the total number of entities to be surveyed. When N entities are dumped in the sink, topographical surveying is complete and time is recorded through the variable *phase1*. Similarly, durations of the other packages can be found by subtracting the start time from the end time when all respective entities get disposed in sinks.

```
if(sink1.count() == N)
{
      phase1 = time();
}
```

As for cost, in order to output the required data, several parameters need to be added. These parameters can be divided into two groups as follows: the unit costs of resources and the quantities of these resources. The cost of each resource used on this project is calculated using the following formula:

$$ResTC = NRes * DC * Dur$$

In the above, *ResTC* is the total cost of using a specific resource, *NRes* is the number of that specific resource used, *DC* is the daily cost of that resource and *Dur* is the duration of the package in which that resource is used. To find the cost of a whole package, simply, the sum of the costs of each resource used on that package is calculated. Similarly, the cost of the whole project is found by adding up the cost of each package. These two values (packages cost and project total cost) are important because they will be used for the optimization as objective functions, when looking to minimize the project cost.

Finally, in addition to cost and time, an additional indicator used to analyze project performance is the utilization rate of each resource type on the project. AnyLogic offers a function named `utilization()` that allows to get that value.

CHAPTER 4

5D VISUALIZATION AND OPTIMIZATION

4.1. Introduction

A simulation model is a useful tool to help the user imitate the behavior of a certain process of the real world. It allows the user to observe, monitor and predict the outcomes and results of the process based on a given input. However, few points need to be raised.

Firstly, simulation is usually quite abstract which makes it hard to validate the model. In fact, every simulation model needs to be verified and validated to confirm that the model is efficient. Verification is defined as ensuring that the model and its implementation are correct [23, 7]. Validation is defined as the confirmation that the model "within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [7]. According to Sargent [7], one of the verification and validation techniques is to display graphically the model's operational behavior as it progresses in time (i.e. 3D animation) and check whether the model and its behavior are reasonable. In this case, face validity is addressed [7]. Additionally, simulation is difficult to understand by people not familiar with simulation concepts especially in construction projects. Stakeholders such as the client could greatly benefit from an animation which is also beneficial to align all stakeholders' understanding of the project. Therefore, it is very essential to visualize the simulated model.

Secondly, as previously mentioned, simulation allows the user to observe, monitor and predict the outcomes and results of the process based on a given input.

However sometimes, instead of predicting the outcome of certain inputs, it is required to find the optimum inputs to start with. In these cases, the simulation model needs to be accompanied with an optimization experiment to perform this role. The latter can be very different depending on the model, the optimization method and the optimized data.

As such, in addition to the simulation model created in Chapter 3, an animation and an optimization experiment will be created in Chapter 4 using AnyLogic 7.0 software.

4.2. 5D Visualization

In the expression “5D Visualization” in construction, the five dimensions refer to the animation of the construction process which is in 3D, the time factor which is the fourth dimension and which allows the viewers to observe the construction process progressing over time, and lastly, the cost data which is the fifth dimension. At any point in time, the model shows the progress of the project and the cost of every construction package.

To create the animation, the *Space Markup Palette,* shown in Figure 7, is used. This palette allows the model to be developed from a regular discrete event simulation model to a network based model. The idea of network based modeling is based on using networks on which entities and resources move. Networks are composed of nodes linked to each other by paths. These elements are the basis behind the movement of all the animation objects. The elements used from Figure 7 are: *Path*, *Rectangular Node*, *Point Node* and *Scale*. The other elements will not be used as part of this model.

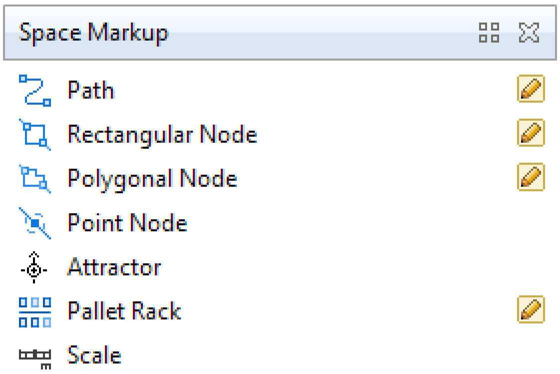


Figure 7: Space Markup Palette

A critical step before creating the necessary networks is to set the model scale so that all shapes' relative sizes can be consistent, accurate and realistic.

In the case of on-shore wind farm construction, three different networks are created; 1) a surveying network where an area to be surveyed is represented by a Point Node, 2) a network for road related activities (earthwork, road construction and electrical works) where road segments and trenches are represented by Rectangular Nodes, and 3) a network for foundation construction and wind turbines installation, where foundations and turbines are represented by Point Nodes located according to the overall chosen turbine layout.

Then, referring to the model in Figure 6, each resource pool is assigned a *resource type* as defined in Table 3. Through the *resource types*, a 3D object can be assigned to each resource pool. The shapes correspond mainly to labor crews, vehicles and cranes. Some of these 3D shapes assigned are shown in Figure 8. In addition to shapes, each resource pool is assigned a speed which depends on the predefined scales. The *service* and *seize resource* elements have a property called "send seized resources to Entity". This option should be selected and causes the resource animation shapes previously selected, to move to the activities' corresponding locations for execution based on the previously defined networks.

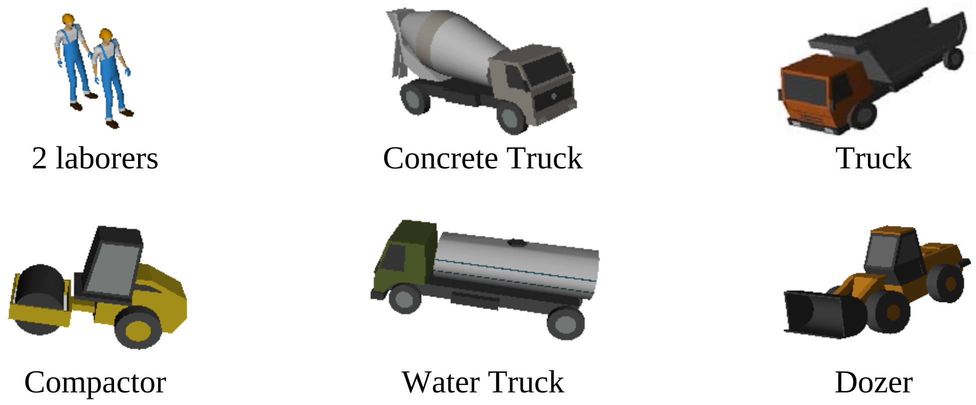


Figure 8: 3D shapes assigned to resources

Additional shapes are added to represent the entities/constructed elements (i.e. road, foundations, turbines, etc.) using AnyLogic's presentation shapes and 3D objects and each is made visible in the model at a node location whenever the related activity is completed. Those shapes are initially added to the animation model as invisible. They would only turn visible when the related activity is complete. For example, after the erection of each turbine tower, the following animation code is executed, where *TowerShape* is defined as a *collection* element storing all turbine tower shapes:

```
TowerShape[i].setVisible(true);
i++;
```

TowerShape in this case is an array which includes variables of type Shape. In this case, the array includes all turbine tower shapes present in the model and the array length is equal to the number of towers on site. "i" is used as an index to indicate which tower is being constructed and increments after each service execution until the total number of turbine towers is reached.

Other animation techniques include changing the color or the size of some the shape. For example, after earthwork completion, the road becomes visible, but after overlaying the shape is still the same, yet the color changes to show that a different material has been overlaid over the existing road. This is done using the following code after the completion of each road segment, where "RoadShape" is again an *array* and "*j*" is the index.:

```
RoadShape[j].setFillColor(gravelTexture);
j++;
```

On the other hand, an instance where the size of the shape is changed occurs during the backfilling of the foundations, where the radius of the animation shape representing the foundation becomes smaller to show that only the tip of the foundation is still above ground. The following code is used:

```
FdtShape[k].setRadius(r);
k++;
```

It is worth mentioning that adding the time and cost dimensions to the animated model leads to a 5D visualization model, whereby viewers are able to check updated time and cost data as the model progresses. This is achieved in AnyLogic by using the *Analysis Palette* shown in Figure 9 and by creating a graphical user interface to display simulation results, in particular time and cost data. The main elements used from this palette or library are the *Data Set* element to record data and the *Bar Chart* element to display results in a user-friendly way.

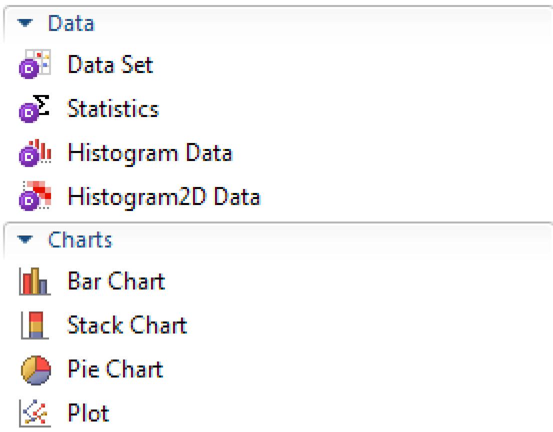


Figure 9: Analysis Palette

4.3. Optimization

4.3.1. Optimization Objective and Parameters

According to the Mathematical Programming Glossary, the definition of optimization is as follows “the selection of a best element (with regard to some criteria) from some set of available alternatives” [8]. “The selection of a best element” usually refers to maximizing or minimizing a certain function. “Set of available alternatives” usually corresponds to a set of parameters, the value of which can vary within a range. The different combinations of these parameters’ values correspond to these mentioned “alternatives”.

In the case of the proposed on-shore wind farm construction model, the objective is to improve construction performance. Construction performance includes a big number of criteria such as project cost, project duration, quality, site safety, environmental impact, etc. In the scope of this research, two of these criteria are addressed which are the construction project cost and duration. This answers the first part of the definition of optimization about selecting a “best element”. So the “best element” in this experiment is having project planning that would lead to the least construction costs and shortest construction duration.

As for the second part of the definition, regarding the “available alternatives”, so many different alternatives exist for the process in hand. However, to increase optimization relevance, it is better to focus on independent parameters separately. The parameters in this model are very wide and include, among many others, wind farm location, wind farm layout, road network design, wind turbines selection and wind turbine design. Since the focus of this research is the construction process, the parameters that will be varied are the number of resources that will be allocated to the different activities, given a fixed location, fixed layout, fixed road network, fixed schedule, fixed equipment and labor cost, etc. The optimization experiment can be thus summarized in the form of the following question: How many of each resource should be allocated to the project to minimize construction costs and duration?

Since both cost and duration need to be minimized, the problem becomes a multi-objective optimization problem. Such problems are more complex than single-objective ones. Several approaches exist to solve them. One of these approaches, called scalarized problem, consists of converting the original problem into a single-objective optimization problem. Most of the other approaches include a decision maker to decide on the optimum solution based on his/her preferences [29, 30]. In the case of the construction model, the preferred approach is the one including the involvement of a decision maker since the weight of the preferred objective whether cost or time will depend on the contractor, the owner, the project situation, etc. In fact, in some cases, financial resources are not a problem and the main focus is to deliver a project as fast as possible. While in other projects, the duration of execution is far less important that the budget.

In this research work, it is assumed that minimizing both cost and duration are important. Minimizing duration only can simply be done by employing all the available resources. However, that would be greatly inefficient as many of these resources would spend a lot of time as idle with low utilization rates. To that end, minimizing cost becomes more relevant and a priority.

On another hand, the optimization process can be quite complex and time consuming. Therefore, it is useful to find methods to reduce complexity to improve optimization performance. In the on-shore wind farm construction problem, a way to reduce the problem's complexity is to dissect the model into smaller sub-parts. For this not to affect the results, these sub-parts must be independent. Topographical surveying, for example, happens initially on its own, so it would make sense to treat this part independently. The same can be applied for earthworks and road construction. The remaining packages need be optimized together and in parallel.

4.3.2. Optimization using AnyLogic 7.0

The AnyLogic 7.0 Optimization Experiment builds on the OptQuest optimization engine developed by OptTek Systems, Inc. The engine incorporates multiple meta-heuristic procedures such as Tabu Search, Neural Networks, Scatter Search, and Linear/ Integer Programming into a composite algorithm [31]. Meta-heuristics help guide the selection of partial search algorithms to provide a near optimal solution for an optimization problem thus using less effort than other computational or heuristic methods [32]. The procedures combined in the meta-heuristic approach such as Tabu Search allow it to prevent getting stuck in suboptimal or confined regions by using a memory structure [33]. This means, when a solution is tested and turns out to be suboptimal, it is marked as "Tabu" and is not visited again during the solution search procedure. This optimizes on the searching process and explores wider possibilities to find the near optimal solution. These methods are embedded in the AnyLogic 7.0 and are used in this study to optimize the on-shore wind farm construction process.

The first input to the experiment is the objective function. As explained in the previous section, the objective function of this model is the project total cost. The objective is to minimize it. The second input is to select the parameters that need to be varied between the different runs. In this case, the optimization parameters are the number of resources of each type. The data required is the range i.e. minimum and maximum values that these parameters can take, as well as the step or increment value.

CHAPTER 5

CASE STUDY: MARJAAYOUN, LEBANON

The created simulation and visualization models are generic (i.e. generic process, activities, resources, daily outputs, etc.) and can be used or easily tailored for any on-shore wind farm. To demonstrate its feasibility, the model is tested on a case study. The selected region is located in Marjaayoun, Lebanon. The case study is essential to test the created model and to evaluate the extent to which it is actually beneficial, applicable and realistic. Additionally, the value of this chapter resides in efficiently designing and planning the construction process of a hypothetical but potential on-shore wind farm in the region of Marjaayoun, Lebanon. The cost and duration of such a project will be found as well as the power output it can generate.

5.1. Site Selection and Layout

5.1.1. Site Selection

The choice of this particular site at the coordinates 33°18'56", 35°34'46" was made mainly due to the fact that the wind power in the area is great and due to the geology and topography of the location which are favorable for earthworks. The site also does not have any major obstacles such as buildings, facilities, utilities, etc.

5.1.1.1. Wind Speed

According to the National Wind Atlas report, Marjaayoun has the highest wind speed in Lebanon which reaches 9.1 m/s on average during the month of July at a height of 10 m above the ground. The lowest recorded month was January with an average of

5.9 m/s. When compared to other regions, the second highest wind speed was recorded in Klaiaat Akkar during the month of January and is equal to 7.2 m/s. The third highest is found for Dahr-el-Baidar at 6.1 m/s for the months of February and March. The average wind speed in Marjaayoun at 10 m above the ground is greater than 7.4 m/s, which is a number greater than the minimum required for a viable wind farm. In fact, the National Wind Atlas report states that "A wind speed of greater than 6.5 m/s at 80 m above ground level has been considered necessary for a viable wind farm" [4]. It is also important to note that wind speed increases with elevation, so the previously mentioned average greater than 7.4 m/s at 10 m above ground would increase at 80 m above ground which would strengthen the idea of a viable wind farm in Marjaayoun compared to the minimum required wind speed of 6.5 m/s. An average wind speed greater than 7.4 m/s at 10 m above the ground can be approximated to an average wind speed greater than 10 m/s at 80 m above the ground [34, 35].

5.1.1.2. Geology and Topography

In addition to the wind speed being adequate, the site is located on a layer from the upper cretaceous epoch as shown in Figure 10. The soil in that area is thus made of chalks and limestone [36] which is suitable for the construction of foundations for such a project [37] noting that each wind turbine will be standing on a spread footing.

Moreover, the exact location of the site was selected in a way to have a suitable topography which, to a certain extent, would make the earthwork for the road construction easier, minimizing the quantities of cut and fill, thus facilitating construction in terms of cost, duration and complexity.

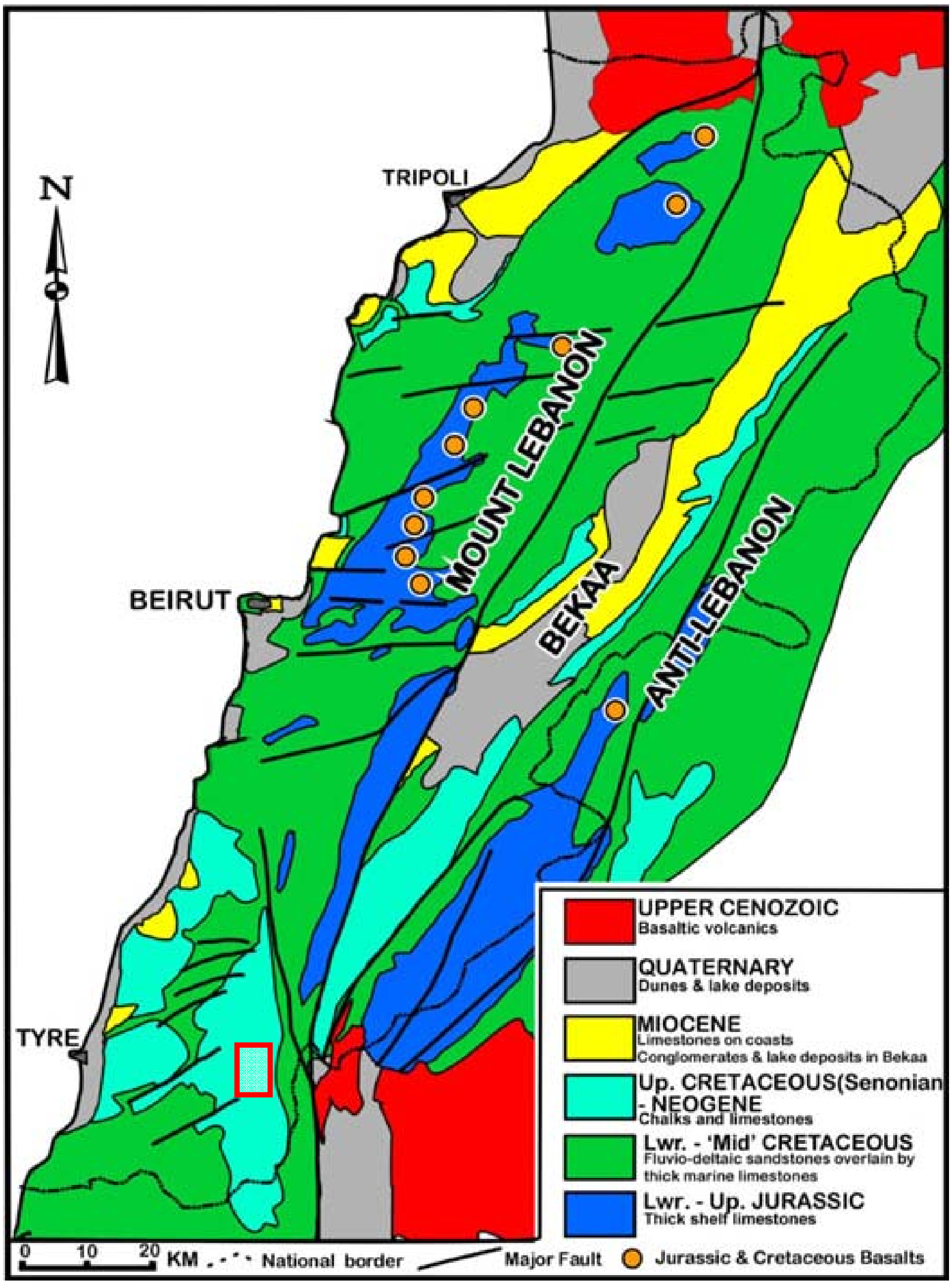


Figure 10: Lebanon's Geological Map [36]

5.1.2. Wind Turbines Layout

Given a relatively large site and relatively high wind speeds, large wind turbines were selected specifically of type Enercon E82-2300. The nominal power for this wind turbine type is 2.3 MW and the rotor diameter is 82 m. It has 3 blades, a swept area of 5,281 m^2, a hub height of approximately 80 m and a weight of 135 tons. Its start-up wind speed is 3 m/s, its nominal wind speed is equal to 13.5 m/s and its maximum wind speed is of 34 m/s [38, 39]. The nominal wind speed is the speed at which the turbine operates best and outputs the maximum possible energy, whereas the maximum wind speed is that above which the wind turbine system stops generating power. The wind speed in Marjaayoun is adequate for that turbine because, as previously mentioned, the annual average speed at 80 m above the ground is greater than 10 m/s.

In order to design the wind turbines layout, the most important constraint to be taken into consideration is wind turbines spacing.

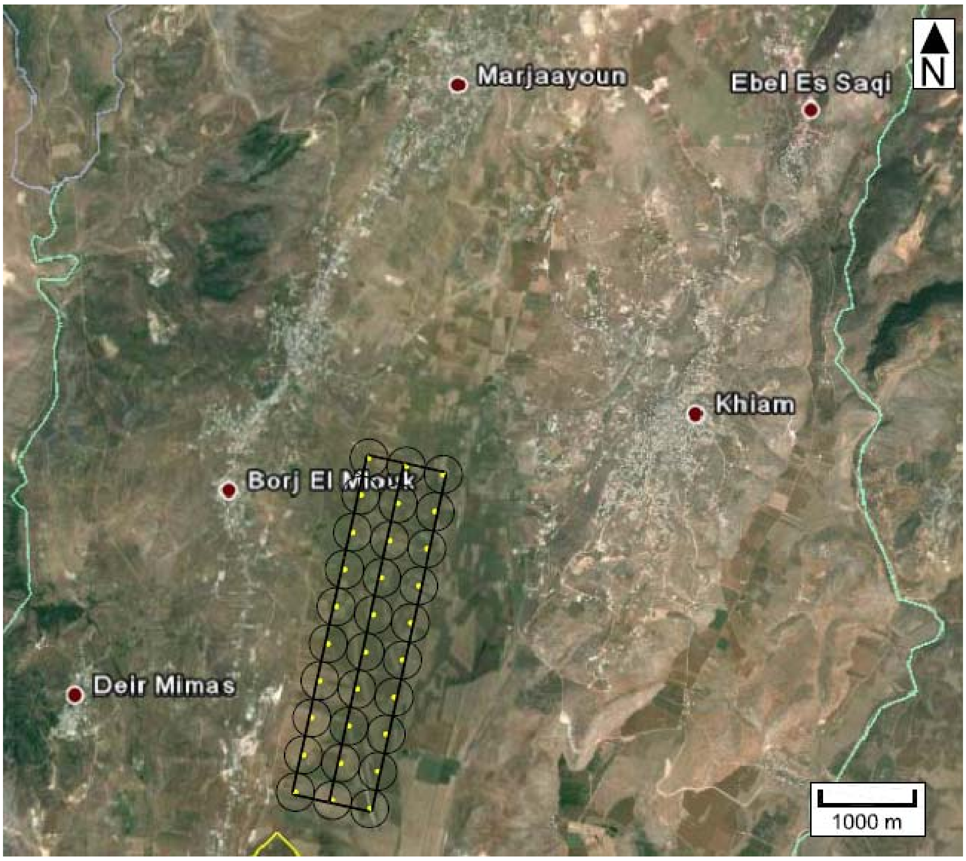


Figure 11: Wind Farm Layout Location (zoom-out)

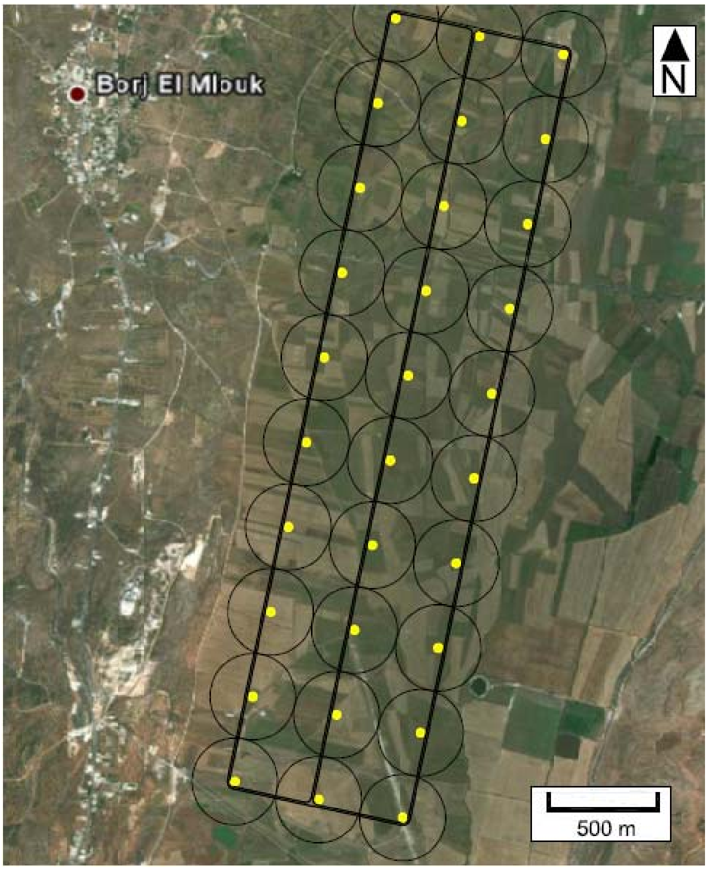


Figure 12: Wind Farm Layout Location (zoom-in)

The minimum spacing from center-to-center required between wind turbines is commonly taken to be equal to five rotor diameters which in case is equal to 410 m [40]. Based on this constraint and based on the site area, 30 E82-2300 wind turbines were evenly distributed over the site according to the layout shown in Figure 11 and Figure 12. This spacing is shown in the figures by black circles and the wind turbines are represented by yellow dots. The detailed analysis regarding the choice of the site, turbine type, their number and their layout (Figure 12) was carried out in a separate study. In this study, this layout was adopted and assumed fixed in the optimization process.

Having 30 E82-2300 wind turbines, the maximum wind farm power is equivalent to 69 MW. Assuming that a household in Lebanon requires around 800 W on average, this wind farm can supply a maximum of 86,250 households which is a relatively high number [41]. In fact, assuming each household includes on average 5 persons, there would be enough electricity generated for over 431,250 individuals which represents around 10% of the Lebanese population. However, it is important to note that this 10% corresponds to the maximum amount of power that can be generated, which will not be reached all over the year. Additionally, this 10% is representative of the households only and does not cover commercial, industrial and public needs. The demand of electricity in Lebanon is estimated to be around 2500 MW, so the maximum amount that can be generated by that wind farm would cover around 2.8% of the total demand [42].

5.2. Construction Quantity Take-off

As part of construction management and construction planning, quantity take-off and estimating quantities is an essential step. It is important because it allows the contractors to estimate the durations of the activities given the number of resources and productivities. It also allows the contractors to estimate the material costs. In the following sections, the quantities for each activity will be calculated.

5.2.1. Topographical Survey

For the first activity, which is topographical surveying, the quantity required is the area to be surveyed. To that end, the location of the site is located on Google Earth and using the polygon tool, the area is marked so that the area can be found. The area is equal to 3.42 km^2 [845 acres].

5.2.2. Earthwork

The quantities for the earthwork consist of the volumes of cut and fill. In order to get these values, road design needs to be performed. The road is designed in a way to allow vehicles to access all wind turbines. The horizontal alignment of the road is shown in Figure 12. The specifications adopted for the road design are shown in Table 4 and the cross-section of the road is shown in Figure 13. The road is made of two lanes of 3.65 m each and two shoulders of 2.5 m each. The slope of the lanes is 2%, as for the shoulders, 4% [43].

Table 4: Road Design Specifications Used

Criteria	**Value**
Minimum turning radius	32 m
Minimum longitudinal radius	200 m
Maximum allowable longitudinal slope	10%
Road width	12.3 m (including two lanes and shoulders)

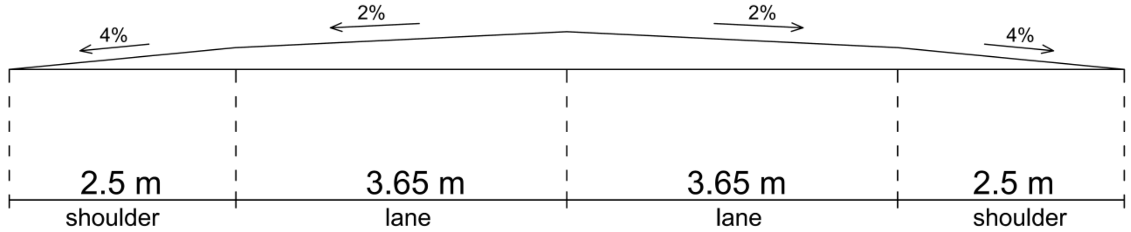


Figure 13: Road Cross Section

Figure 14 is a snapshot of the vertical profile of the road. The red line represents the existing alignment, whereas the blue one corresponds to the designed road.

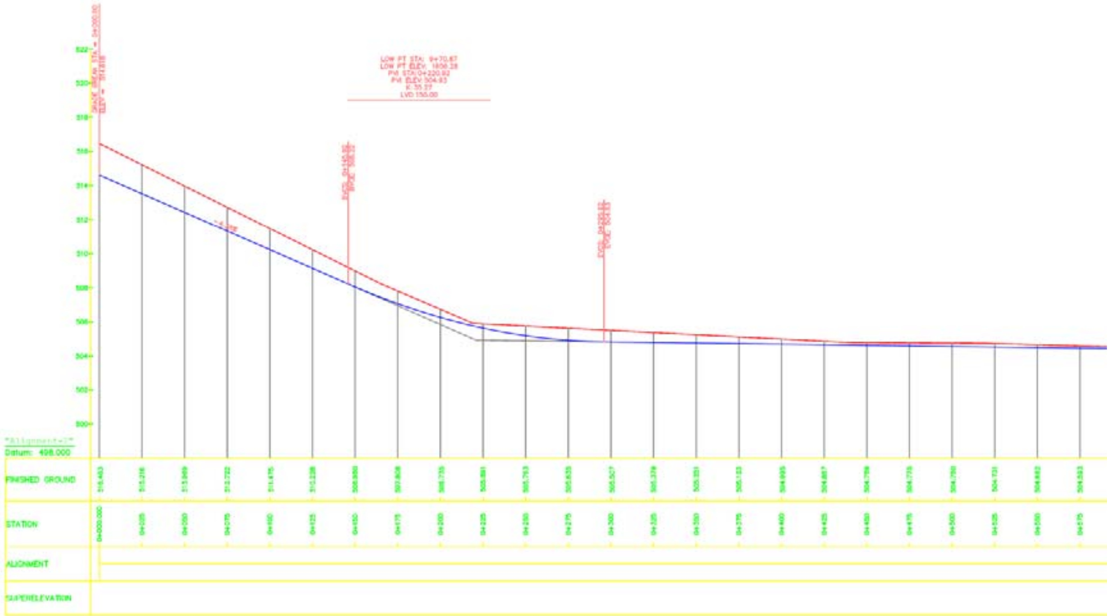


Figure 14: Road Vertical Profile Snapshot

Based on the road design, there are 60,416 m^3 of soil to be cut in comparison to 171,309 m^3 of soil to be filled. Therefore, there is a need of 110,893 m^3 of borrow on site to cover the amount of fill that cannot be covered by the cut quantity. Moreover, the road length is equal to 14 km.

5.2.3. Road Construction

The quantities required for road construction are the area of the road and the volume of aggregate base course needed. Having a road of 14 km length and a width of 12.3 m (i.e. 3.65 m * 2 + 2.5 m * 2), the total area covered by the road is equal to

171,200 m^2. The aggregate base course is a layer of 30 cm. Therefore, a volume of 51,660 m^3 of aggregate base course is needed for the project.

5.2.4. Foundation Construction

Each of the thirty wind turbines will be standing on a spread footing. A typical footing design for E82 wind turbines is shown in Figure 15 and Table 5 [44]:

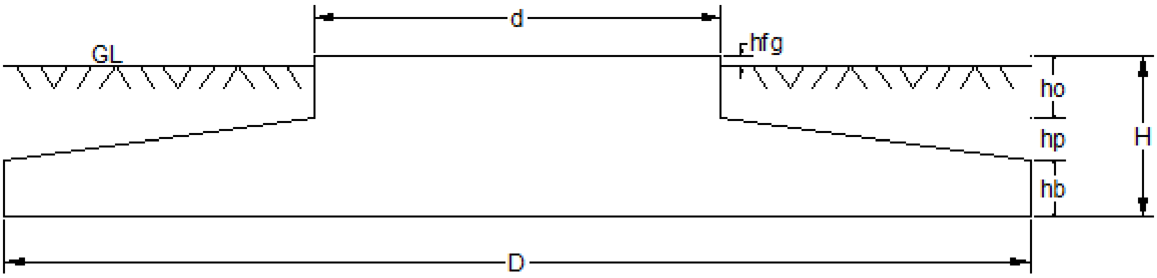


Figure 15: Foundation Design for E82 Wind Turbines

Table 5: Key for Figure 15: Foundation Design for E82 Wind Turbines

	Symbol	Dimension
Outer Diameter	D	16.70 m
Base Diameter	d	6.60 m
Foundation Height	H	2.60 m
Base Height	hb	1.00 m
Inclination of plinth	hp	0.70 m
Height Outside Diameter	ho	0.90 m
Difference top of foundation – top of ground	hfg	0.15 m
Concrete Class and Volume	C 25/30	311 m^3
Reinforcement Steel and weight	BSt 500 S (A)	32.8 t

The activities involved in this package are as previously mentioned, formwork erection, steel installation, concrete pouring, curing and backfilling, so the quantity for each needs to be calculated. Based on the above and following quantity calculations, the results are as follows: 257.78 m^2 of formwork, 32.8 tons of steel, 311 m^3 of concrete, 292 m^2 of curing and 333.88 m^3 of backfilling are required for each wind turbine foundation.

5.2.5. Electrical Works

Regarding electrical works, the length of cables and the volume of soil that needs to be excavated for the electrical trenches are the quantities needed. The calculation of these quantities is directly related to the road length because the electrical trenches and cables will be passing by right next to the road. Consequently, 14 km of cables are needed for this project. Considering a trench having a cross section of 1.5 m^2 * 1.5 m^2, 31500 m^3 of soil are to be excavated.

5.2.6. Wind Turbines Erection

Finally, as shown in the layout in Figure 12, the wind farm consists of 30 E82 wind turbines. An additional number needed for the turbines installation is the wind speed. Based, on the information provided earlier regarding the wind speed in Marjaayoun, it is assumed to vary uniformly between 5 and 13.5 m/s [4]. As previously mentioned, crane operations need to be stopped when the wind speed is greater than 9.8 m/s and can only proceed when the wind speed becomes lower than that value.

5.3. Construction Costs

The second set of data required as input for the simulation model and for the optimization, in addition to the material quantities, is the cost data. The labor, equipment and material costs are presented in the following sections. This set of data is also important to get a total estimate of the project cost. The cost data was mainly acquired from the Lebanese market and cost data manuals [45].

5.3.1. Labor Cost

All activities require human presence whether it's by having crews working or equipment operators using the vehicles. Since the case study is in Lebanon, typical labor wages from Lebanon were used. Table 6 presents these typical daily wages.

Table 6: Typical Labor Daily Wages in Lebanon

Position	**Daily Wage**
Unskilled Worker	$20
Chief of Party	$70
Foreman	$50
Truck Driver	$35
Equipment Operator	$50
Carpenter	$40
Rodman	$40
Electrician	$50

Using the data from the above table, the daily costs of the crews involved in the on-shore wind farm construction process are calculated. In addition to laborers' wages, the tools' cost were added as well. For example, the surveying crew includes the cost of an electronic level. These crews' daily costs are shown in Table 7.

Table 7: Daily Costs of Crews Involved in Wind Farm Construction Process

Crew	Daily Cost
Survey Crew	$230
Formwork Crew	$140
Steel Crew	$160
Concrete Crew	$220
Two Common Laborers	$40
Electrical Crew	$150
Tower Erection Crew	$170
Bolting Crew	$130

5.3.2. Equipment Cost

In addition to the labor cost, the equipment cost is required as well and is found based on local and international manuals. The equipment costs are shown in Table 8 and are divided under the different project packages. The vehicles' daily costs include the cost of their operators.

5.3.3. Material Cost

The third cost item is the material cost. In order to calculate it, both the quantity of materials and the unit cost of these materials are required. The quantities were previously calculated. As for the unit costs for most of the materials, estimates from the Lebanese market were acquired. A typical price range for wind turbines is $1.2 million per MW [46]. The E82-2300 turbines in this study, having a power of 2.3 MW, were assumed to cost around $2.76 million each. The detailed material cost data for each activity and for the whole project are shown in Table 9.

Table 8: Equipment Daily Cost for Each Construction Package

Package	Equipment Daily Cost
Earthwork	$4,941
Road Construction	$3,633
Foundation Construction	$1,892
Electrical Works	$1,000
Wind Turbine Installation	$2,830

Table 9: Material Cost

Activity	Unit	Quantity	Material Total Cost
Surveying	km^2	3.42	$15,380
Overlaying Road	m^2	172,200	$3,151,260
Formwork Installation	m^2CA	7,733 (257.78*30)	$3,200,000
Concrete Pouring	m^3	9,330 (311*30)	
Steel Rebars Installation	ton	984 (32.8 *30)	
Concrete Curing	m^2	8760 (292 *30)	
Cable Installation	km	14	$397,208
Turbine Installation	Ea.	30	$82,800,000
Total Material Cost			**$89,563,848**

5.4. Activities' Delay Times

Thirdly, the delay times are adjusted as explained in Chapter 3, depending on the quantities of each package's entity. For instance, dividing the Marjaayoun site into 28 surveying sub-areas leads to each entity quantity being 122,143 m^2 (Total surveying area= 3.42 km^2 /28). Based on this quantity and a daily output of 13,355 m^2, the delay time is thereby 9.14 days per entity. Similarly, in the case of excavation, the delay time per entity was obtained by dividing an entity quantity equivalent to a truck capacity of 9 m^3 by the excavation daily output of 489 Bank m^3. The delay is thereby 0.0184 day per entity. The same logic was adopted for obtaining the other activities' delay times.

5.5. Simulation and 5DVisualization

For this case study, it is assumed that the range for each resource is different. For example, skilled and specialized crews such as bolting crews involved in turbine erection are assumed to vary between one and a maximum of three, while other more common resources such as the dump trucks are assumed to vary between four and eight. As such, each resource is assigned a range within which its quantity may vary. Generally, scarce resources are assigned a maximum of three while more common ones are assigned a maximum of six or eight.

Based on the data obtained in the previous sections, the simulation model was run. As a first step, the model was run with the average number of available resources within each resource type specified range. Before presenting the results, few assumptions need to be highlighted. The way cost is calculated, for each resource, is based on the assumption that when a resource is assigned to a construction package it remains on the construction site until that specific package is fully executed.

Following the initial run, the project duration was found to be 548.5 days equivalent to 2.1 years (considering a 5 day work week) as shown in the following Gantt chart (Figure 16) and the total cost incurred for the project was approximately $94.79 million (Figure 17). The utilization rates for each resource are also shown in Figure 18.

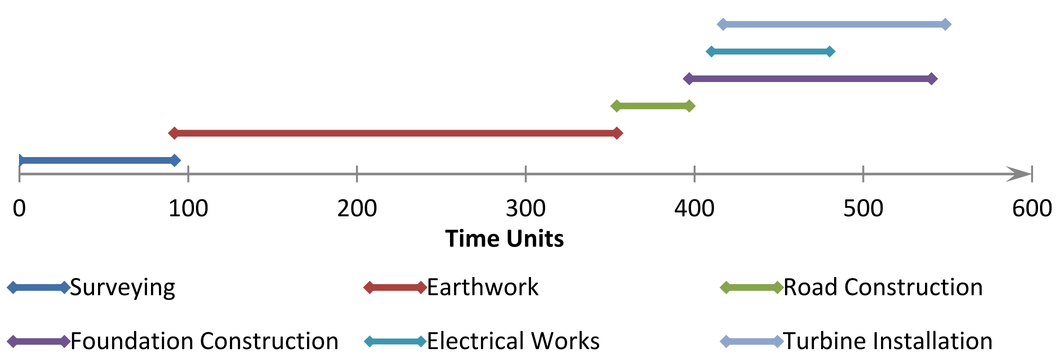


Figure 16: Gantt Chart of the Project

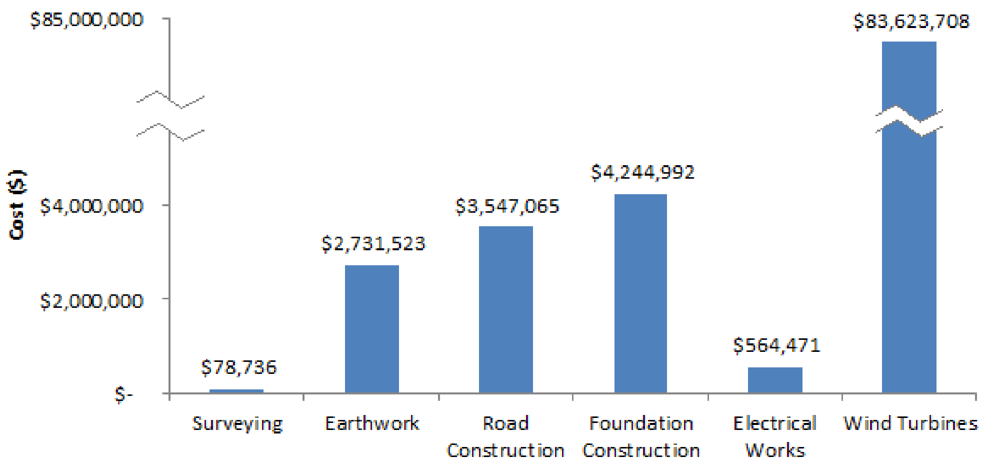


Figure 17: Total Cost for Each Package

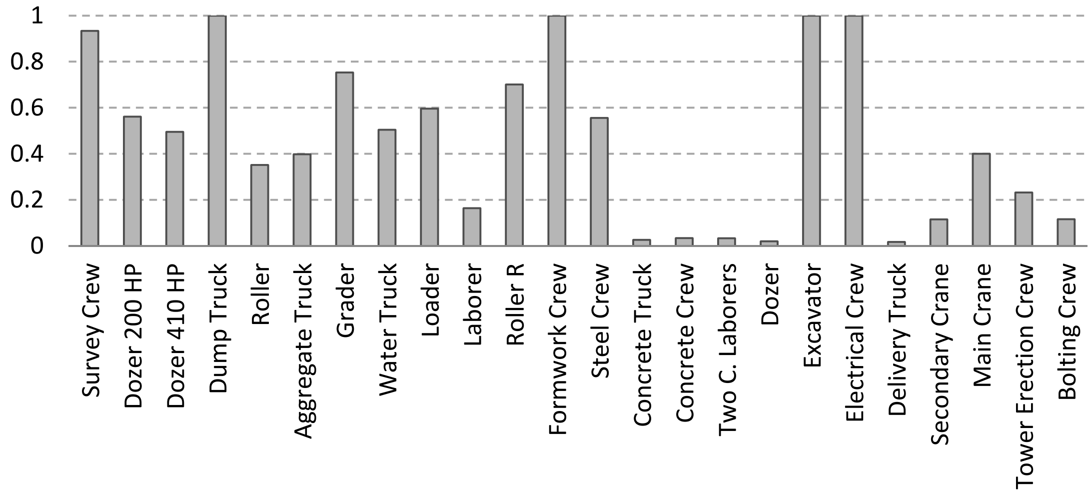


Figure 18: Initial Resource Utilization Rates

Next, a 3D animation of the whole process was created to verify and validate the simulation model and initial results. Although the visualization had been previously explained in details, it is still useful to provide an additional explanation for the case study, since some parts of it would change from a case study to another. First of all, the network added for the foundations and wind turbines is made of 30 nodes overlapping with the location of the wind turbines. The network for the electrical works, earthworks and road construction is overlapping with the horizontal alignment of the road. Lastly, the network for surveying consists of nodes equally spread over the site. The selected number of nodes is 28.

Second of all, the scale needs to be selected based on the specific site. The scale adopted for this case study is 0.24 pixels per meter, which allows the actual site size to fit in the computer window. As for the time scale, one time unit is modeled to represent the working hours of one day i.e. eight hours. The non-working times are not shown in the animation. Given the scales, the speeds of the workers and the vehicles are specified as follows: 82,244 pixels/time unit [4.5 km/hour] for the crews and laborers, 61,605 pixels/time unit [32 km/hour] for the vehicles and trucks, and 38,166 pixels/time unit [20 km/hour] for the cranes.

After all the information is integrated, the result is a pictorial representation of the actual operations being conducted in a 3D virtual environment. The animation can be replayed at varying speeds and the user can jump to any desired time and inspect the state of the system. Figure 19 presents AnyLogic animation snapshots of the Marjaayoun wind farm construction operations.

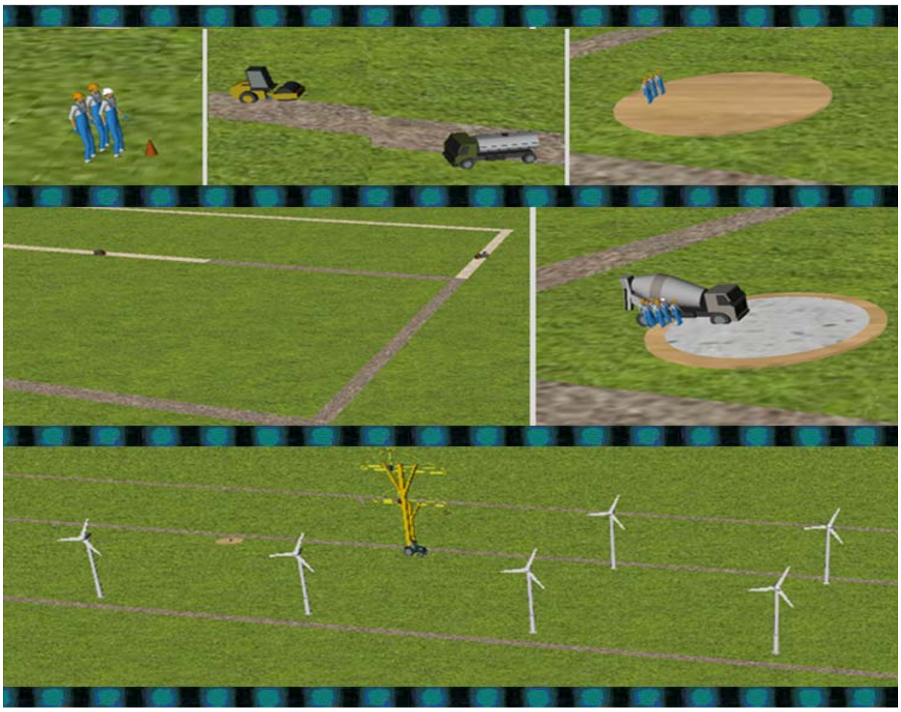


Figure 19: AnyLogic Animation Snapshots of the Wind Farm Construction Operations

The final result and output of the 5D visualization is shown in Figure 20. It includes the 3D animation, the cost (labor and equipment only) and time data for each package.

	Duration	Cost		Duration	Cost
Surveying:	46.086	$ 63,598.756	Cables Installation:	45.183	$ 13,554.91
Earthwork:	143.215	$ 1,882,851.987	Electrical Trenches Excavation:	73.997	$ 73,991.618
Road Construction:	111.842	$ 874,939.917	Turbine Installation:	53.899	$ 466,180.881
Foundation Construction:	73.997	$ 593,190.802	**Total:**	**375.14**	**$ 3,968,308.87**

Figure 20: Case Study 5D Visualization Screenshot

The model also allows the viewers to access more detailed cost data. In fact, the viewers can access cost data for every resource in every package as shown in Figure 21. Moreover, detailed data is also available for the duration, as the schedule is presented in the form of a Gantt chart and the utilization rate for every resource is shown in a bar chart. These figures are shown in the results section that follows.

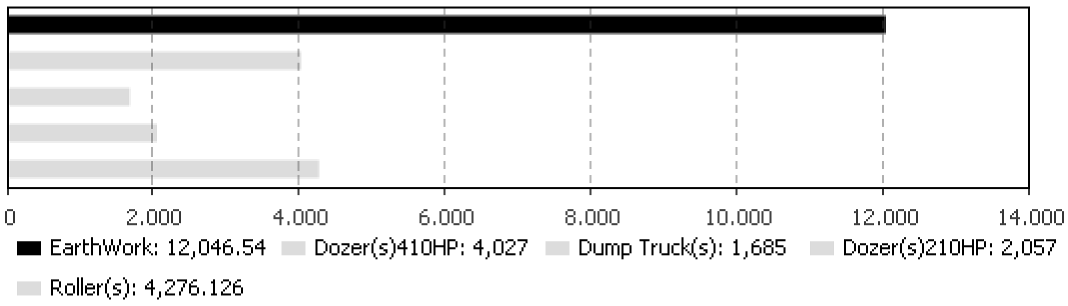


Figure 21: Example of Cost Data Output

5.6. Optimization Results and Findings

The parameters and assumptions used to create Maarjayoun model include a fixed layout, fixed turbine type, fixed location and fixed road alignment. These were considered to be fixed during optimization and the optimization was solely based on the number of resources assigned for each activity.

5.6.1. Initial Results

Figure 16, Figure 17 and Figure 18 present the results of the initial run. These results will be referred to as the initial results. At a first glance, few issues can be highlighted. In fact, regarding the schedule, the foundation construction and the electrical works are packages that happen in parallel. This implies that the total duration of the project is only affected by the longest duration of these packages, so there is no benefit in aiming at reducing the duration of a package other than the longest one between these two. In the initial schedule a big difference is found between these packages' durations varying from 70.3 time units for electrical works to 143.5 time units for foundation construction. It would make sense to allocate resources in a way to bring these two durations as close as possible to each other and to avoid adding extra resources to accelerate one without resulting in the acceleration of the whole project or at least without resulting in a cost decrease. Another issue, which is even more alarming, is the uneven utilization rates between the different resources. In fact, as shown in Figure 18, some of the resources have a very low utilization rates (less than 0.1 in some cases) while others have a utilization rate of 1. Very low utilization rates for resources mean that these resources are spending a lot time idle on site which is equivalent to a waste of money. Utilization rates equal to 1 coupled with resources having low utilization rates means that the resource allocation is unbalanced and resources with the low utilization rates need to be increased. Therefore, it is clear that the initial project performance can be greatly improved. To that end, the construction process is optimized.

To improve the optimization experiment and to get the best possible results, the problem is simplified by dissecting the model into sub-models. In fact, since the first three packages (surveying, earthworks and road construction) are finish-to-start activities, optimizing them separately is equivalent to optimizing the three of them as once. When optimized separately, clearer and faster results can be gathered.

5.6.2. Optimization of Activities with one Resource

The first of the independent packages is topographical surveying and has only one resource which is the surveying crew. Having only one resource the range of which is one to six, the number of possible outcomes for this activity is equal to six. So it makes sense to evaluate all possible outcomes instead of running the optimization experiment, the purpose of which is to lead us to the optimum outcome with the fewest runs. As a matter of fact, the optimization experiment becomes useful for packages with a high number of resources such as earthworks, road construction, foundation construction and wind turbines erection. As for the packages with a single resource, all outcomes are evaluated and the results are shown in Table 10.

Table 10: Results for Processes with One Single Resource

#[4]	**Surveying** Surveying Crew			**Cables Installation** Electrical Crew			**Trench Excavation** Excavator		
	UR[1]	**Dur.[2]**	**Cost[3]**	**UR[1]**	**Dur.[2]**	**Cost[3]**	**UR[1]**	**Dur.[2]**	**Cost[3]**
1	1	256.4	58,976	1	87.2	13,083	1	148.9	148,855
2	1	128.5	59,090	**0.97**	**45.2**	**13,560**	0.97	76.9	153,713
3	0.93	91.8	63,358	0.94	31.2	14,037	0.94	52.9	158,567
4	1	64.4	59,285	0.97	22.8	13,679	**0.97**	**38.5**	**153,820**
5	0.93	55.2	63,508	0.89	20	14,991	0.89	33.7	168,266
6	**0.93**	**46**	**63,480**	0.86	17.2	15,467	0.86	28.9	173,128

[1]: Utilization Rate; [2]: Duration in time units; [3]: Cost in $; [4]: Number of Resources

For the case of surveying, the decision is simple. Clearly and naturally, the more resources are applied, the faster the process is completed. The utilization rate is nearly constant. The cause of the slight variations from 0.93 to 1 was understood by observing the 3D animation. The reason is depending on the number of resources, the crews might finish work at the same time or some might finish before others. In the first case, the utilization rate is equal to 1, while in the other cases, it slightly decreases because some crews have to wait for the others to finish their work. This fluctuation is also reflected in the varying cost. In all cases, these variations are minimal (around 7%) and did not form the basis of selection. That said, it would be best to allocate six surveying crews which would shorten the execution from 256.4 to 46 time units without significantly affecting the utilization rate and cost. The same logic is applied for the other two remaining activities. However, no decision is to be made at this point since these activities are not independent as previously described, they are overlapping with the foundation construction. The allocation decision is made only when the latter package is optimized.

5.6.3. Optimization of Activities with more than one Resource

All the remaining packages have more than one resource working at the same time which makes the optimization quite harder, whereby the need to use the software's *Optimization Experiment*. Earthworks and road construction are independent so they can be optimized independently. To that end, the optimization experiment is first run for earthworks only. The output of the experiment is shown in Figure 22. The gray graph referred to as "current" represents the total cost for each simulation run. The blue graph referred to as "best feasible" represents the best resource allocation so far. It can be noticed that with more runs, the best feasible graph is stabilized and stops decreasing which means that the software is no longer finding better solutions. As such, regarding earthworks, the resource allocation that yielded the lowest cost is as follows: eight dump trucks, three dozers 200 HP, two dozers 410 HP and two rollers.

Similarly, the same experiment is repeated for the road construction and the output is shown in Figure 24. The lowest cost was found for the following allocation: two loaders, four graders, two rollers, two water trucks, two aggregate trucks and three laborers. The exact optimum costs can be found in Table 11.

The remaining packages are not independent, so the optimization procedure is slightly different. As previously explained, shortening the duration of an activity happening in parallel to another that is of greater duration does not shorten the total project duration. Consequently, the goal is to reduce each package's duration as long as it reduces the project duration. The first step is to start by optimizing the cost of foundation construction and wind turbines erection. The output graphs are shown in Figure 23 and Figure 25 respectively.

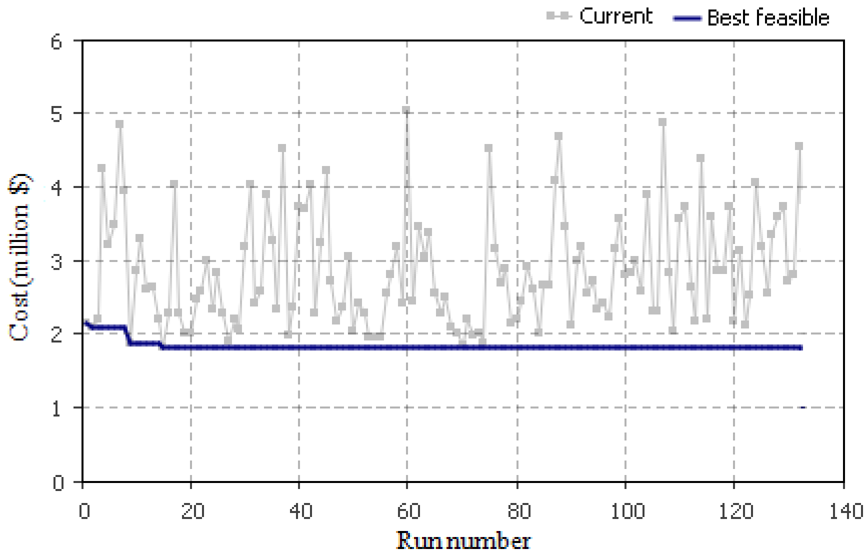


Figure 22: Earthworks Cost Optimization

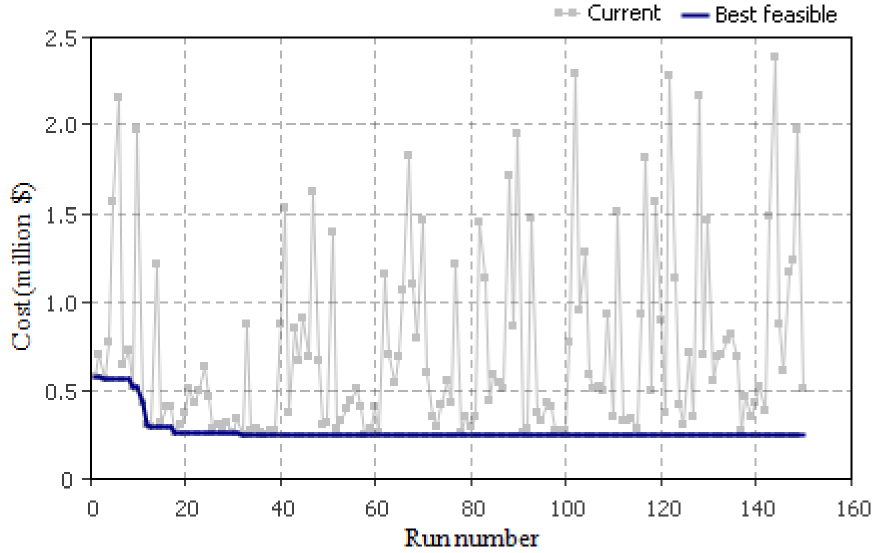


Figure 23: Foundation Construction Cost Optimization

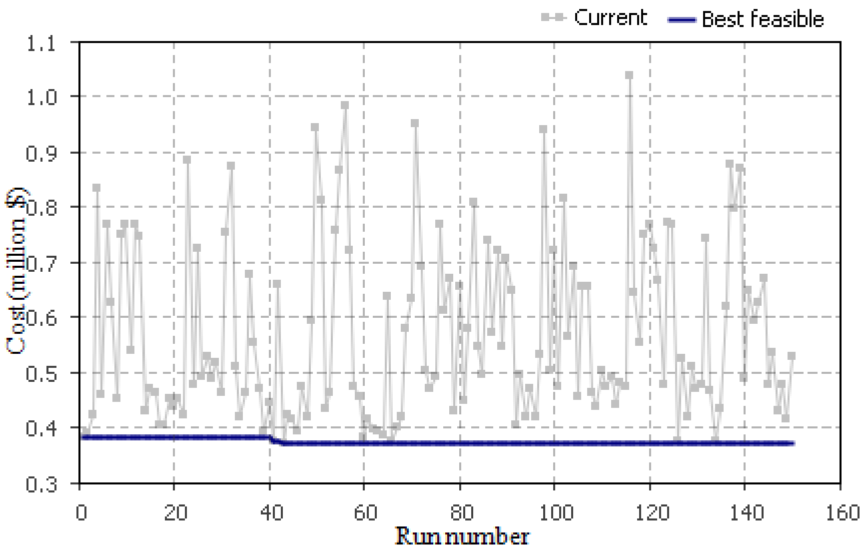


Figure 24: Road Construction Cost Optimization

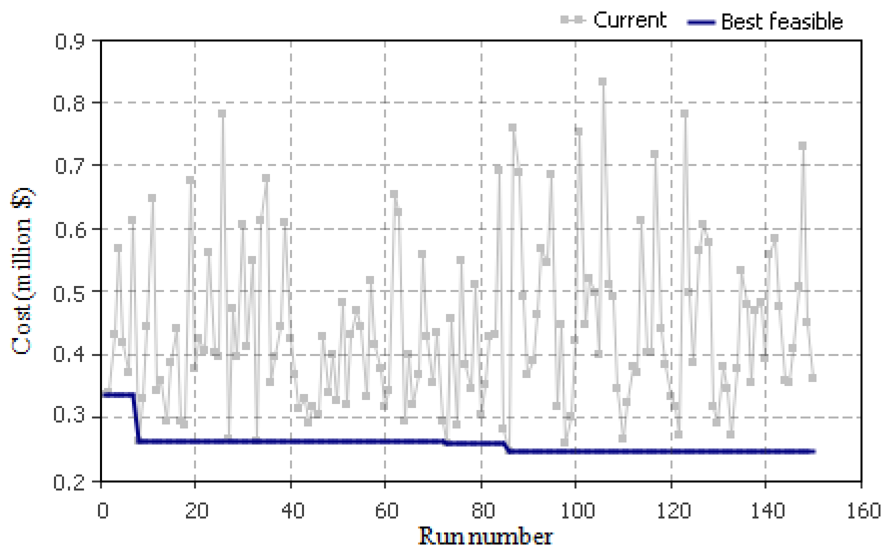


Figure 25: Wind Turbines Installation Cost Optimization

The results show that the lowest labor and equipment cost for the foundation construction is at $244,283 and occurs for the allocation of six steel crews, six formwork crews, one concrete truck, one concrete crew, one dozer and one common laborer. The duration for these resources is 61.8 working days. As for wind turbines erection, the lowest cost is at $287,732 and occurs for the allocation of two main cranes, two tower erection crews, two bolting crews and one of each of the following: secondary crane and delivery truck. The duration for these resources is 55.2 working days.

Given these two packages' durations, it is now possible to select the resource allocation for the remaining two activities: cable installation and electrical trenches excavation. Similarly, as long as these two activities' durations are less than 61.8, the project duration is not increased. As such, referring to Table 10, the number of resources selected is the one that leads to the lowest cost among the options that have a duration shorter than 61.8. Accordingly, two electrical crews and four excavators are selected.

5.6.4. Optimized Results

Given the results found in the previous sections, the model is run for the optimized resource allocation. The optimized schedule is shown in Figure 26, the optimized resource utilization rates are shown in Figure 27 and the optimized cost in Table 11. With these resources, the project duration is reduced from 548.5 to 275.5 working days, which is a 49.8% reduction. Assuming a 5-day work week, the duration was reduced from 2 years, 1 month and 10 days to 1 year and 21 days. The cost was reduced from $94.8 million to $92.5 million which is a 2.4% reduction.

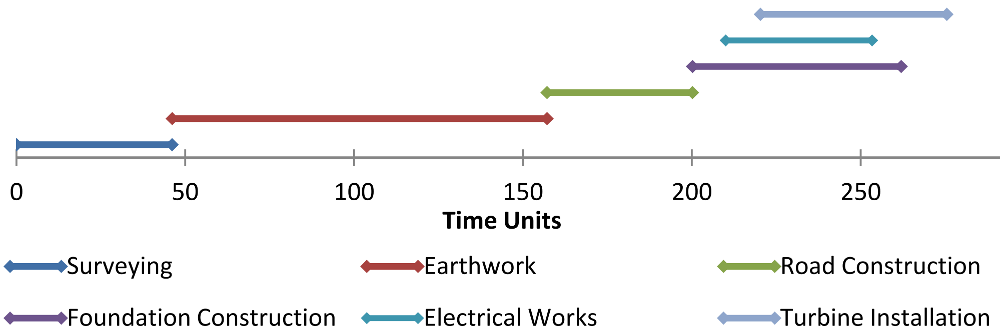


Figure 26: Project Gantt Chart After Optimization

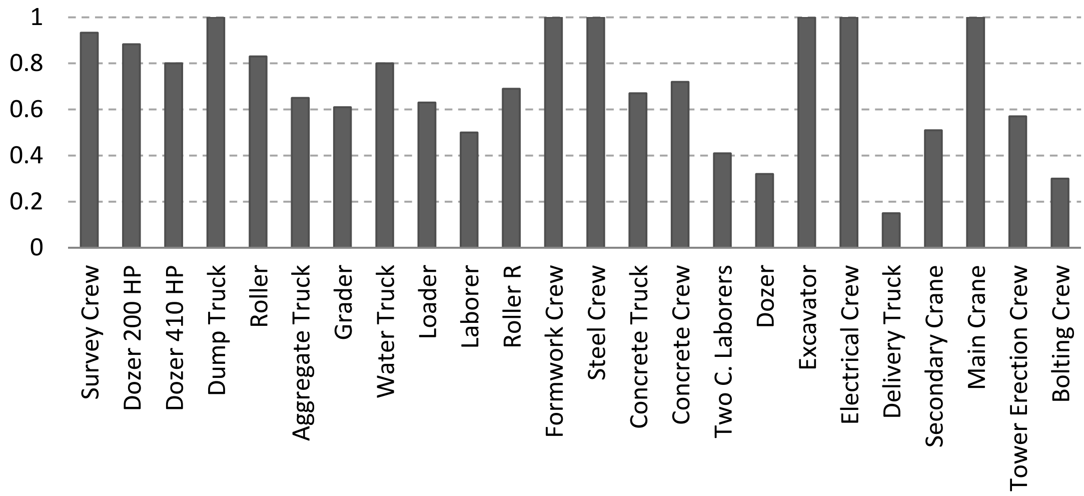


Figure 27: Optimum Resource Utilization Rates

When comparing Figure 18 and Figure 27, it is clear that the utilization rates have considerably increased which means that idle time and wastes were greatly reduced. The load between the resources is more balanced as well. Some of the resources still have a low utilization rate. The ones with a utilization rate below 0.5 will be addressed. In fact, one of each of the following is allocated to the project: two common laborers crew, dozer 200 HP for the road and delivery truck. A low utilization rate for these resources is acceptable since only of them is allocated, to increase their utilization rate, other resources need to be increased which cannot be done since a constraint is placed on the maximum number of resources. As for the resources used for the wind turbine erection process, fair utilization rates are expected because there is a constraint on wind speed. So, the idleness of resources is expected due to weather conditions and not due to bad planning. This is not applicable to the main crane, since for modeling purposes, it was assumed that the main crane is in use at all times which makes its utilization rate not fully representative. In total, the utilization rates increased from an average of 0.46 to 0.71. The standard deviation decreased from 0.35 to 0.25 which shows that the load is now more evenly distributed.

Table 11 summarizes the comparison between the initial and optimized results. It shows the duration and cost for every package before and after optimization. It also presents the percentage change between the initial and optimized scenarios. The table clearly shows that the duration and cost for the project greatly decreased.

Table 11: Initial vs. Optimized Results

	Duration (in time units)			**Total Cost** (in million $)		
	Initial	**Optimized**	**% change**	**Initial**	**Optimized**	**% change**
Surveying	91.8	46.1	-49.78%	0.079	0.079	0.00%
Earthworks	262.1	111.0	-57.65%	2.732	1.819	-33.42%
Road	42.9	43.1	0.47%	3.547	3.518	-0.82%
Foundations	143.5	61.8	-56.93%	4.245	3.444	-18.87%
Electrical Works	70.3	45.2	-35.70%	0.564	0.564	0.00%
Wind Turbines	131.6	55.2	-57.98%	83.624	83.088	-0.64%
Total	**548.5**	**275.5**	**-49.77%**	**94.790**	**92.512**	**-2.40%**

CHAPTER 6

CONCLUSION

6.1. Summary of Research Findings

The optimization of on-shore wind farms had previously focused on improving the design of wind turbine systems, the layout, the maintenance procedures, etc. This research work proved that there is still room to further optimize such projects by focusing on one major component of this supply chain, i.e. the construction process. Simulation, 5D visualization and optimization proved to be very beneficial tools indeed that can be used to improve construction performance. Simulation's main advantage is that it allows the user to predict the outcomes of different scenarios prior to the construction. 5D visualization is mainly useful in verifying and validating the simulation model and in helping the viewers to better understand the whole construction process. Lastly and most importantly, optimization allowed minimizing the project costs and duration.

The first step to design the simulation model consists in clearly defining the construction activities and relationships. The second step is to gather all the general required data that will serve as input to the model, such as the resources required and the productivities. Such data is enough to create a generic model that can be customizable to any on-shore wind farm construction. However, to test the simulation model on a certain case study, more input data are required such as the required quantities for each activity, wind speed and construction costs. To that end, the model was tested on a case study in Lebanon which would greatly benefit from the construction of a wind farm. The case study was selected to be in Marjaayoun based on several factors such as the elevated wind speed there, the convenient topography and the adequate geology. The quantities for all activities were calculated in details and cost data was gathered. Once all the required data was available, it was input to the model which would output the project detailed durations and costs based on the number of resources allocated for the different activities.

Afterwards, the 5D visualization was modeled and was mainly useful to validate that the simulation model reflects reality and to provide the viewers with an animation to help them better understand the process. Once the simulation model and visualization ready, the on-shore wind farm construction process was ready to be optimized. The goal of the optimization was to find the optimum resource allocation that would result in the lowest construction costs and shortest project duration. The results were in fact significant as a simple resource allocation alteration resulted in a project duration decrease of 49.8% (equivalent to around one year reduction) and a project cost decrease of 2.4% (equivalent to around two million dollars decrease). One of the advantages of the designed simulation model is that it can be easily adapted to other case studies and can be easily used by other users having a user-friendly interface that is easy to use.

6.2. Research Significance

The significance and contributions of this research study are as follows:

- The research effort highlighted that modeling one important component of the wind farm supply chain, construction operations, is of paramount importance and contributes positively to the overall process.

- It showed that simulation modeling can indeed be a useful tool when it comes to construction planning.
- The proposed study offers the generic simulation modeling of the whole on-shore wind farm construction process from topographical survey to wind turbines installation and provide generic data (e.g. materials, resources, daily productivities, etc.) that can be adopted for any other project and easily tailored to match its scale.
- This study uses AnyLogic 7 (Educational Version), which has been rarely used in construction, and takes advantage of its various features to not only simulate wind farm construction processes in detail but also verify and validate their credibility by visualizing them in 3D.
- This research effort visualizes project time and cost data and thereby presents a 5D visualization model as well as uses the available optimization features to efficiently allocate resources and minimize time and cost.
- This paper, modeling for a specific challenging site in Lebanon (Marjaayoun), can serve as a guide for using AnyLogic 7 for simulation, 5D visualization and optimization of not only wind farm construction operations but any other construction operation or even other processes in various fields.

6.3. Research Limitations and Recommendations for Future Research

Some limitations of the current study need to be further studied and addressed in future research works. These include the following:

- The created model was tested on one case study. More case studies could be tested which might reveal additional challenges not taken into consideration in the current model.
- Time-cost tradeoff was not taken into consideration. Further research may evaluate the extent to which this tradeoff affects the results and whether it would lead to different optimum resource allocations. This would also require taking into consideration the indirect costs which as well were not included in the scope of this study.
- Future studies will address wind farm layout and road network layout optimization problems, and an advanced optimization scheme will be designed to tackle all different problems and reach optimal results. Sensitivity analyses will be carried out as well for better understanding of optimal solution changes.
- Despite the construction performance improvements, it is important to highlight that optimization was based specifically on resource allocation and utilization, and did not take into consideration other factors that could have also affected the results such as the congestion of resources, the effects of learning curve on labor productivity, etc.
- Future studies could widen the scope of the model to include the Operations and Maintenance (O&M) phase and assess how that phase affects the viability of the project. Other aspects that could be evaluated as well are the access roads to reach the site, the construction of the substation and other works pertaining to the supply chain of on-shore wind farms.
- Other performance factors could be evaluated, in addition to duration and cost. A few examples are safety and construction impact on the environment.

- Constraints were placed on the number of resources. In the future, real data from contractors (e.g. set of available resources) can be acquired and used in the optimization process to efficiently assess results and validate the model.

Aside from the future steps based on current limitations, it is interesting to highlight that the model in this case study is a discrete event simulation model. Nowadays, different simulation methods are gaining popularity such as Agent Based Modeling (ABM). Additional research efforts could recreate the model for the same construction process using different simulation methods such as ABM, which is also provided by the same software used in this study, AnyLogic. The advantages of one modeling approach compared to another when modeling such construction projects could be listed.

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