processes

Article

Rapid Site Selection of Shale Gas Multi-Well Pad Drilling Based on Digital Elevation Model

Jijun Zhang, Nan Hu * and Wenjing Li

School of Economics and Management, Southwest Petroleum University, Chengdu 610500, China; 198931010017@swpu.edu.cn (J.Z.); 201031010092@swpu.edu.cn (W.L.)
* Correspondence: hunan@swpu.edu.cn

Abstract: Drilling and completion platform construction is a fundamental part of oil and gas reservoir development, and the location of construction directly affects the whole process of shale gas drilling and development. Due to the complex surface conditions and fragile ecological environment in mountainous areas, having an appropriate platform location can significantly reduce shale gas development and environmental costs. The DEM (digital elevation model) includes geographic elevation, surface complexity, land use type, and other data, so it can be used for rapid site selection for shale gas multi-well pad drilling. In this study, first, research results related to drilling platform site selection were analyzed and summarized, and then a platform site selection method aiming to minimize the total well construction cost was developed. Second, the well construction costs were decomposed into the surface construction costs and the underground construction costs, and the site selection model with the lowest total multi-well pad construction costs was established. Third, ground feature data obtained from DEM (digital elevation model) processing were substituted into the site selection model and solved using the genetic clustering algorithm. Finally, two practical cases were used to verify the research method developed in this study. The results show that the platform site selection results can be used to not only guide the formulation of development plans, but also to reduce the scope of the field investigation in the process of site selection, reduce the intensity of field work, and improve the work efficiency.

Keywords: shale gas; multi-well pad drilling; platform location; genetic clustering algorithm

check for updates

Citation: Zhang, J.; Hu, N.; Li, W. Rapid Site Selection of Shale Gas Multi-Well Pad Drilling Based on Digital Elevation Model. *Processes* **2022**, *10*, 854. https://doi.org/10.3390/pr10050854

Academic Editors: Tianshou Ma and Yuqiang Xu

Received: 4 March 2022
Accepted: 21 April 2022
Published: 26 April 2022

1. Introduction

The success of the "shale gas revolution" in the United States and the rapid growth of shale gas production in China have proven that the multi-well development mode has a significant impact on the improvement of shale gas development efficiency [1,2]. The shale gas production cycle has a direct impact on commercial development benefits. Shortening well construction time, accelerating production, and improving development efficiency are the only ways to realize commercial development, resulting in higher requirements for shale gas development engineering technology. The location of a multi-well drilling platform for shale gas directly affects the total drilling footage, which, in turn, affects the total cost of drilling and completion. In addition, the location of the platform has a great impact on the cost of the preliminary infrastructure construction, the difficulty of drilling and completing wells, and the implementation of stimulation measures for shale gas development. Under the current trend of the integration of geology and engineering in shale gas development, the determination of the platform and well location in pre-drilling engineering designs should first meet the geology and engineering requirements. When the complex surface shape does not meet the construction requirements, the wellhead position should be adjusted within the surface range permitted by the underground geological targets [3]. The marine shale development area in South China is considered to be the most promising shale gas block in existence [4–6]. However, the complex surface conditions in the area impose constraints on shale gas well placement, heavy cargo transportation, water and electricity supplies, and environmental protection, increasing the costs and technical difficulty of shale gas development in the area. Therefore, scientific site selection for multi-well pad drilling is an important prerequisite for the efficient development of shale gas.

Devine and Lesso [7] established an optimal location planning model for offshore platforms with the objective of minimizing drilling costs. Later, Frair and Devine [8] extended the above model, taking into account factors such as the platform construction cost and output at each stage, and optimizing the model with the goal of maximizing the net present value. Costa [9], Dogru [10], Grimmett [11], Garcia-Diaz JG [12], and others also conducted further studies on this problem. Rodrigues H W L [13], Walesca [14], and Mohammed Almedallah [15] et al. established a location optimization model for offshore drilling platforms and proposed a linear programming model that minimizes the overall development costs of a given oilfield. It addresses the number, location, and capacity of production platforms; the number and location of wells; where manifolds must be installed; the interconnections between platforms, manifolds, and wells; and whether each part of the well should be vertical or horizontal. Zeeshan Tariq [16–20], Mohamed Mahmoud [21], Mohammad Rasheed Khan [22], and Ah-med Sadeed [23] used machine learning, particle swarm optimization, and other methods to optimize drilling and completion plans and injection–production plans in real time, achieving results that significantly improved their economic indicators.

Ge Yunhua et al. [24] established an optimization model aimed at minimizing the sum of the investment in oilfield surface engineering construction and oil and gas well construction, studying the internal rules concerning the size, number, and position of platforms and the investment in oilfield surface engineering construction and oil and gas well construction under the technical condition of horizontal well clusters. Yan Tie [25] investigated well targets, such as the objective function of minimizing the sum of the horizontal projection distance using projection disjoint or fewer intersections as constraint conditions. They constructed a well cluster distribution model using the ant colony algorithm, which can be used to quickly identify the optimal distribution plan for the wellhead; however, they did not consider that the difference between the actual well track and the projection may lead to errors in the model. Liu Zhen et al. [26] used graph theory and the weighted center problem of network analysis to develop an optimal selection model for choosing the location of the central platform for offshore oil fields. Shi Yucai [27] considered the drilling target distribution and the minimum target horizontal displacement sum of squares as the optimization targets, basing their construction on the number of platforms. Regarding subordinate well relations, they used a combination of several different ocean drilling platform location optimization model scenarios. Then, they used the dynamic clustering analysis method for the evaluation.

According to the distribution of geological targets, Li Wenfei et al. [28] established a mathematical programming model for the location optimization of clustered well drilling platforms, solving the model with the genetic algorithm. Based on the minimum sum of total well depth method, Zhang Yuchen et al. [29] comprehensively considered the influences of the different drilling costs of different well types on the platform location and optimized the platform location. Wang Zhiyue et al. [30] used the drilling learning curve of the "well factory" to establish and solve a position optimization model for a horizontal well platform under the well factory mode. Huo Hongbo et al. [31] established position optimization technology based on an economic evaluation of an integrated exploration and development platform in the Bohai Sea through a comparison between the new production platform based on the exploration of the well's location and the optimization scheme without considering the location of the exploration well platform. This was combined with an investigation of the influence of the location of the exploration well's building platform on the drilling difficulty.

Although there have been many achievements regarding the optimization of drilling sites or platform positions, all of the developed methods have some limitations: (1) The common site selection method uses topographic and geological mapping combined with a field investigation to identify the appropriate location for a well drilling site. However, the traditional method mainly depends on the person's subjective judgment, so it is difficult to consider the complex location factors and their influences, and China's enriched areas of shale gas resources located in places such as forests or mountains cannot rely on having artificial universal coverage advantageous drilling areas in field investigations, which eventually leads to the development of a scheme to meet the demands of drilling and the subsequent project. (2) All of the research methods fail to take into account the restrictions of the surface conditions in terms of their effects on platform site selection, which has a significant impact on the construction of shale gas drilling pads (from the aspects of construction cost and environmental protection). Based on previous research results, this study analyzed the influence of surface conditions on platform site selection and developed a multi-well drilling pad site selection method based on regional digital elevation data to produce site selection results that are more suitable for the efficient development of shale gas in areas with complex surface conditions.

2. Problem Statement and Formulation

Of the total reservoir development costs, drilling and fracturing costs account for a large proportion. Since the fracturing costs are not affected by the location of the platform, the impact of the fracturing costs is not considered when the optimization goal is to minimize the well construction costs. After determination of the reservoir development plan, the more drilling and total footage of the drilling pad there is, the more land area is required, the greater the surface construction costs for the drilling pad and for moving and installing the rig are, and the greater the total well construction costs of the platform are. Therefore, for a certain number of drilling pads, the total cost of well construction should be the lowest possible to achieve the maximum development benefit. On the basis of geological modeling, the locations and number of target points are known, and the optimization objective is to minimize the total well construction costs of the horizontal pad. A multi-objective optimization model was established for the location of the shale gas platform to optimize the location of the multi-well drilling pad.

Based on the known coordinates of the underground well pattern, the surface morphological characteristics, the land use, and various cost standards, investment in shale gas development and construction can be divided into two aspects. On one hand, there is the investment in drilling pad construction, including the construction costs of the platform or well site and the cost of moving or installing drilling rigs. On the other hand, there are the costs related to underground well construction, mainly drilling and completion costs. Thus, the total investment in shale gas multi-well drilling pad construction is

$$C = CG + CD \tag{1}$$

where C is the total investment in platform development and construction (in 10^4 \$), CG is the ground construction investment of the platform (in 10^4 \$), and CD is the investment in the underground well construction of the platform (in 10^4 \$).

2.1. Ground Construction Cost Model

The amount of land required for shale gas development depends on the density of the well cluster, the size of the well cluster, the number of wells in each well cluster, and the specific conditions of the shale reservoir being developed. Shale gas development typically uses the factory drilling model with multiple horizontal wells on a single tablecloth. This significantly reduces the land use demand, especially in mountainous areas of southern China and in places with complex surface conditions. The area of the multi-well drilling pad for shale gas is determined by the number of wells on the platform, the well layout, and the rig configuration. The platform wellhead arrangement can be divided into single layout and double layout wells. Drilling operations can be completed by single or double drilling rigs. Commonly used drilling rig models can be divided into "*ZJ50*" and "*ZJ70*" drilling rigs. The "*ZJ50*" drilling rig is suitable for drilling operations with depths of less than 5000 m, and the "*ZJ70*" drilling rig is used for drilling operations with depths of more than 5000 m. In addition, the "*ZJ70*" drilling rig is equipped with more equipment than the "*ZJ50*" rig, and the cost of rig installation and relocation is also more than for the "*ZJ50*" rig. Therefore, it is necessary to select a suitable type of rig to complete the drilling project at the lowest possible cost.

In addition, the area of the well site should also meet the requirements of drilling and fracturing operations. According to the demands of the well site for shale gas development and construction, a calculation model for the drilling platform area was established:

$$S = [X_R + (N/A - 1) \times 5] \times Y_A \tag{2}$$

where S is the area of the platform well site (in m^2); X_R is the length of the well site which drilling with different rig, such as a single drilling rig (X_R = 65 m), double "*ZJ50*" drilling rig (X_R = 105 m), or another drilling rig combination (X_R = 115 m); and Y_A is the width of the well site which set with different layout wells. For single-layout wells, this is Y_A = 50 m; for double-layout wells, it is Y_A = 80 m. N is the number of platform cloth wells and A is the platform wellhead arrangement, where a single well has a value of A = 1 and a double well has a value of A = 2.

The Digital Elevation Model (*DEM*) is a digital simulation of a topographic surface or a digital representation of a topographic surface form developed with limited topographic elevation. The *DEM* is equally spaced in the horizontal and vertical directions, and the plane coordinates of the grid dot are hidden in the column number, which is usually stored in the matrix structure; that is, the elevation values of the grid cells are recorded one-by-one according to the row (or column). When adopting the *DEM* for site selection optimization, the accuracy of the *DEM* in the study area is ε (in m). Then, the regional *DEM* can be divided into grids with a size of $\varepsilon \times \varepsilon$, and platforms with different well layouts and rig configurations can be transformed into a region composed of $X/\varepsilon \times Y/\varepsilon$ *DEM* grids.

The costs involved in well site construction include the land requisition costs, well site leveling costs, and infrastructure construction costs. The land requisition fee is determined by the local government according to the area occupied and the type of land requisitioned. It can be expressed as

$$C_{zd} = S \times C_{zds} \times K \tag{3}$$

where C_{zd} is the platform land acquisition cost (in 10^4 \$), C_{zds} is the unit price of the land acquisition cost (in 10^4 \$/m^2), and K is the land type coefficient occupied by the platform.

The cost of well site leveling is determined by the level and area of land occupied by the well site: the smaller the elevation difference is, the flatter the land will be, and the less basic engineering needed to level the well site. Therefore, in terms of site selection, a location with the flattest surface possible, a gentle slope, and a small degree of cutting should be chosen. *DEM* raster data are used to extract the raster average elevation difference to represent the land flatness, which can be specifically expressed as

$$C_{pz} = S \times \sum_{i=1}^{Ng} G_i \times C_{pzs}. \tag{4}$$

where C_{pz} is the cost of well site leveling engineering (in 10^4 \$), C_{pzs} is the unit price for well site leveling in (10^4 \$/m^3), N_g is the number of grids that make up the platform, and G_i is the elevation difference in grid i (in m). G_i is calculated using the average elevation of a single grid minus the average height of all grids in the well site. It is a single grid elevation difference that levels a well site to the same elevation throughout the grid. Above average heights can be extracted from the *DEM* data. The quantity of the well site can be determined from the composition of the well site elevation difference for all grids multiplied by the area of the corresponding grid, where positive values indicate excavation and negative values indicate filling, both of which are included in the engineered area.

Multi-well drilling pad infrastructure engineering mainly involves leveling the well site, tamping the foundation, laying the ground of the well site, and building the foundation conditions before drilling. Thus, the cost of the multi-well drilling pad infrastructure project is mainly determined by the area of the well site. It can be expressed as

$$C_{pc} = S \times C_{pcs} \tag{5}$$

where C_{pc} is the cost of infrastructure construction projects (in 10^4 \$) and C_{pcs} is the unit price of the infrastructure project cost (in 10^4 \$/m^2).

Multi-well pad drilling for shale gas can significantly reduce rig moving and installation costs. In general, the fewer platforms there are in the block, the less the rig moves, and the lower the rig moving cost is. The moving and installing costs of the platform rig are determined by the number of wells on the platform, the method of well placement, and the configuration of the rig. They can be expressed as

$$C_m = C_{m1} + C_{m2} \times (N-1)/A + C_{m3}/A \tag{6}$$

where C_m is the cost of moving and installing the rig (in 10^4 \$), C_{m1} is the initial installation cost of the rig (in 10^4 \$), C_{m2} is the cost of translating the well within the same row (in 10^4 \$ per unit of time), and C_{m3} is the cost of moving the drill well between rows (in 10^4 \$ per unit of time).

Based on the above analysis, the surface construction cost of a multi-well drilling pad can be expressed as

$$CG = C_{zd} + C_{pz} + C_{pc} + C_{pr} + C_m \tag{7}$$

2.2. Drilling and Completion Cost Model

The costs of drilling and completion are determined by the well structure, borehole trajectory, drilling construction procedure, and drilling and completion technology. When the drilling and completion plan for the block have been determined, the main factors affecting the drilling and completion costs are the shape of the well track and the length of footage. Once the reservoir engineer has determined the well location, the target position, vertical depth, and horizontal section length of the horizontal well are all fixed. When the platform position changes, the wellbore trajectory and well depth change with the wellhead position, resulting in changes in the drilling and completion costs.

The well trajectory design generally follows the following principles: (1) ensuring that the purpose of drilling directional wells is achieved; (2) consideration of the ground conditions; (3) correct selection of the deflection point, borehole curvature, and maximum deviation angle; and (4) a profile design that is conducive to safe and fast drilling whilst also reducing drilling costs [32]. Under the premise of satisfying the drilling purpose, the vertical section should be kept as long as possible, and in order to adjust the vertical depth at the end of the deflection section and improve the hit target rate, we adopted the three-dimensional profile of the "vertical section + increasing deviation section + steady deviation section + torsional azimuth section + horizontal section" to determine the well trajectory. When calculating the trajectory parameters of a 3D horizontal well, it is necessary to first provide some trajectory parameters and then determine the rest of the trajectory parameters and the total footage.

In Figure 1, O is the wellhead position, K_a is the deviation building point, K_b is the initial point in the stabilized section, K_c is the end point in the stabilized section, T_A is the first target in the horizontal section, and T_B is the end target in the horizontal section. R_1 and R_2 are the curvature radii of the deflection section and the torsional azimuth section, respectively. L_1, L_2, L_3, and L_h are the length of the building section, the length of the steady slope section, the length of the torsion bearing section, and the length of the horizontal section, respectively.

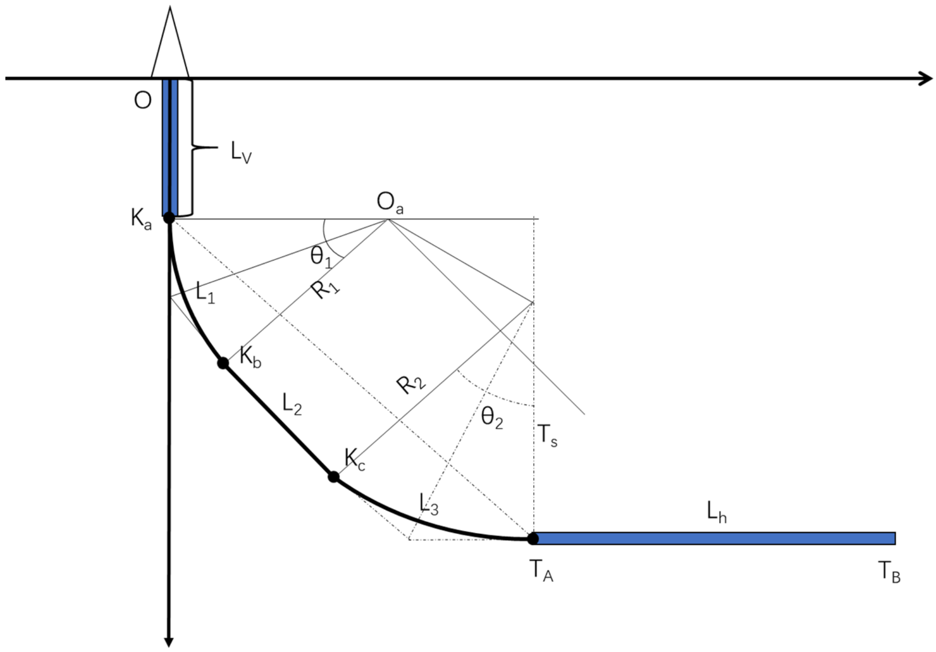

Figure 1. Drilling section design (projection of the plumb plane).

The known conditions include the T_A coordinates of the first target in the horizontal section (X_{ti},Y_{ti},Z_{ti}), the K_a coordinates of the deflection point (X_{ki},Y_{ki},Z_{ki}), the well inclination angle α_3, the azimuth angle φ_3, and the deflection slopes K_1 and K_2 of the deflection section and torsional azimuth section. According to the analytical method used in [33,34], the building section length L_1, the steady section length L_2, the torsional azimuth section length L_3, as well as the well inclination angle α_2 and the azimuth angle φ_2 in the steady section were obtained through the following steps.

The solution to the 3D borehole trajectory design model was transformed into three dimensional nonlinear equations:

$$\begin{cases} 2(T_s + L_2)L_m + 2(T_t + L_2)L_n + 2(1 - \cos\theta)L_m L_n = H^2 - L_2{}^2 \\ K_1{}^2 L_m{}^2 [T_s + (1 - \cos\theta)L_n + L_2] = 2L_m + (1 + \cos\theta)L_n + L_2 - T_s \\ K_2{}^2 L_n{}^2 [T_t + (1 - \cos\theta)L_m + L_2] = 2L_n + (1 + \cos\theta)L_m + L_2 - T_t \end{cases} \tag{8}$$

where H is the straight distance between the building angle and the first target (in m); T_s and T_t are the projection lengths of the straight segment $K_A T_A$ on the direction vector of the skew point and the horizontal segment, respectively (in m); and θ is the angle between the borehole direction vector at the deflection point and the borehole direction vector in the horizontal section.

$$H = \sqrt{(x_t - x_k)^2 + (y_t - y_k)^2 + (z_t - z_k)^2} \tag{9}$$

$$T_s = z_t - z_k \tag{10}$$

$$T_t = [(x_t - x_k)\cos\varphi_3 + (y_t - y_k)\sin\varphi_3]\sin\alpha_3 + (z_t - z_k)\cos\alpha_3 \tag{11}$$

Suppose that $\begin{cases} x = \frac{L_m}{H} \\ y = \frac{L_n}{H} \\ z = \frac{L_2}{H} \end{cases}$, and $x, y, z \in (0,1)$; meanwhile, $\begin{cases} t_1 = \frac{T_s}{H} \\ t_2 = \frac{T_t}{H} \end{cases}$, $\begin{cases} k_1 = \frac{K_1}{H} \\ k_2 = \frac{K_2}{H} \end{cases}$, $\begin{cases} a = 1 - \cos\theta \\ b = 1 + \cos\theta \end{cases}$. Thus, the ternary nonlinear equations can be transformed into

$$\begin{cases} k_1{}^2 x^2 (t_1 + ay + z) = 2x + by + z - t_1 \\ k_2{}^2 y^2 (t_2 + ax + z) = bx + 2y + z - t_2 \\ 2(t_1 + z)x + 2(t_2 + z)y + 2axy = 1 - z^2 \end{cases} \tag{12}$$

The nonlinear equations can be quickly solved by the quasi-analytical method, and the design parameters of borehole trajectory were obtained. The values of the central angles θ_1 and θ_2 of the two arc segments can be calculated using the following formula:

$$\cos\theta_1 = \cos\alpha_2 \tag{13}$$

$$\cos\theta_2 = \cos\alpha_2\cos\alpha_3 + \sin\alpha_2\sin\alpha_3\cos(\varphi_3 - \varphi_3) \tag{14}$$

After solving the track design parameters, the calculation expression of the total track footage of a single well hole can be obtained as follows:

$$L_i = L_v + L_1 + L_2 + L_3 + L_H \tag{15}$$

In summary, the total well depth of the horizontal well on the platform is

$$L_T = \sum_{i=1}^{N} L_i. \tag{16}$$

The drilling and completion cost is a function of the well depth and the drilling and completion cost, expressed as

$$CD = \sum_{i=1}^{N}(L_{vi} \times P_{vs} + L_{ki} \times P_{ks} + L_{hi} \times P_{hs}). \tag{17}$$

where P_{vs} is the unit price of drilling and completion in the vertical section (in 10^4 \$/m), P_{ks} is the unit price of drilling and completion in the deflecting section (in 10^4 \$/m), and P_{hs} is the unit price of drilling and completion in the horizontal segment (in 10^4 \$/m).

2.3. Constraint Conditions

In order to avoid fishhook boreholes and reduce the drilling difficulty, the center of the platform should be located in the polygon area composed of all targets, that is, the boundary of the area where all well targets are selected for the platform:

$$\begin{cases} x_{min} < X < x_{max} \\ y_{min} < Y < y_{max} \end{cases} \tag{18}$$

According to the requirements of oil drilling HSE, the selected platform site should be no less than 500 m away from the plane of residence:

$$\sqrt{\left(X \pm \frac{X_R}{2} - x_h\right)^2 + \left(Y \pm \frac{Y_A}{2} - y_h\right)^2} \geq 500 \tag{19}$$

where (x_h,y_h) are the grid coordinates of human settlements (in m).

The selected position of the platform should not occupy agricultural land or a river water source. Based on the *DEM* grid data of land use in the block, unsuitable site selection areas such as agricultural land and river water source areas were removed, and the feasible region *R* for the platform's location was determined:

$$(X, Y) \in R \tag{20}$$

In order to obtain the range of *R*, different types of *DEM* data (such as elevation data, land use type data, etc.) are used for a Boolean operation, and the intersection is obtained as the area in line with the site selection requirements.

3. The Method and Process Used to Solve the Optimization Model

Because the subordination relationship between the platform and the well is known, the exhaustive method can be used to solve the optimization problem; however, because of the large amount of calculations involved, the genetic algorithm is used to solve the location problem. The genetic algorithm is a simulated evolutionary process of the random search algorithm. First, randomly generated values that satisfy the restrictions of the actual problem are used as the initial solution set (parent), and then through genetic coding, genetic operations such as selection, crossover, and mutation determine the offspring solution from the parent solution to better adapt to the given fitness function and determine the optimal solution to the problem, or to approximate the optimal solution [35]. The basic process of solving the genetic algorithm is shown in Figure 2.

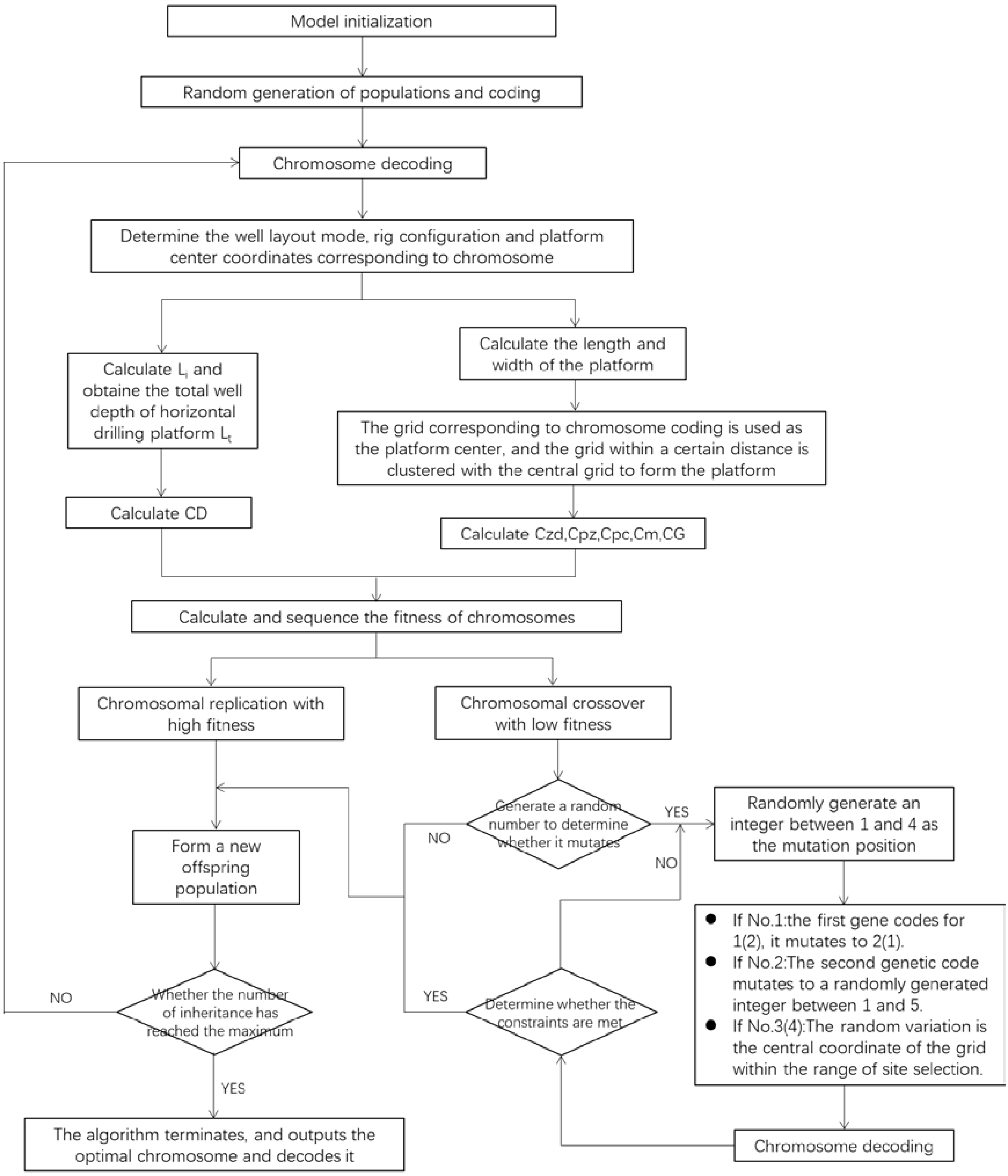

Figure 2. The process of determining the genetic algorithm solution.

As shown in Figure 2, firstly, the model is initialized, and the chromosome encoding and decoding rules are determined. Secondly, a population is randomly generated, and the chromosomes in the population are taken as the primary solution. Thirdly, the required length and width of the well site are determined according to the well layout method corresponding to the initial solution, and the location of the well site is obtained by grid clustering based on the center coordinates of the initial solution according to certain rules. Fourth, the platform construction cost model and drilling cost model are used to calculate the platform construction and drilling costs, respectively, which are put into the site selection model to obtain the platform location and the total cost of well construction corresponding to the initial solution. Fifth, the fitness of individuals in each initial population is calculated according to the fitness function, and the fittest individuals are selected to pass on to the next generation. All of the other chromosomes randomly generate mutation and crossover positions for the offspring solution set and retrieve the level of fitness. Sixth, the fitness of the new generation of individuals is recalculated. The best chromosome is selected to move to the next generation, whilst the remaining the chromosomes cross and mutate. The third step is performed until the condition indicating the end of the algorithm is reached. Finally, the optimal solution decoded is used as the optimal site selection scheme.

3.1. Initialization and Encoding

The initial population size is generated by random selection. The encoding method is mixed, and the chromosome form is "well layout + rig configuration + well site location (the grid position of the center of the well site)". The specific encoding method is as follows:

In terms of the well layout code, a single layout well is indicated by "1"; double-arranged wells are indicated by "2".

The drilling rig configuration codes are as follows: "1" for "*ZJ50*", "2" for "*ZJ70*", "3" for "*ZJ50* + *ZJ50*", "4" for "*ZJ50* + *ZJ70*", and "5" for "*ZJ70* + *ZJ70*".

In terms of platform center position coding, the grid number is coded from any vertex in the feasible site area. For example, in the double-layout well mode, the "*ZJ50* + *ZJ70*" drilling rig is used, and the grid number of the platform center is (113,230), so the chromosome code is "1301130230".

3.2. Cluster

The length and width of the platform were calculated according to the well distribution mode corresponding to the chromosome and rig configuration. The grid corresponding to the chromosome code was taken as the platform center, and the grid within a certain distance was clustered with the central grid to form the platform. Then, the grid covered by the platform was

$$\begin{cases} O_R \pm (X/2\varepsilon + 1) \\ O_C \pm (Y/2\varepsilon + 1) \end{cases} \text{or} \begin{cases} O_R \pm (Y/2\varepsilon + 1) \\ O_C \pm (X/2\varepsilon + 1) \end{cases} \quad (21)$$

where O_R and O_C are the row and column numbers of the platform's center grid, respectively.

3.3. Selection

Taking the grid corresponding to the platform center position as the platform center, the length and width of the platform, the platform construction cost for all grids within the platform range, and the drilling and completion costs from the target point to the platform center position were determined to form the fitness function. Optimal preservation strategies were adopted to ensure that the chromosome with the highest fitness function value in each generation could be further inherited:

$$f_i = M - CG_i - CD_i \quad (22)$$

where f is the fitness of the chromosome and M is an infinite number.

3.4. Crossover

The crossover operation can randomly exchange some genes from two chromosomes and generate new chromosomes. After crossover of the genes, it may appear that individuals do not meet the constraints of site selection. Therefore, the strategy of partial matching crossover is adopted. The specific method used to determine the intersection position is as follows:

$$P_c = \text{random}(1,\ 4) \tag{23}$$

where P_c is the cross location and random(1, 4) represents the random generation of an integer between 1 and 4.

3.5. Mutation

The mutation operation can randomly change the selected chromosome genes, which can avoid the solution process falling into local convergence. For every part of each offspring in the cross offspring set, a random number is generated. If the random number is less than the mutation probability, the location of the mutant gene is determined according to Equation (23), and the corresponding mutant gene is randomly determined within the corresponding gene boundary range to form a new chromosome.

3.6. Calculated Fitness

The fitness levels of all chromosomes were recalculated. The chromosomes with the greatest fitness levels in the father generation were copied to the offspring, and the chromosomes with the least fitness in the offspring generation were eliminated, forming a new offspring population. We then returned to step (3.2).

3.7. Termination of the Algorithm

The value of the chromosome fitness function in the population tends to be stable, which represents the convergence of the algorithm, and the algorithm terminates.

4. Results and Discussion

According to the established site selection model, the location of the multi-well drilling pad, the arrangement of the platform wellhead, and the configuration of the drilling rig can be obtained with a minimal well construction cost by solving the site selection model under the conditions of the known target coordinates of the horizontal section, the coordinates of the building deviation point, and the relevant parameters of the directional well. The parameters involved in the model solution are shown in Table 1.

Table 1. Basic calculation parameters obtained from experience.

Parameter	Value	Parameter	Value
C_{zds} (\$/m^2)	0.01	P_{vs} (\$/m)	500
C_{pzs} (\$/mp)	150	P_{ks} (\$/m)	1500
C_{pcs} (\$/m^2)	160	P_{hs} (\$/m)	2500
C_{m1} (\$)—*ZJ50*	120,000	C_{m1} (\$)—*ZJ70*	160,000
C_{m2} (\$)—*ZJ50*	19,000	C_{m2} (\$)—*ZJ70*	28,000
C_{m3} (\$)—*ZJ50*	33,000	C_{m3} (\$)—*ZJ70*	45,000
K (barren land)	1	K (forest)	1.2

4.1. The First Case

The Y well group is located in Xuyong County, Luzhou City, Sichuan Province, which is located in the southern margin of the Sichuan Basin. The highest altitude in this area is 1304 m; the lowest altitude is 480 m. These altitudes represent a mountain landform with a deeply local topography cut. The area has convenient transportation and lush trees throughout. It is an environmentally sensitive area. There are five horizontal wells in the well group. The target layer is the Lower Silurian Longmaxi Formation, which is generally distributed in a comb shape on the plane and has a horizontal section length of 1000–1200 m, a well spacing of about 340 m in the horizontal section, and a depth of 500 m for the inclination point. Table 2 shows the specific drilling design of the Y well group.

Table 2. Y well group drilling design.

Npw	Target Coordinates			L_h
	x_i	y_i	z_i	
Y1	1664	1456	909	1200
Y2	1393	1247	934	1030
Y3	1084	1145	961	1000
Y4	763	1089	986	1100
Y5	396	1141	1016	1100

According to the geological design data from the well group, a single well arrangement mode was adopted, and the length and width of the well site were determined to be 85 m and 50 m by the platform area model. The center coordinates of the platform are (1207,1483) and the corresponding rig model is "ZJ50" under the condition of the lowest cost obtained by the genetic algorithm. As shown in Figure 3., the selected location is easily accessible for engineering vehicles and is nonagricultural, which meets the HSE requirements for shale gas drilling. The drilling design data show that the actual drilling platform centers are located at (1496,1223), and the center of the selected platform is 388 m away from the actual drilling platform center; however, there are many farmers around the actual drilling platform, and the nearest farmer anomaly platform is only 80 m, which proves that the site selection method in this paper is feasible and effective.

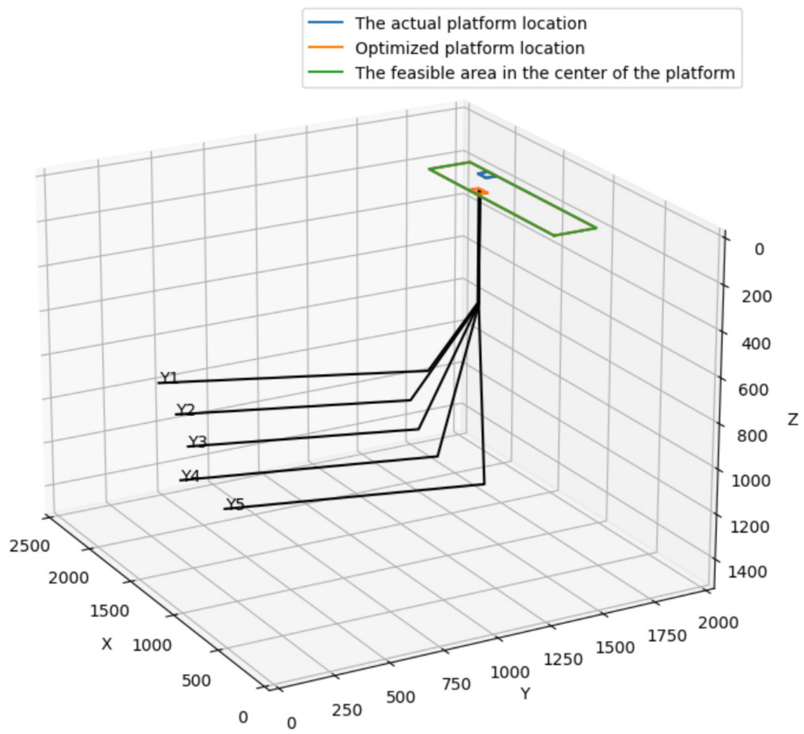

Figure 3. Y well group drilling platform optimization.

4.2. The Second Case

The J59 well group is located in Fuling District, Chongqing City in China, which is located in the transition zone between basins. The terrain is mainly low mountains and hills and is generally high in the southeast and low in the northwest, with the highest elevation being 1977 m and the lowest being 138 m, mostly ranging from 200 to 800 m. The surface conditions are extremely complex. A total of six horizontal wells were deployed and designed in the well group. The target layer was shale gas intervals of Upper Ordovician Wufeng Formation–Lower Silurian Longmaxi Formation, and the drilling rig was configured as a dual drilling rig. The specific design is shown in Table 3.

Table 3. The drilling design of the J59 well group.

Npw	z_k	**Target Coordinates**			L_h
		x_i	y_i	z_i	
J59-1	1000	3427	79	2533	1300
J59-2	1500	3427	679	2860	1300
J59-3	1450	3427	1279	2478	1300
J59-4	1700	1730	1279	2548	1700
J59-5	1600	1550	679	2566	1500
J59-6	900	1230	79	2618	1200

In order to avoid complex wellbore orbits and reduce the difficulty of drilling engineering, different well layout methods in the feasible platform location regions can be preliminarily determined according to the drilling design data. The area of the following platform is then determined according to the actual demands of the well site, as shown in Table 4.

Table 4. Possible wellhead alignment, combined with the rig configuration.

No.	N_{pw}	A	*DM*	S (m^2)	X_R (m)	Y_A (m)	**Feasibility**
1	6	1	*ZJ50* + *ZJ50*	6500	130	50	Infeasible
2	6	1	*ZJ50* + *ZJ70*	7000	140	50	Feasible
3	6	1	*ZJ70* + *ZJ70*	7000	140	50	Feasible
4	6	2	*ZJ50* + *ZJ50*	9200	115	80	Infeasible
5	6	2	*ZJ50* + *ZJ70*	10,000	125	80	Feasible
6	6	2	*ZJ70* + *ZJ70*	10,000	125	80	Feasible

As shown in Figure 4., the maximum designed drilling depth of the J59 well group is 4710 m. According to the principles of drilling rig selection, "*ZJ50*" and larger drilling rigs should be selected. The load capacity and configuration of drilling rig equipment should meet the required well drilling depth of 5000 m, so the "*ZJ50* + *ZJ50*" drill rig configuration scheme was deleted. According to the above model, the length of the well site was determined to be 125 m and the width was determined to be 80 m. Combined with the *DEM* of the well area, the feasible platform site selection area was determined. Based on the model of minimum well construction costs for the platform, the central coordinate of the platform (the grid position of the center of the well site) with the double-layout well and "*ZJ50* + *ZJ70*" rig configuration was determined to be located at (2475,949), with civil houses located 580 m southeast of the selected location. Transportation in the area is convenient, the nonagricultural land is nearly 350 m away from the actual drilling platform center, and the area meets the HSE requirements for shale gas drilling.

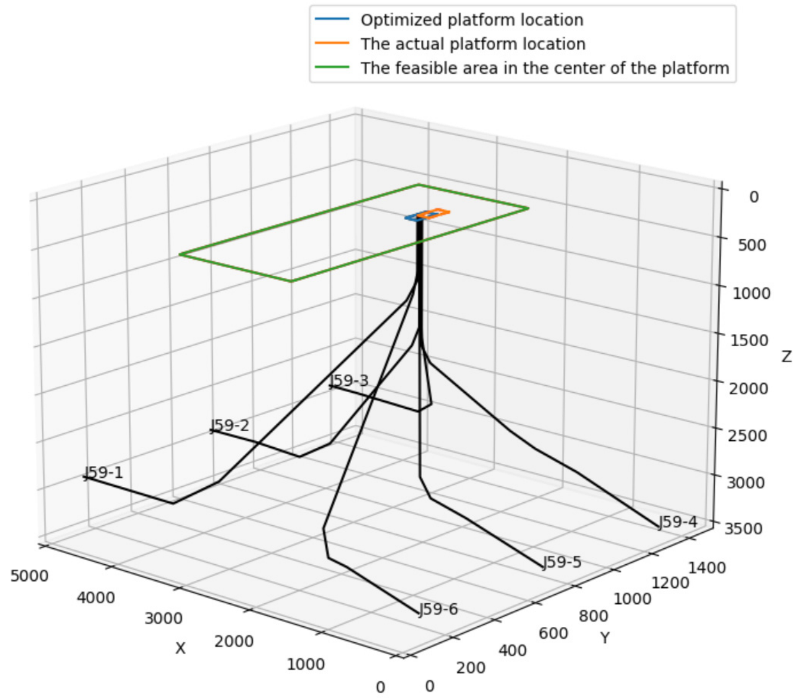

Figure 4. J59 well group drilling platform optimization.

5. Conclusions

Shale gas development is a capital-intensive project, and well construction investment accounts for the largest proportion of total oilfield construction investment. Rapid site selection under complex terrain conditions can effectively shorten the time required to formulate development plans, and making shale gas to be rapidly developed and put into production. From the perspective of the time value of capital, rapid well construction and initiation of production can significantly improve development benefits.

By analyzing the factors influencing well construction cost, a construction cost model of the shale gas factory multi-well pad and a drilling cost model were established and a site selection scheme with minimum construction costs for the pad was proposed. The drilling data from the first case were used to determine the location of the drilling platform, which was 388 m away from the platform's location; the selected location was found to meet the requirements of drilling engineering and HSE, proving the feasibility of the location selection model. In the second case, a quick site selection method was used to determine the characteristics of the single pad and double layout well, where the length and width of the well field were 125 m and 80 m, respectively. The selected rig configuration was "ZJ50 + ZJ70", and the selected wellsite location was 350 m away from the actual location. The analysis shows that the method is not only applicable to platforms with known well group relations, it is also applicable to symmetry relations of unknown situations, as it is able to quickly choose a platform under complex initial position surface conditions on the basis of further evaluation of the multi-well drilling pad position, and it can greatly reduce the exploration field work required, thereby improving productivity.

This paper discussed the feasibility of rapidly identifying the location of a shale gas multi-well drilling pad using the DEM, but there are still some factors that have not been fully considered, such as the different angle penetration lengths in the strata, complex geological structures, the sensitivity of the factors that affect costs, and the speed analysis and comparison of algorithms. Moreover, the location methods for the resolution of terrain data used in the article have a higher level of demand, and if the resolution increases, the corresponding lattice grid number increases four-fold. Thus, the algorithm should be improved to improve its speed and accuracy.

Author Contributions: Conceptualization, J.Z.; methodology, software, validation, N.H.; formal analysis, investigation, W.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by The Humanities and Social Science Special Fund—Scientific Research Starting Project of SWPU (No. 2018QHR006) and The Special Project of Science and Technology Strategic Cooperation between Nanchong City and Southwest Petroleum University (No. SXHZ012).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Zou, C.; Zhao, Q.; Dong, D.; Yang, Z.; Qiu, Z.; Liang, F.; Wang, N.; Huang, Y.; Duan, A.; Zhang, Q.; et al. Geological characteristics, main challenges and future prospect of shale gas. *Nat. Gas Geosci.* **2017**, *28*, 1781–1796. [CrossRef]
2. Long, S.; Cheng, Z.; Xu, H.; Chen, Q. Exploration domains and technological breakthrough directions of natural gas in SINOPEC exploratory areas, Sichuan Basin, China. *J. Nat. Gas Geosci.* **2020**, *5*, 307–316. [CrossRef]
3. Feng, X.; Liao, X. Study on Well Spacing Optimization in a Tight Sandstone Gas Reservoir Based on Dynamic Analysis. *ACS Omega* **2020**, *5*, 3755–3762. [CrossRef]
4. Qi, W.; Xing, L.; Chenggang, X.; Xun, L. Geoscience-to-Production Integration Ensures Effective and Efficient South China Marine Shale Gas Development. *China Pet. Explor.* **2015**, *20*, 1–23.
5. Caineng, Z.O.U.; Guangming, Z.H.A.I.; Zhang, G.; Hongjun, W.; Zhang, G.; Jianzhong, L.; Wang, Z.; Wen, Z.; Ma, F.; Liang, Y.; et al. Formation, distribution, potential and prediction of global conventional and unconventional hydrocarbon resources. *Pet. Explor. Dev.* **2015**, *42*, 13–25.
6. Yue, Y.; Wu, X.; Zhang, Q.; Zhao, H.; Jiang, W. Integration and scale application of shale gas exploration and development engineering technologies in Sichuan and Chongqing areas. *Nat. Gas Ind. B* **2018**, *5*, 523–532. [CrossRef]
7. Devine, M.D.; Lesso, W.G. Models for the Minimum Cost Development of Offshore Oil Fields. *Manag. Sci.* **1972**, *18*, 378–387. [CrossRef]
8. Frair, L.; Devine, M. Economic Optimization of Offshore Petroleum Development. *Manag. Sci.* **1975**, *21*, 1370–1379. [CrossRef]
9. Costa, L.R. Optimization Models for Offshore Oil Field Development. Ph.D. Thesis, Case Western Reserve University, Cleveland, OH, USA, 1975.
10. Dogru, S. Selection of Optimal Platform Locations. *SPE Drill. Eng.* **1987**, *2*, 382–386. [CrossRef]
11. Grimmett, T.; Startzman, R. Optimization of Offshore Field Development to Minimize Investment. *SPE Drill. Eng.* **1988**, *3*, 403–410. [CrossRef]
12. Garcia-Diaz, J.C.; Startzman, R.; Hogg, G.L. A New Methodology for Minimizing Investment in the Development of Offshore Fields. *SPE Prod. Facil.* **1996**, *11*, 22–29. [CrossRef]
13. Rodrigues, H.W.L.; Prata, B.A.; Bonates, T.O. Integrated optimization model for location and Sizing of offshore platforms and location of oil wells. *J. Pet. Sci. Eng.* **2016**, *145*, 734–741. [CrossRef]
14. Walesca, H.; Rodrigues, L.; De, B.; Prata, A.; De Oliveira, T.; Assistant, B. New integrated approach for location and sizing of offshore multicapacitated platforms and location of oil wells. *Petrol* **2016**, *145*, 734–741.
15. Mohammed, K.; Almedallah, S.D.C. Walsh Integrated well-path and surface-facility optimization for shallow-water oil and gas field developments. *J. Pet. Sci. Eng.* **2019**, *174*, 859–871.
16. Tariq, Z.; Mahmoud, M.; Abdulraheem, A.; Al-Shehri, D.; Khan, M.R.; Janjua, A.N. An Intelligent Solution To Forecast Pressure Drop in a Vertical Well Having Multiphase Flow Using Functional NetworkTechnique. In Proceedings of the PAPG/SPE Pakistan Section Annual Technical Conference and Exhibition Islamabad, Islamabad, Pakistan, 10–12 December 2018.
17. Tariq, Z.; Mahmoud, M.; Al-Shehri, D.; Sibaweihi, N.; Sadeed, A.; Hossain, M.E. A Stochastic Optimization Approach for Profit Maximization Using Alkaline-Surfactant-Polymer Flooding in Complex Reservoirs. In Proceedings of the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam, Saudi Arabia, 23–26 April 2018.
18. Tariq, Z.; Mahmoud, M.; Abdulraheem, A. Real-time prognosis of flowing bottom-hole pressure in a vertical well for a multiphase flow using computational intelligence techniques. *J. Pet. Explor. Prod. Technol.* **2019**, *10*, 1411–1428. [CrossRef]
19. Tariq, Z.; Aljawad, M.S.; Hasan, A.; Murtaza, M.; Mohammed, E.; El-Husseiny, A.; Sulaiman, A.A.; Mohamed, M.; Abdulazeez, A. A systematic review of data science and machine learning applications to the oil and gas industry. *J. Pet. Explor. Prod. Technol.* **2021**, *11*, 4339–4374. [CrossRef]
20. Tariq, Z.; Mahmoud, M.; Abouelresh, M.; Abdulraheem, A. Data-Driven Approaches to Predict Thermal Maturity Indices of Organic Matter Using Artificial Neural Networks. *ACS Omega* **2020**, *5*, 26169–26181. [CrossRef] [PubMed]
21. Mahmoud, M.; Tariq, Z.; Kamal, M.S.; Al-Naser, M. Intelligent prediction of optimum separation parameters in the multistage crude oil production facilities. *J. Pet. Explor. Prod. Technol.* **2019**, *9*, 2979–2995. [CrossRef]

22. Khan, M.R.; Sadeed, A.; Asad, A.; Tariq, Z.; Tauqeer, M. Maximizing Oil Recovery in a Naturally Fractured Carbonate Reservoir Using Computational Intelligence based on Particle Swarm Optimization. In Proceedings of the PAPG/SPE Pakistan Section Annual Technical Conference and Exhibition, Islamabad, Pakistan, 10–12 December 2018.
23. Sadeed, A.; Tariq, Z.; Janjua, A.N.; Asad, A.; Enamul Hossain, M. Smart water flooding: An economic evaluation and optimization. In Proceedings of the SPE Kingdom of Saudi Arabia Annual Technical Symposium and Exhibition, Dammam, Saudi Arabia, 23–26 April 2018.
24. Yunhua, G.; Aimin, Y.; Yongrong, G.; Xueping, T. Drilling pad optimization for oilfield development by cluster horizontal wells. *Pet. Explor. Dev.* **2005**, *32*, 94–100.
25. Tie, Y.; Wenfu, J.; Xueliang, B.; Ting, X.; Yang, Y.; Guangdong, L. An allocation method for platform wellheads of cluster well based on ACA. *Fault-Block Oil Gas Field* **2014**, *21*, 224–227.
26. Zhen, L.; Bin, P.; Lianbao, W. Position optimization for central platform of offshore oilfield. *China Offshore Platf.* **2002**, *17*, 28–30.
27. Yucai, S.; Zhichuan, G.; Qiuyan, C.; Yanjun, Z. Location optimization method for drilling platform. *J. China Univ. Pet.* **2007**, *31*, 44–47.
28. Wenfei, L.; Kuanliang, Z.; Zhichuan, G.; Ming, C.; Yunpeng, L.; Yucai, S. Location optimization for the drilling platform of large-scale cluster wells. *Acta Pet. Sin.* **2011**, *32*, 162–166.
29. Yuchen, Z.; Hai, L.; Likong, C.; Hailong, L. Research and practice of position selection methods of wellhead platforms for offshore cluster wells. *J. Yangtze Univ. (Nat. Sci. Ed.)* **2016**, *13*, 36–39.
30. Zhiyue, W.; Deli, G.; Binbin, D.; Degao, H. Optimization of platform positioning considering the learning effect in the "well factory" mode. *Nat. Gas Ind.* **2018**, *38*, 102–108.
31. Hongbo, H.; Zhiheng, L.; Pinghua, D. The platform location optimization technology for the exploration-development integration of middle and deep reservoirs in the Bohai Sea. *Oil Drill. Prod. Technol.* **2018**, *40*, 84–86.
32. Ping, C. *Drilling & Completion Engineering*; Petroleum Industry Press: Beijing, China, 2005; pp. 246–276.
33. Xiushan, L. *Well Trajectory Geometry*; Petroleum Industry Press: Beijing, China, 2006.
34. Xiushan, L.; Jun, G. The description and calculation of space circular orbit. *Nat. Gas Ind.* **2000**, *20*, 44–47.
35. Gen, M. *Genetic Algorithm and Engineering Optimization*; Qinjie, Y., Gengui, Z., Eds.; Tinghua University Press: Beijing, China, 2016.