Proceedings of the 13th European Wave and Tidal Energy Conference 1-6 Sept 2019, Naples, Italy

Optimisation of Tidal Lagoon using Genetic Algorithm

Jingjing Xue, Reza Ahmadian, and Owen Jones

Abstract—**This paper focused on facilitating the development of Tidal Range Structures (TRSs) including tidal lagoons by using an improved Genetic Algorithm (GA) model instead of common Grid Search (GS) method which has traditionally been used for the optimisation of operation schemes. The GA model splits the operation into single tidal cycle and optimise the operation of TRSs through the process of mutation, recombination and selection, which create the new schemes. The GA model which takes the 0-D approach as the fitness function was established and developed with different recombination methods, to reveal an enhanced efficiency of the GA with a ring structure recombination method. With a proposed case study of tidal lagoons, the optimised operational scheme using the GA was in consist with the GS method, with an approximately 10% increase of the electricity generation, comparing to the fixed head schedule. However, better convergence can be obtained with the application of the GA than the GS method, which proved the feasibility of utilising the GA model to solve the operational characteristics optimisation in TRSs.**

Keywords—**Tidal Range Structures; Tidal Lagoons; Genetic Algorithm; Optimisation of Operation Schemes.**

I. Introduction

WITH a constant increasing tendency in global energy demanding, focus has been transferred from consumption of traditional energy resources to the development of renewable energy alternatively [1]. Tidal renewable energy works by creating a water level difference to drive turbines [2]. It is of interest due to the predictability and stability of tides to deliver energy from tides to electricity generation constantly. It was reported that between 25 and 30 GW of electricity generation can be potentially exploited by tidal range resources [3]. A number of proposals of tidal lagoons were proposed although they were still controversial as the price competitive [4], which highlighted the significance of the optimisation of such TRSs to maximize the electricity generation and hence reduce the energy cost.

In TRSs, two of the key parameters influencing the electricity generation are the water level differences besides the impoundment when generation commences and stops, respectively. They were firstly carried out by Prandle in a simplified 0-D methodology of the tidal range operation [5], which assumed these parameters were dimensionless and fixed values. However, because of the different tidal ranges existing during spring and neap tides, some tidal energy might be wasted due to the unsuitable generation heads. It was proposed that if utilising a flexible operation scheme for the TRSs, the electricity generation could be improved potentially [6, 7]. Recently, Athanasios et al. applied a gradient-based optimisation techniques coupled with the 0-D model for the achievement of flexible operation schemes [8]. It has been demonstrated that the flexible control parameters could benefit an approximately 10% increase of electricity generation for the optimisation of the TRSs operation without pumping. Meanwhile, a cutting-edge method of Genetic algorithms (GAs) were demonstrated to be a competitive method in the fields of computer science and engineering [9, 10], including the Marine Renewable Energy (MRE). For example, GAs was developed to optimise the deployment of tidal power arrays [11] with minimum cost and improved performance, concluding that GAs were able to produce noteworthy solutions for some complex problems in TRSs optimisations.

A case study of the proposed Swansea Bay Lagoon, located in Swansea Bay, the South West of the United Kingdom, was used in this study due to its completed design data provided by Tidal Lagoon Power [12]. The scheme would consist of 16 bulb turbines with diameter of 7.2m [12] and the area of the sluice gates would be approximately 800 m^2 [13, 14]. This paper focused on facilitating the development of TRS by using an improved GA model for the optimisation of flexible operation schemes, with a benchmark of the common GS method

Paper ID number: 1764, Conference track: European Wave and Tidal Energy Conference Series (EWTEC) 2019.

J. Xue is at Cardiff School of Engineering, Queen's Building, the Parade, Cardiff, U.K. CF24 3AA (e-mail: XueJ7@cf.ac.uk).

Dr. R. Ahmadian is with Cardiff School of Engineering, Queen's Building, the Parade, Cardiff, U.K. CF24 3AA (e-mail: AhmadianR@cf.ac.uk).

Prof. O. Jones is at Cardiff School of Mathematics, Cathays, Cardiff, U.K. CF24 4AG (email: joneso18@cf.ac.uk)

which has traditionally been used. The GA model coupled with the 0-D approach was established. It was developed with a Sequential Mutation Method (SMM) and two recombination methods, namely Linear Recombination Methods (LRM) and Ring Recombination Methods (RRM), respectively [15-17]. Finally, the flexible schemes using LRM and RRM within the proposed GA model was compared with the GS model, allowing a maximum electricity generation produced with an enhanced efficiency.

II. Methodology

A. 0-D modelling

In 0-D modelling, the time series of the upstream water level is significantly governed by its previous upstream and the relevant downstream water level, developed according to the continuity equation. Given the upstream water level (Z_{up}, i) and the downstream water level (Z_{dn}, i) at any point in time step Δt, the next upstream water level $(Z_{up}, i+1)$ can be calculated as follows [18, 19]:

$$Z_{up,i+1} = Z_{up,i} + \frac{Q(H) + Q_{in}}{A} \Delta t \quad (1)$$

where Q_{in} is the seaside or riverside discharge.; A is the wetted surface area of the lagoon which varies with the basin water elevations and high-resolution bathymetric data of the case study. $Q(H)$ is the total discharge through the turbines and sluices. The discharge through turbines and the power output were driven from the hill-chart for the Andritz Hydro triple-regulated bulb turbine [13], and the flow through a sluice gate Q was obtained by linking Q with the corresponding water head H, as follows [20]:

$$\mathrm{Q} = \mathrm{C_d A}\sqrt{2\mathrm{gH}} \quad (2)$$

As mentioned above, a large number of simulations would be required for further optimisation, which would be very time-consuming. Hence, for the optimisation, the 2nd neap-spring-neap cycle in 2012 was selected as the typical cycle in this study with electricity production of about 21.3 GWh. It deviated slightly from the average electricity generation under an optimised fixed scheme for the Swansea Bay Lagoon, as shown in Table I. It should be noted that the seaward water levels for the 0-D modelling was obtained from a validated multi-dimensional model, with details can be found in [21, 22].

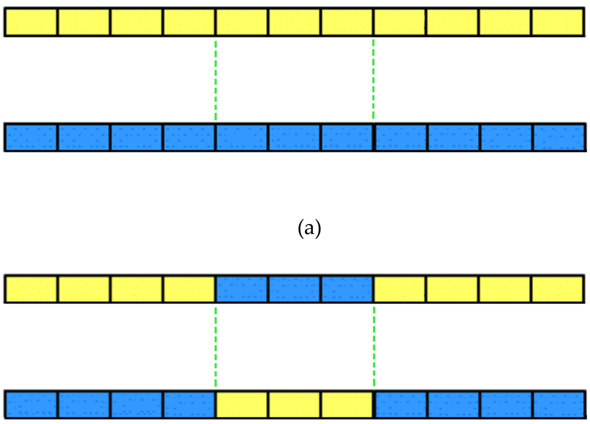
Evidently, the applications of flexible operational schemes can improve the electricity generation by fully exploring the tidal ranges of MRE. In this study, an Every Half-tidal cycle and Next (EHN) method of GS approaches was considered as a benchmark to verify the effect of the GA modelling. In EHN model, tides were separated into small components based on a unit of every half-tide, namely flood tides and ebb tides. Secondly, a full range of operation heads will be applied on every two successive half-tides until a maximum electricity generation achieved during these two half-tides. Hence, the operation heads for the former half-tide can be regarded as the flexible optimised heads for this half-tide, and the rest can be done in the same manner. It is worthy to be mentioned that a range of starting heads for generation were considered, varying from 2.0 m to 8.0 m with 1 cm increments, and for a range of ending head for generation from 0.5 m to 4.5 m and also with 1 cm increments. The advantage of this approach is that not only a comprehensive grid search range of operation heads can be calculated for every half-tide, but also a balance of the electricity generation can be kept for every two successive half-tides during the iterative process. As illustrated in Table I, The flexible operation schemes using the EHN model can bring an approximately 12.5% improvement of electricity generation in comparison to the fixed head operational schedule.

B. Genetic Algorithms

GAs were firstly described in the book of Adaptation in Natural and Artificial Systems by John Holland [23], which simulated the Darwinian evolutionary process and the natural selection process to solve complexity optimisation problems computationally [24]. In GAs [25], the process of mutation, recombination and selection are operated on the chromosomes of individuals with the probability parameters of P_m, P_r and P_s, respectively. In selection, individuals who have stronger fitness capabilities to the environment are more likely to be survived and then transfer their genetic information to their next generation which forms a new population [26]. This new populations will be performed and reproduced iteratively until a particular termination criterions are satisfied.

Two limitations can be implemented to terminate the program, one is the maximum number of generation, another is the ideal fitness prescribed by customers [27]. Once the generations reaches the maximum number assumed, the GA program will be stopped and output the best solution so far representing the most optimised scheme [25]. Instead, once the ideal fitness designated by customers produced, the model will be stopped in the current generation of the population and output the corresponding solution. Hence, the optimisation achieved.

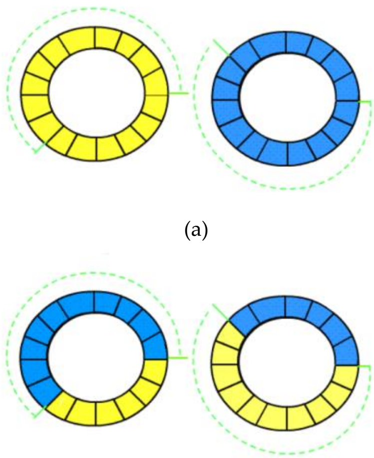
Mutation is one of the significant operators in GAs which contribute the changed gene or genes on the selected chromosome. A SMM was implemented in this study. Literally, 'Sequential' highlights that the place that mutation happens is following a sequence which goes one step further with the generations increasing [16]. Only one gene will be selected to be mutated and changed to a randomly number with a normal distribution during current generation. This distribution provides the natural of mutation that the genes' mutation of children keep a certain relationship with the genes from their parents.



(a)

(b)

Fig. 1. Linear Recombination Methods (LRM) illustration: a) before LRM; and b) after LRM.



(a)

(b)

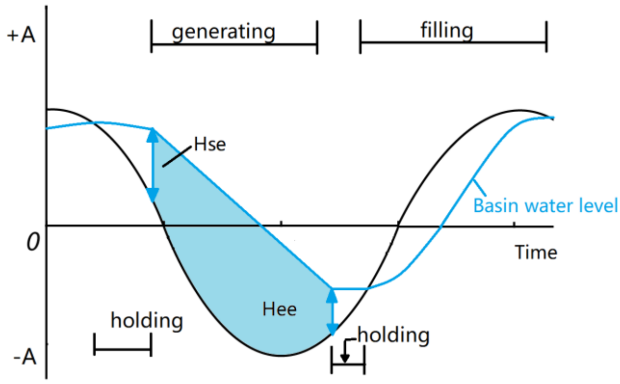
Fig. 2. Ring Recombination Methods (RRM) illustration: a) before RRM; and b) after RRM.

Recombination allows the genetic information from two chromosomes is able to be swapped, ensuring a creative effects on sexual individuals. LRM [28] is one of the most popular recombination methods which uses a specific linear representation of the chromosomes, as shown in Figure 1. During the recombination of every generation, a pair of two cross-over points with the same length have a chance to be picked up from parents' chromosomes, as can be seen in Figure 1(a). Next, as shown in Figure 1(b), the selected gene or genes swapped to form the new chromosomes for their children. Evidently, this linear recombination is very promising and support the use of GAs [28]. It should be noted that the selected position of the start point is limited to be prior to the end point and its length should be smaller than the total length of the chromosome in LRM. However, a RRM was carried out by a discovery that some polyoma DNA molecules in a form of circle structure in 1963 [29, 30]. In the proposed RRM, the two cross-over points were released from these limitation because of the loop structure of chromosomes, as shown in the Figure 2 [15, 17]. It has been demonstrated that applying the RRM with the SMM can speed up finding optimum solutions instead the use of LRM [16].

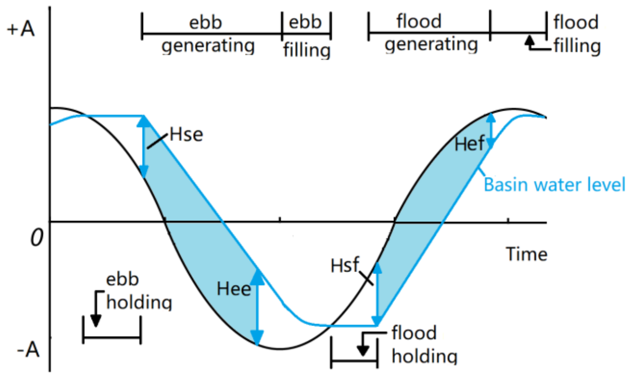
III. TIDAL RANGE SCHEMES

As the operation of TRSs, ebb-only and 2-way generation has been widely used as the effective ways for power production [31] by delaying the change of basin water level to generate a sufficient water head difference. A schematic of the ebb generation and 2-way generation schemes are illustrated in Figure 3(a) and (b), respectively.

In holding phase, it starts when the water levels in the impoundment are almost the same with it at seaside. All the turbines and sluice gates are closed until a sufficient water head difference created. This water head difference denotes the ending of holding phase which is also known as the starting of generation phase, referencing the H_{se} herein in ebb-only generation mode or the H_{se} and H_{sf} in 2-way generation mode during ebb and flood tides, respectively. When generating stage commences, the electricity generation would be converted efficiently from tidal energy with turbines running. It will be finished until the water head difference at the two sides of the impoundment is smaller than an assumed ending head, known as the H_{ee} in ebb-only generation mode or H_{ee} and H_{ef} in dual-way generation mode during ebb and flood tides, respectively. As tides changing, a filling phase begins by opening the turbines and sluice gates to balance the water levels on both sides of the impoundment embankment and prepare the holding phase for next tides.



(a)



(b)

Fig. 3. Schematic representation of the operational schemes: (a) one-way ebb-generation; (b) a two-way tidal power plant.

IV. DEVELOPMENT OF THE GA MODEL

C. *Preparation of the GA model*

The GA model was used to provide an indication of the operational characteristics optimisation in TRSs. The objects of this model was to maximize the electricity generation for the Swansea Bay Lagoon by applying optimised operation heads, e.g. H_{se} and H_{ee}. This will ignore the flexible optimisation schemes in term of the demand of residential electricity consumption, although it can increase the total electricity generation during the typical cycle [7].

The four major preparation involved in this GA model were listed below [32]:

- Determine the initial schemes.
- Determine the fitness function.
- Determine the parameters in the GA process.
- Determine the criterion for terminating a run.

1000 initial schemes of the first generation were generated randomly, following a uniform distribution which was between 2.0m to 8.0m of H_{se} and H_{sf}, 0.5m to 4.5m of H_{ee} and H_{ef}. A couple of operation heads were designed to operate during the corresponding half-tide in the typical cycle and hence, the quantity of couples of operation heads on each scheme equals to the size of half-tides within the typical cycle.

The 0-D methodology was considered as the measurement of fitness in this GA model which was implemented in the process of selection. In every generation, the electricity generation of the 'parents' and 'children's' schemes were evaluated with a computational time step of 60 seconds and then sequenced. Next, based on the principle of 'fitness of survivals', shrinking the size of schemes to the initial population size (1000 herein) which were also used as the 'parents' schemes for the next generation.

The fundamental parameters of P_m , P_r and P_s can significantly affect the efficiency of GAs and a higher convergence speed might be achieved with lower parameters [27, 33]. Thus, the P_m, P_r and P_s were assumed to be 0.5, 0.5 and 1 herein based on the fact that this study mainly focused on the feasibility of the GA modelling rather than the efficiency investigation.

The criterions for terminating a run were required to avoid an infinity running of this GA model, namely 'Target' and 'Another iteration' in the flow chart of executing the GA model in Figure 4, respectively. As mentioned in Section II, 'Target' refers to the ideal fitness defined by customers, which set to infinity to obtain the maximum electricity generation in this study. 'Another iteration' herein denotes the maximum number of generations which was designed to be 3000, ensuring a convergence results generated within an affordable cost-time.

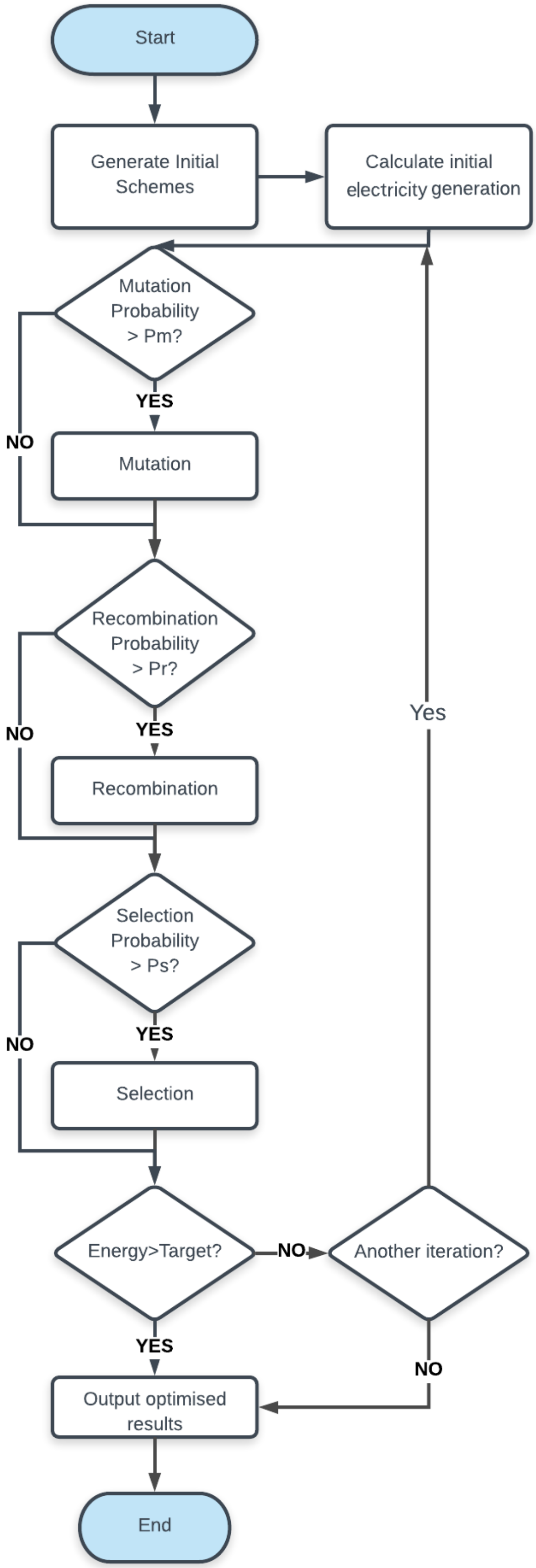


Fig. 4. Flow chart of the GA model.

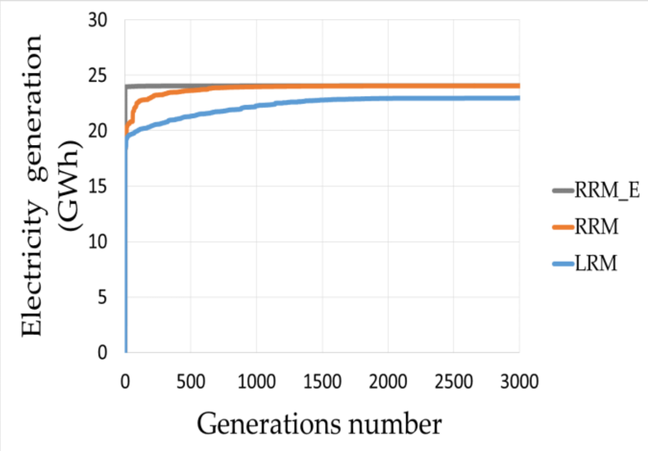


Fig. 5. Convergence characteristics comparison.

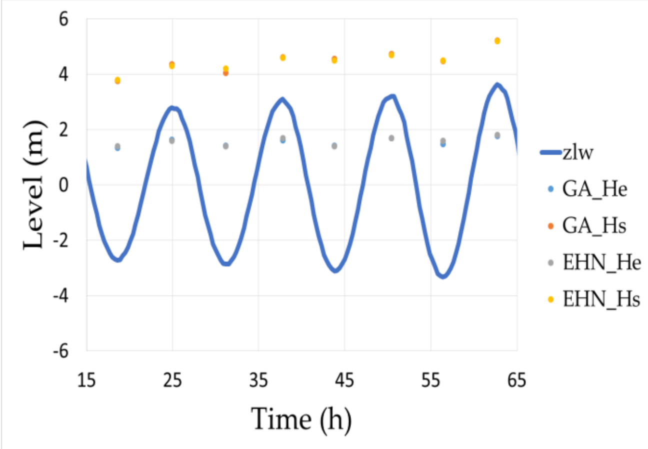


Fig. 6. Optimised operation heads comparison between the EHN and GA model.

D. *GA model*

As shown in Figure 4 [11], once the generation process commences, initial schemes with flexible operation heads for every half-tides are created randomly and then be evaluated through 0-D methodology. By copying the existing schemes to new schemes, the new schemes will be generated through the mutation, recombination and selection with possibilities of P_m, P_r and P_s, respectively. This process will be iteratively performed until the termination criterions are satisfied. It should be noted that parallelization is one of the outstanding advantages of this GA model, which is achieved by utilising the Open Multi-Processing (Open MP). Options allow the recombination methods of the LRM and RRM to be switched, aim to compare the efficiencies of them respectively in the GA model [16].

E. *Optimisation using GA*

The results of convergence speed in 3,000 runs were shown in Figure 5, in which the 'LRM' and 'RRM' indicated the optimised electricity generation and the efficiencies of the GA model during the typical cycle, with the usage of LRM and RRM, respectively. It can be seen that proposed RRM revealed a higher efficiency and a greater energy generation, which is consistent with the findings by Nia and Alipouri [24].

The optimum schemes generated from the EHN model was implemented in the GA model as one of the initial schemes, referred to RRM_E in Figure 5, to achieve the efficiency improvement. It was shown that with the elite scheme involved, the electricity generation using RRM_E was consistent with the electricity prediction using RRM but with a higher convergence speed. Therefore, the efficiency of the GA model could be improved significantly with an increased energy generation of 24.1 GWh, corresponding to a 13.1% increase comparing to the fixed head schedule in Table I.

As shown in Table I, about equal electricity generation were reached by the EHN model and the GA model, respectively, with a more than 50% of cost-time could be saved by using the GA with RRM at its approximately 1200th generations. Figure 6 described the optimised operational heads for the four neap tides in the EHN and GA models, to present the optimised results of both approaches and also to highlight the feasibility of using a GA to optimise the operational characteristics in TRSs. The GA_H_e , GA_H_s , EHN_H_e and EHN_H_s denoted the optimised ending head and starting head for generation in the GA and EHN models, respectively. It showed that only slightly difference existed using the two approaches in terms of the optimum operation heads. Thus, it has been proved that the GA model was able to be potentially developed to solve the operational characteristics optimisation in TRSs.

TABLE I
OPTIMISATION SCENARIOS FOR TYPICAL TIDAL CYCLE.

Scenario	Energy (GWh)	Change to fixed head schedule
Fixed head schedule	21.3	-
EHN model	24.0	12.5%
GA model	24.1	13.1%

V. CONCLUSION

A developed GA coupled with 0-D modelling as the fitness function has been performed well in optimising the flexible operation schemes in TRSs. Incorporating a mutation method of SMM and two recombination methods of LRM and RRM, respectively into the GA model, it has been demonstrated that the RRM implemented with SMM are an effective way to improve the optimisation performance and efficiency of the GA model. Both of the GA and the GS method which considered as the benchmark in this study can yield a more than 10% increase of electricity generation, in comparison with the traditional fixed head schemes. However, it appears to be at least 50% more efficient of the GA model than the GS model. In this sense, this GA model is a strong tool and can be developed to solve the optimisation problem of tidal lagoons.

ACKNOWLEDGEMENT

Miss Jingjing Xue would like to thank China Scholarship Council (CSC) and Cardiff University for supporting this work.

REFERENCES

[1] M. J. Burke and J. C. Stephens, "Political power and renewable energy futures: A critical review," *Energy Research & Social Science,* vol. 35, pp. 78-93, 2018/01/01/ 2018.

[2] R. Ahmadian, C. Morris, and R. Falconer, "Hydro-environmental modelling of off-shore and coastally attached impoundments off the North Wales Coast," presented at the Proceedings of the 1st European IAHR Congress, Edinburgh, UK, 2010. Available: http://orca.cf.ac.uk/id/eprint/7601

[3] E. I. S. Department for Business. (2013). *Wave and tidal energy: part of the UK's energy mix*. Available: https://www.gov.uk/guidance/wave-and-tidal-energy-part-of-the-uks-energy-mix#tidal-range-potential

[4] BBC. (2018). *£1.3bn Swansea Bay tidal lagoon project thrown out*. Available: https://www.bbc.co.uk/news/uk-wales-south-west-wales-44589083

[5] D.Prandle, "Simple theory for designing tidal power schemes," 1984.

[6] R. Ahmadian, J. Xue, R. A. Falconer, and N. Hanousek, "Optimisation of Tidal Range Schemes," *Proceedings of the 12th European Wave and Tidal Energy Conference,* no. ISSN 2309-1983, p. 1059, Sep. 2017.

[7] N. Yates and B. Tatlock, "Optimising Tidal Lagoons," presented at the European Wave and Tidal Energy Conference, Republic of Ireland, 2017.

[8] A. Angeloudis, S. C. Kramer, A. Avdis, and M. D. Piggott, "Optimising tidal range power plant operation," *Applied Energy,* vol. 212, pp. 680-690, 2018.

[9] B. F. M. Child and V. Venugopal, "Optimal configurations of wave energy device arrays," *Ocean Engineering,* vol. 37, no. 16, pp. 1402-1417, 2010/11/01/ 2010.

[10] S. Basu, A. Sarkar, K. Satheesan, and C. M. Kishtawal, "Predicting wave heights in the north Indian Ocean using genetic algorithm," *Geophysical Research Letters,* vol. 32, no. 17, 2005.

[11] P. Sullivan and P. McCombie, "Optimisation of tidal power arrays using a genetic algorithm," (in English), *Proceedings of the Institution of Civil Engineers - Energy,* vol. 166, pp. 19-28, 2013.

[12] www.tidallagoonpower.com/projects/swansea-bay/. *Swamsea Bay-Tidal Lagoon*.

[13] S. Petley and G. Aggidis, "Swansea Bay tidal lagoon annual energy estimation," *Ocean Engineering,* vol. 111, pp. 348-357, 2016.

[14] G. Rajgor, "Time for tidal lagoons?," *Renewable Energy Focus,* vol. 17, no. 5, pp. 202-204, 2016.

[15] B. Pavez-Lazo and J. Soto-Cartes, "A deterministic annular crossover genetic algorithm optimisation for the unit commitment problem," *Expert Systems with Applications,* vol. 38, no. 6, pp. 6523-6529, 2011/06/01/ 2011.

[16] M. B. Nia and Y. Alipouri, "Speeding Up the Genetic Algorithm Convergence Using Sequential Mutation and Circular Gene Methods," in *2009 Ninth International Conference on Intelligent Systems Design and Applications*, 2009, pp. 31-36.

[17] S. B. A. Bukhari, A. Ahmad, S. Auon Raza, and N. Siddique, *A ring crossover genetic algorithm for unit commitment problem*. 2016, pp. 3862 – 3876.

[18] A. Angeloudis, R. Ahmadian, R. A. Falconer, and B. Bockelmann-Evans, "Numerical model simulations for optimisation of tidal lagoon schemes," *Applied Energy,* vol. 165, pp. 522-536, 2016.

[19] G. A. Aggidis and D. S. Benzon, "Operational optimisation of a tidal barrage across the Mersey estuary using 0-D modelling," *Ocean Engineering,* vol. 66, pp. 69-81, 2013.

[20] R. A. Falconer, J. Xia, B. Lin, and R. Ahmadian, "The Severn Barrage and other tidal energy options: Hydrodynamic and power output modeling," *Science in China Series E: Technological Sciences,* vol. 52, no. 11, pp. 3413-3424, 2009.

[21] R. Ahmadian and R. A. Falconer, "Assessment of array shape of tidal stream turbines on hydro-environmental impacts and power output," *Renewable Energy,* vol. 44, pp. 318-327, 2012.

[22] I. Fairley, R. Ahmadian, R. A. Falconer, M. R. Willis, and I. Masters, "The effects of a Severn Barrage on wave conditions in the Bristol Channel," *Renewable Energy,* vol. 68, pp. 428-442, 2014.

[23] J. H. Holland, *Adaptation in Natural and Artificial Systems*. Univerisity of Michigan Press, 1975.

[24] J. R. Koza, "Genetic programming as a means for programming computers by natural selection," *Statistics and Computing,* journal article vol. 4, no. 2, pp. 87-112, June 01 1994.

[25] S. R. Ladd, *Genetic Algorithms in C++*. Hungry Minds, Incorporated, 1995, p. 384.

[26] E. Zitzler, K. Deb, and L. Thiele, "Comparison of Multiobjective Evolutionary Algorithms: Empirical Results," *Evol. Comput.,* vol. 8, no. 2, pp. 173-195, 2000.

[27] S. R. Ladd, M. Sprague, Ed. *Genetic programming in c++*. New York, United States of America: Paul Farrell, 1996.

[28] A. Guven, "Linear genetic programming for time-series modelling of daily flow rate," *Journal of Earth System Science,* vol. 118, no. 2, pp. 137-146, 2009/04/01 2009.

[29] R. Weil and J. Vinograd, "The cyclic helix and cyclic coil forms of polyoma viral DNA," *Proceedings of the National Academy of Sciences,* 10.1073/pnas.50.4.730 vol. 50, no. 4, p. 730, 1963.

[30] R. Dulbecco and M. Vogt, "EVIDENCE FOR A RING STRUCTURE OF POLYOMA VIRUS DNA," *Proceedings of the National Academy of Sciences of the United States of America,* vol. 50, no. 2, pp. 236-243, 1963.

[31] R. Ahmadian, R. A. Falconer, and B. Bockelmann-Evans, "Comparison of hydro-environmental impacts for ebb-only and two-way generation for a Severn Barrage," *Computers & Geosciences,* vol. 71, pp. 11-19, 2014.

[32] D. E. Goldberg, *Genetic Algorithms in Search, Optimization and Machine Learning*. Addison-Wesley Longman Publishing Co., Inc., 1989, p. 372.

[33] D. Whitley, *Genetic algorithm and neural network*. John Wiley & Sons Ltd, 1995.