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Article

Integration of Water Transfers in Hydropower Operation Planning

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Abstract: The rising demand for clean energy production due to climate change emphasizes the importance of optimizing water resources, particularly in countries with significant hydropower potential. Existing models for the Operational Planning of Hydropower Systems (HPSOP) typically focus on the natural flows of rivers, often overlooking the potential of water transfers between rivers and basins. To address this gap, this article employs an improved mathematical model of hydropower production, considering the adjustment of the water transfer in the operation schedule as an additional optimization variable. A customized meta-heuristic, named the Evolutionary Socio-Bio Inspired Technique (ESBIT), has been tailored to integrate water transfer mechanisms into the operational planning model. The proposed model was validated through a case study at the Henry Borden Complex in São Paulo, Brazil, using real power plant parameters and inflow data from the Brazilian system. The results obtained from the test case, both with and without water transfer, demonstrate that the proposed methodology effectively captures the operational characteristics of a system that allows water transfers between rivers or basins to optimize the available water resources and system costs.

Keywords: operation planning; hydropower; water transfers; optimization; ESBIT

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1. Introduction

The production of clean energy is increasingly essential due to climate conditions [1,2]. In the context of electricity production, especially in countries with significant hydropower potential, the optimized use of water resources becomes indispensable. Hydropower plants are viewed as a clean, cost-effective, and renewable energy source [1]. For example, in Brazil, hydropower generation stands out as one of the primary methods for electricity production. The country has immense potential, with 681 hydropower plants and 428 small plants distributed throughout the national territory, accounting for over 60% of the installed capacity in the Brazilian Interconnected System [3].

Efficient water management not only optimizes energy generation but also contributes to environmental sustainability and water security in a country. When water availability is insufficient to meet the specific demands of consumption centers, a viable solution is to transfer water between rivers and basins [4–6]. In some cases, even when water supply may be adequate, it may still be necessary to construct retention structures to manage drought conditions or even large pipelines or ducts to deliver water to the final consumer. Another operational aspect of reservoirs is the control and reservation of water, effectively preventing floods and making it available for future use, thereby reducing the uncertainty of natural inflows [7–10].

The operational complexity of hydropower reservoirs is evident in several aspects: optimizing the cascade production of power plants, managing the stored energy, defining the best strategy for transmitting the generated energy, and finalizing financial and commercial arrangements. This complexity requires a significant collaborative effort from all companies involved, which can only be achieved through large-scale computational tools and highly precise measurement systems that are continuously monitored [7,11].

To address this complexity, optimization techniques are important for the operational planning of hydropower systems. However, their application faces challenges due to high dimensionality and the nonlinear and dynamic characteristics involved [2,11–13]. Given this complexity, Genetic Algorithms (GAs) and other meta-heuristics have been widely used in the optimization process of hydropower systems [1,12,14–17].

An area that remains underexplored in this energy planning landscape is the utilization of water transfers for electricity generation. From an energy perspective, the potential to leverage these transfers has been largely overlooked, as priority has been given to harnessing the natural flow of rivers. Current modeling approaches for the Operation Planning of Hydropower Systems (HPSOP) do not account for water transfer mechanisms. Consequently, simulators and optimization programs still need to be improved for this possibility, which limits opportunities to enhance electricity production.

In this context, this article contributes with a model for the Operational Planning of Hydropower Systems, which includes the possibilities of water transfers between rivers and/or watersheds. Therefore, the proposed intelligent optimization technique is based on the evolutionary behavior of a species, similar to Genetic Algorithms, and additionally considers its integration into a social environment. This proposal has been named the Evolutionary Socio-Bio Inspired Technique (ESBIT) [11], and the developed model was tested in a case study at the Henry Borden Complex in the state of São Paulo, Brazil. It should be noted that the methodology can be applied to any test system.

2. Mathematical Model

The scheduling of hydroelectric power plants is the subject of the optimization in the problem of Operation Planning of Hydropower Systems. It aims to solve the operator dilemma that deals with the uncertainty of the water availability and future costs. The dilemma gains importance in a highly hydro-dominated system that depends on uncertain seasonal rain regimes. Despite the uncertainty, the operator needs to decide between (1) using the water stored in reservoirs in a certain instant, depleting the energy stored there with low costs at that moment, or (2) preserving the water in reservoirs for future use by activating costly thermal production instead (because thermal electricity may be insufficient or more costly in the future).

Thus, given an expected scenario of energy consumption and inflows, power plants with reservoirs can optimize their storage capacity to regulate the flow and accommodate variations of the consumption and uncertain inflows along the planning horizon, in order to minimize the total cost of the operation. This optimization results in the proper scheduling of the hydroelectric production as well as in the adequate storage volume in each reservoir for each period of time.

The mathematical model used in this article primarily aims to present the proposed change in the water balance (Equation (1)) to incorporate the possibility of water transfer between rivers and basins, whenever there is water availability and transfer means between the involved regions. The variables of the water balance are illustrated in Figure 1.

$$x_i^t = x_i^{t-1} + yn_i^t - u_i^t + \sum_{l \epsilon \Omega_i} \left(u_l^t - yn_l^t \right) + \sum_{j \epsilon \phi_i} ya_j^t \tag{1}$$

where:
$x_i^{\{t,t-1\}}$ is the reservoir volume at plant i in period $\{t,\ t-1\}$;
$u^t_{\{i,\ l\}}$ is the controlled outflow by plant $\{i, l\}$ in period t;

$yn^t_{\{i,l\}}$ is the natural inflow received by plant $\{i,\ l\}$ in period t;
ya^t_j is the directional artificial flow from plant j to plant i in period t. The value of ya^t_j is defined as positive for flows from j to i and negative in the opposite direction;
Ω_i is the set of plants immediately upstream of plant i;
ϕ_i is the set of plants that have resources for artificial flow transfer with plant i.

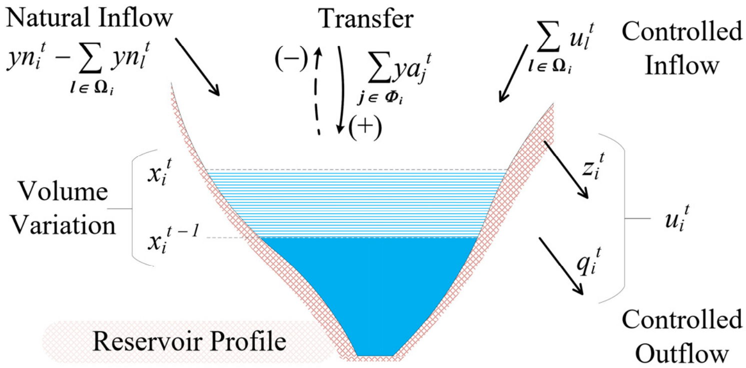

Figure 1. Schematic diagram: water transfer between rivers and basins.

The introduction of the artificial flow component, ya^t_j, in the water balance and its combined optimization together with the hydroelectric scheduling (planned operation of each power plant, i, at each period, t, along the planning horizon, T) is an important contribution of this work to the traditional Hydro Power System Operation Planning. The HPSOP's problem is typically formulated as a cost minimization model (Equation (2)). In this model, the objective function ($O.F$) aims to minimize the total cost of the planned system operation (along the planning horizon, T), denoted by C_0, which represents the present value of the marginal costs (Equation (3)) associated with the operation of the thermoelectric system, known as C^t_{term} (Equation (4)). This cost is a function of the thermoelectric complementation, E^t_{term}, which is evaluated by the energetic balance described as the difference between the energy consumption, D^t, and the hydroelectric production, GH^t (Equation (5)).

Thus, the minimal operation cost is obtained by an optimal scheduling of the hydroelectric production, P^t_i (Equation (6)), of all power plants, that is a function of the management of the water and reservoirs. Therefore, the objective function ($O.F$) from traditional HPSOP, the operation of which can be described as a function of the reservoir's volumes, x^t_i, received a new state variable once the operation became impacted by the volume of water transferred artificially, ya^t_j, introduced in the constrain of the water balance (Equation (1)).

$$O.F = \min_{x^t_i, ya^t_j} C_0 \tag{2}$$

$$C_0 = \sum_{t=1}^{T} \frac{C^t_{term}}{(1+J)^{t/12}} \tag{3}$$

$$C^t_{term} = \psi\left(E^t_{term}\right) \tag{4}$$

$$E^t_{term} = D^t - GH^t \tag{5}$$

$$GH^t = \sum_{i=1}^{N} P^t_i\left(x^t_i,\ u^t_i, q^t_i\right) \tag{6}$$

where:

J is the annual interest rate in the period;
ψ is the marginal cost function of the operation of the thermoelectric system;
E^t_{term} is the thermal complementation in period t;

D^t is the consumption in period t;
GH^t is the total hydroelectric production in period t.

The total hydroelectric production incorporates the production function, P_i^t, of each of the N power plants of the system. In other words, this function depends on the physical properties of water, turbine-generator efficiency, and water balance variables, as presented in Equations (7)–(10).

$$P_i^t\left(x_i^t, u_i^t, q_i^t\right) = k_i\left[h_{up}{}_i^t\left(x_i^t\right) + h_{down}{}_i^t\left(u_i^t\right)\right]q_i^t \tag{7}$$

$$h_{up}{}_i^t\left(x_i^t\right) = a_0^i + a_1^i \cdot x_i^t + a_2^i \cdot \left(x_i^t\right)^2 + a_3^i \cdot \left(x_i^t\right)^3 + a_4^i \cdot \left(x_i^t\right)^4 \tag{8}$$

$$h_{down}{}_i^t = b_0^i + b_1^i \cdot u_i^t + b_2^i \cdot \left(u_i^t\right)^2 + b_3^i \cdot \left(u_i^t\right)^3 + b_4^i \cdot \left(u_i^t\right)^4 \tag{9}$$

$$u_i^t = q_i^t + z_i^t \tag{10}$$

where:

k_i is the constant that encompasses gravity acceleration, water density, turbine-generator efficiency, and unit conversion for the plant, i;
q_i^t is the turbine flow rate by plant i in period t;
u_i^t is the controlled outflow by plant i in period t;
z_i^t is the spilled flow rate by plant i in period t;
$h_{up}{}_i^t$ is the reservoir level upstream of plant i in period t;
$h_{down}{}_i^t$ is the tailrace channel level downstream of plant i in period t;
$a^i_{\{0,\ldots,4\}}$ are the constants of the level–volume polynomial;
$b^i_{\{0,\ldots,4\}}$ are the constants of the level–flow rate polynomial.

Finally, besides the water and energy balance (Equation (1) and Equation (5), respectively), the operational constraints are additionally determined by Equations (11)–(13).

$$x_{min,i} \leq x_i^t \leq x_{max,i} \tag{11}$$

$$q_{min,i} \leq q_i^t \leq q_{max,i} \tag{12}$$

$$GH^t, E_{term}^t, u_i^t,\ z_i^t \geq 0 \tag{13}$$

The initial and final volumes were fixed at 100% of the reservoir's useful volume. This consideration was applied in the works of [7,11,17–21], and its cyclical nature ensures the consideration of water depletion costs within the planning horizon.

3. Solution Algorithm

The intelligent optimization technique proposed in this article for solving the HPSOP is based on the evolutionary behavior of a species, similar to Genetic Algorithms (GAs), and additionally considers its insertion into a social environment, unlike GAs, which works with a single population. The approach adopted in this article is called the Evolutionary Socio-Bio Inspired Technique (ESBIT) [11]. The algorithm seeks to represent the population universe by considering how individuals group into societies, as well as the interrelations within a society and between societies during the evolutionary process. Figure 2 illustrates the coexistence of generations within a society.

In this evolutionary strategy, the universe is made up of multiple societies or colonies, and each colony is a multigenerational population structure where at least two generations of individuals coexist. In these populations, each individual is determined by their genes, which correspond to a set of values for state variables that represent a complete solution to the problem.

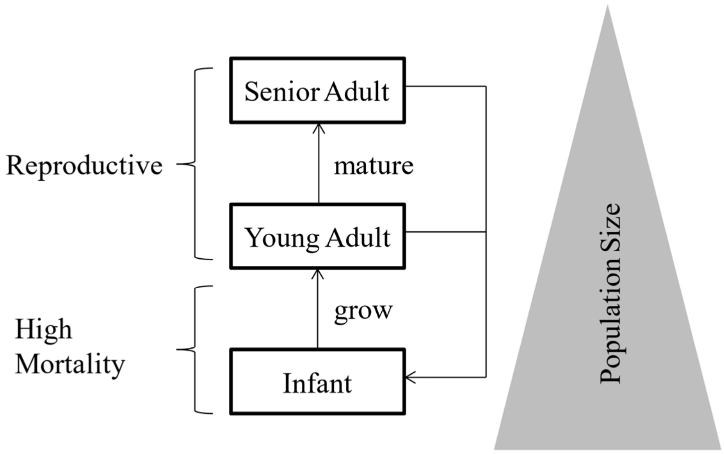

Figure 2. Simplified representation of coexisting generations.

In this case of operational planning, the individuals' characteristics (individuals' genes) are represented by a vector of dimension $(N + A) \cdot T$, containing all the normalized reservoir volume values, x_i^t, of all N plants and artificial flow rates, ya_j^t, for all available water transfer canals, A, in each period, t, within the simulated system and planning horizon, T.

In addition to the multigenerational characteristic (Figure 2) that allows for broadening and varying the range of reproduction strategies throughout evolution, in the ESBIT, the complexity is also adjusted (increasing the number of discrete levels of state variables and, consequently, the search universe) throughout the evolutionary process, mimicking the natural processes of evolution. During early evolution stages, the optimal solution is pursued with large variations of the state variable's values, and a rough solution is obtained. Once evolution progresses and stabilizes, discretization of volumes increases stepwise and more precise solutions are progressively found.

The evolution of the species is not only a matter of a random combination of genes that are available for a certain group at once, but also dependent on continuous cycles of insulation and refinement succeeded by sporadic interactions with other groups which took slightly different development paths, as shown in Figure 3.

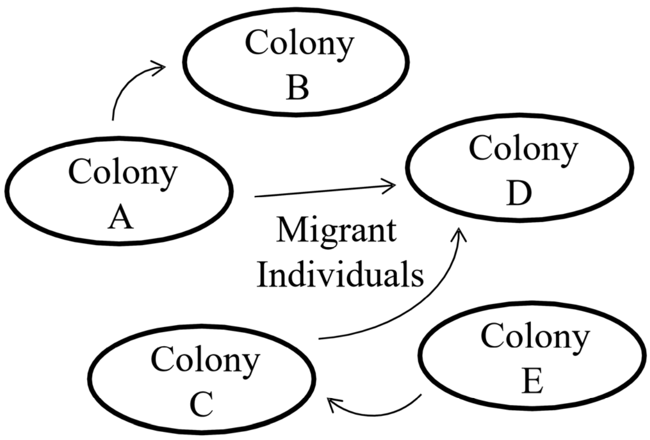

Figure 3. Species development into several separate social groups, where individuals may eventually migrate between groups.

Based on this universe architecture, this new meta-heuristic for solving hard-to-solve problems was proposed with the goal of efficiently exploring the search space without going through all possible solutions, thus allowing the encoding of large and complex multidimensional problems such as the HPSOP, which is a non-convex problem. The ESBIT has been tailored to solve problems with multiple local minimums, where the gradient acceleration provided by algorithms such as Particle Swarm Optimization (PSO) [22] and similar meta-heuristics makes it hard to escape from a local minimum, without reducing its acceleration efficiency up to the point it is unnecessary. The ESBIT's advantage over traditional GAs derives from the fact that it extended its pros of the wider search of the universe of solutions with variable discretization and a more flexible reproduction strategy due to coexisting generations. Besides that, the addition of multiple parallel searches (multithreading) in each insulated colony, which are apt to communicate among themselves, reduces the probability of inconsistent results, therefore increasing the computational efficiency.

A brief description of the proposed algorithm is presented below to provide an overview of the computational tool developed in this work.

Problem Encoding: Metaphorically, an individual is characterized by its genes, which, in the case of evolutionary meta-heuristics such as the ESBIT, is represented by one complete solution, i.e., one individual is an entity (object of vector, for example) with a specific value for each state variable (gene) of the optimization problem. In this way, for each given individual, the value of the objective function can be evaluated. Therefore, different individuals will have different genes (or values for the state variables) and will compute different values for the objective function

The optimization is obtained by creating (reproducing) individuals based on the best fitted ones from previous generations introducing combinatory and aleatory variations inspired by evolutionary studies. For the representation of the problem described in the previous session, all variables that define a state are represented by normalized discrete values. In this study, the individual will represent the normalized useful volume of the reservoir of each plant for each month of the planning period, as well as the normalized volume of artificial water transfer each month, as a proportion of the canal's capacity; these are the state variables of Equation (2) (x_i^t, ya_j^t).

Initial Population: The initial population consists of individuals with one aleatory value of useful volume and transfer along the period of the simulation, emulating a feasible operating condition. In this configuration, the hydro power plants operate solely with natural inflows, characterizing behavior like that of run-of-river plants, for example.

Evaluation Function: Each individual in the population is assessed and ranked according to the objective function ($O.F$). In this case, the total operation cost. Based on a set of state variables (individual genes), the operation cost is determined using Equation (3).

Population Sorting: The proposed algorithm classifies the population by calculating the evaluation function for all individuals and then ordering them according to the problem's objective. Thus, considering the minimization objective of Equation (2), the population of individuals (multiple possible solutions, set of state variables) will be organized from the lowest to the highest cost, ensuring that the first individual in each population always has the lowest cost.

Selection: Selection is performed to identify the fittest individuals, those with a higher likelihood of reproduction, producing an offspring that are equally or even more fit.

Reproduction: The reproduction operators are similar to those used in Genetic Algorithms, including uniform crossover, soft mutation, and local mutation. Combinatory and aleatory variations, inspired by evolutionary studies, of genes of selected individuals from previous generations will result in a new different individual (offspring) that can reveal a more adapted characteristic. In such cases, new individuals will rank better according to the $O.F$, leading the optimization process a step closer to a quasi-optimal solution.

Termination Criterion: The proposed algorithm uses the rate of variation of the objective function as a termination criterion.

Precision: Precision increases as the number of discrete intervals grows. A higher level of precision also results in increased system complexity for problem resolution.

Thus, the computational execution can be summarized by the following steps of a generic evolutionary algorithm loop, illustrated by Algorithm 1:

Algorithm 1. Evolutionary algorithm

```
Initialize the population with individuals of (N + A) · T genes.
Evaluate the cost function for all individuals.
Sort the population.
   While the convergence criterion is not reached,
       Select the individuals that will participate in the reproduction process.
       The selected individuals reproduce to obtain a new generation.
       Evaluate the cost function for all new individuals.
       Sort the population.
   End.
Return best individual
```

A more specific flowchart of the ESBIT is available as Appendix A and more details of the technique can be found in reference [11].

For the execution of the simulations, the code was implemented in Java 8 on the Energ.IA platform (www.ia.abc.br). The JAR file, containing the necessary parameters, was loaded onto the Titanio cluster at the Federal University of ABC. For each simulation, a computational node with the following specifications was used: SGI H2106-G7 model, equipped with 64 cores distributed across 4 sockets, featuring an AMD Opteron Sixteen-Core 6376 processor operating at 2.3 GHz, 6 MB of cache, a transfer rate of 6.4 GT/s, and 256 GB of DDR3 RAM at 1600 MHz. Table 1 describes the parameters used in the ESBIT.

Table 1. ESBIT parameters adopted in the simulations.

Parameter Description	Value
Quantity of individuals per colony (adults)	10
Quantity of individuals per colony (young adults)	100
Initial discretization	10
Final discretization	10,000
Convergence criterion (zero variation of the cost function over this number of generations)	2000
Number of colonies	5
Minimal generations of colony insulation	50
Probability of emigration	0.005
Probability of immigration	0.002

4. Description of the Study Area

To validate the methodology presented in this paper, a test system involving the Henry Borden power plant complex was adopted. This complex is fed by the water of the Billings Reservoir, which was built to enable the non-natural transfer of water between rivers in the state of São Paulo, Brazil. Billings Reservoir is located in the southeastern region of Brazil, in the state of São Paulo. It serves both urban and rural areas of six municipalities in the Metropolitan Region of São Paulo.

Considering the installed capacity, Henry Borden is currently the 32nd largest power plant from a total of 1768 plants in Brazil. This ranking position is a result of its design and location in the bottom of the mountain range. This provides a geographic advantage due to the altitude difference between the reservoir and the generators, which results in high productivity.

Additionally, the complex is larger than 1039 of the 1042 existing thermal plants in Brazil. It is only smaller than the Angra II nuclear power plant with 1350 MW, the Leonel Brizola thermal plant (TermoRio) with 1058.3 MW, the Santa Cruz thermal power plant with 1000 MW, and the Mário Lago thermal power plant (formerly Macaé, Merchant) with 922 MW.

In terms of productivity, it is the second largest power plant, just behind the Governor Parigot de Souza plant (previously named Capivari/Cachoeira) at the state of Paraná. To illustrate the strategic significance of the plants, it is important to emphasize its location in Cubatão-SP, one of the largest industrial centers in Brazil (Figure 4).

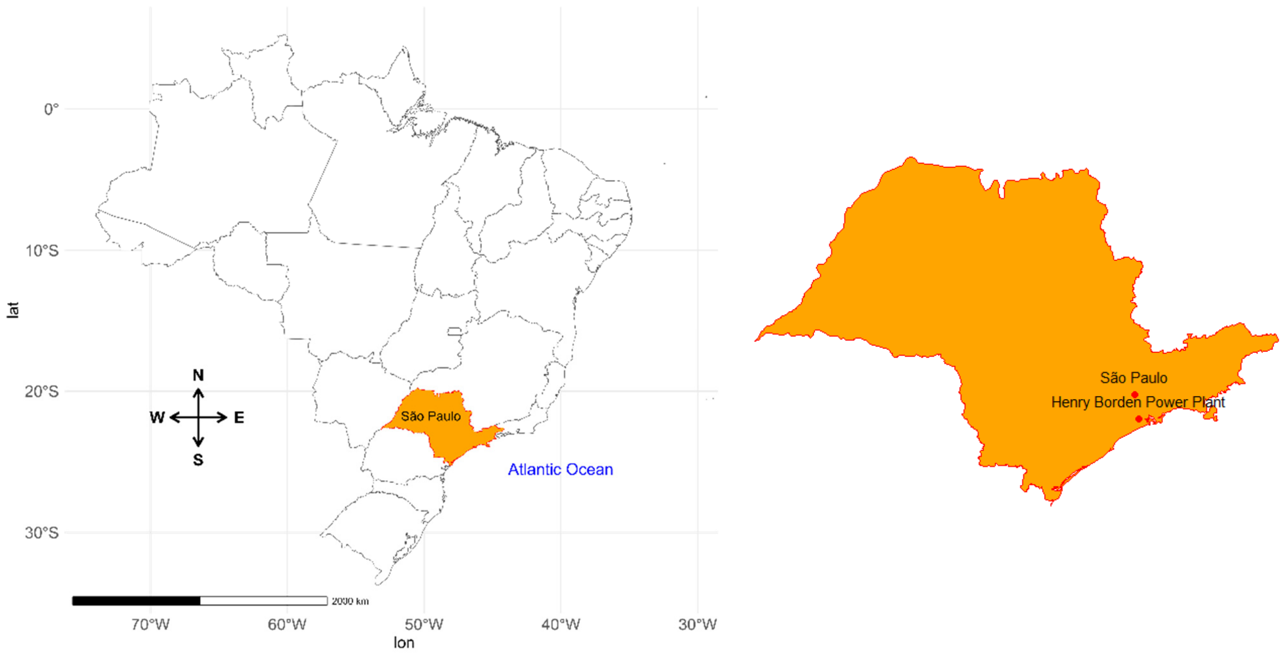

Figure 4. Location of the Henry Borden power plant.

The strategic importance of the complex lies in its proximity to Brazil's largest city and load center, providing great reliability for the local electrical system. Additionally, in the case of a blackout, the Henry Borden power plant can directly feed priority loads in the main areas of São Paulo, such as the city center, hospitals, subway, etc., due to its design characteristic that allows black-start. Recently, it also provided a significant contribution to the reactive control of the interconnected system [23].

However, its location suffers the consequences of an unplanned large urban center, developed around the water reservoir, and the energy availability provided by the plant. Currently, rivers in the region have been polluted due to untreated residues and regulations limit the power plant's operation, as detailed in the next session.

5. Operating Condition and Results

The Henry Borden Complex is illustrated in Figure 5. Its full operation hinges on the availability of water in the Pedras River and Billings reservoir, which are solely allocated to electricity generation. The sharing of the water from reservoirs with the public supply and lack of treatment of the sewer water launched into the Pinheiros (converted into a canal) and Tietê rivers triggered an intense societal debate about the quality of the water and the best approach to take in regards its multiple uses. Such debate culminated in the promulgation of São Paulo's constitution of 5 October 1989 [24], which in article 46 of its transitory constitutionals' laws, prohibited the transfer of water from the Tietê and Pinheiros rivers to the Billings reservoir. It states that if within three years following the enactment, the public, Municipal Authorities did not take effective measures to stop the pumping of sewer waters, waste, and other polluted substances to Billings reservoir, there would be repercussions [25].

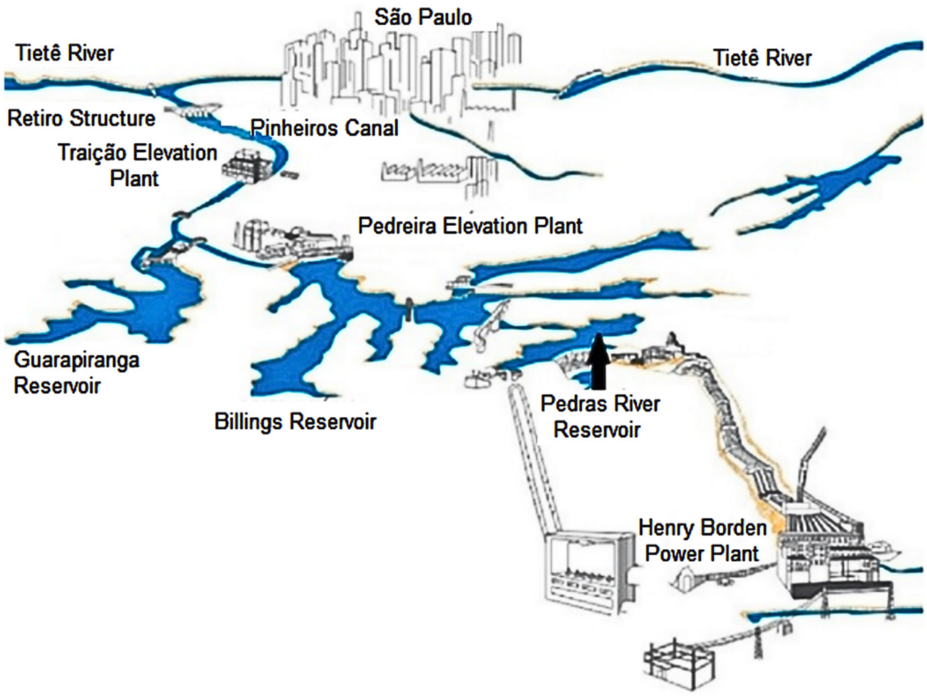

Figure 5. Diagram of the Henry Borden Complex. Adapted from [26].

Then, since 1992, once the measures requested by São Paulo's constitution were not met, the pumping operation from the Tietê and Pinheiros rivers to the Billings reservoir have been allowed to control flooding of the São Paulo's metropolitan region. Therefore, energy generation at the Henry Borden power plant complex was reduced to nearly 15% of its full capacity, due to the problem of pollution in the Tietê and Pinheiros rivers.

Not even the attempted treatment of the waters from the Pinheiros River with the flotation system had achieved sufficient quality characteristics to allow a continuous pumping operation, despite the fact that the test results indicated a superior water quality after the flotation treatment, compared to the quality of the water occasionally pumped to control the flooding in the Metropolitan Region of São Paulo.

The Henry Borden power plant complex has an installed power capacity of 899 MW. Its effective producibility is 5.654 MW/(m^3/s), one of the largest on the planet, needing about 157 m^3/s of water to maintain itself at full load. Itaipu, the major electricity producer of the country, needs more than 5.3 times this flow to produce the same amount of power, that is, 836.45 m^3/s.

In relation to this power plant complex, it is possible to state that there are benefits similar to a thermal power plant, whose installations are normally close to the load centers, with short transmission lines and few losses. On top of that, the hydraulic power plant does not have fuel costs and is considered less polluting [27].

Therefore, despite not being the focus of this work, it is urgent and necessary to collect and treat sewage in the Henry Borden Complex region to make the water resource viable in the area. Additionally, it is essential that the computational model used for planning the operation schedule of the electrical system contemplates the water transfer that is necessary for sustainable electricity production at the Henry Borden hydroelectric power plant.

Based on this context, this work presents the simulations carried out involving the Henry Borden Complex, a hydroelectric power plant located at the bottom of the mountain range named Serra do Mar. The power plant is located approximately 700 m below its water intake, being fed by the available water in the Billings reservoir. Besides the natural flow from rainfall and small water streams, it also receives artificially transferred water from the Pinheiros and Tietê rivers.

It is noteworthy that the water from the Tietê river, in its natural course (without any water transfer to Billings reservoir), would reach the reservoir of Barra Bonita hydroelectric power plant and eight other downstream plants until Itaipu, at the Paraná river, the last power plant in the cascade in the way to the sea level. Therefore, the hydroelectric plants on the Tietê river (Barra Bonita, Bariri, Ibitinga, Promissão, Nova Avanhandava, and Três Irmãos) and three other hydroelectric plants in the Paraná river chain (Jupiá, Porto Primavera, and Itaipu), are going to have their inflow reduced (and consequently their electricity production reduced as well) when water is transferred for electricity generation at the Henry Borden power plant. Figure 6 shows a schematic diagram of the power plant's relative location and the Pinheiros river (currently, a canal) where the water flow may be reversed (pumped) from the Tietê river in the direction of Billings reservoir.

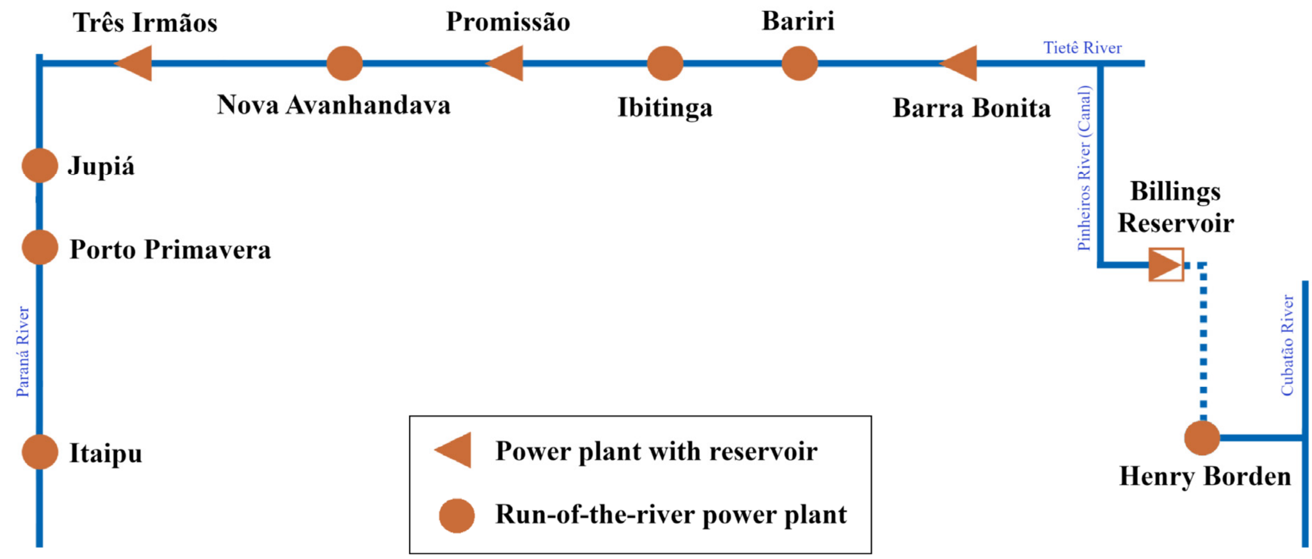

Figure 6. Diagram of hydroelectric power plants used in the test case. Adapted from [28].

Thus, it is important to evaluate the total impact of the water transfer, not only in Henry Borden, but in the complete system. For the characterization of a relevant test system, real data of the power plant parameters available from the Brazilian Electric Energy Trading Chamber were used [29] to compute Equations (7)–(12) [30]. Additionally, a second-order Taylor's regression of the cost of the thermal generation has been evaluated with data from [29] and applied in Equation (4). A planning period, T, of 24 months was also adopted, starting in May (the end of the rainy season) and marking the beginning of the dry season. The natural inflow used is equal to the long-term average obtained from the database, which has a flow history back to 1931. The average energy consumption in the simulation was set at 80% of the installed power capacity of all hydroelectric plants modeled, and an interest rate of 10% has been used to evaluate the present value of the total operation costs of (Equation (3)).

In order to evaluate the effect of the water transfer, a benchmark simulation was conducted, without any possibility to transfer water from the Barra Bonita reservoir to Henry Borden $\left(ya_j^t = 0,\ \forall j, \forall t\right)$. Thus, the optimal operation planning solution, without transfer, can be graphically represented by the trajectories of the reservoirs' volumes, x_j^t, along the planning horizon, T, as shown in Figure 7. In this case study, only three power plants are equipped with regulating reservoirs and, therefore, they are the only ones capable of contributing to the optimization. Thus, the set of volumes planned for each month at each of these three power plants (namely: Barra Bonita, Promissão, and Três Irmãos), which results in the minimal operational cost, characterizes the solution of the HPSOP problem.

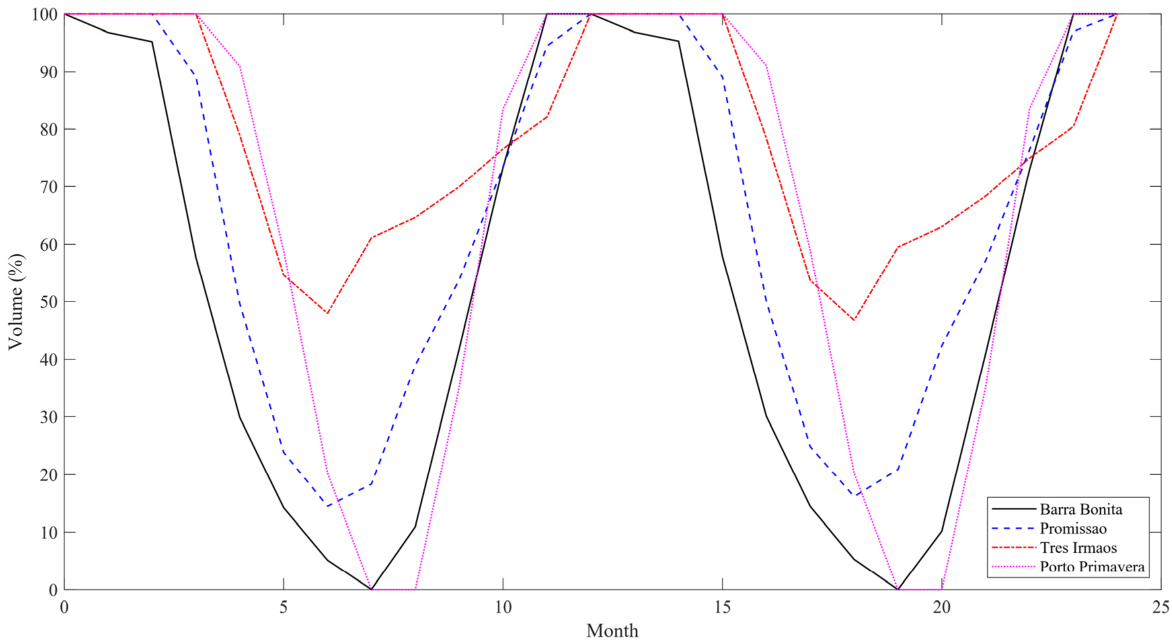

Figure 7. Relative working volumes of system reservoirs simulated without transfer.

This benchmark result of Figure 7 can be compared with the equivalent trajectories of Figure 8, where the optimal transfer, ya_j^t, along each period of the planning horizon, T, was obtained as part of the state variables in the simulation according to the new model proposed. It is worth pointing out that the reservoirs of these three power plants, which are used to regulate the flow in the Tietê river, started the optimization with their reservoirs (x_j^0, $\forall j$) at their maximum volumes (100%) in May and recovered themselves in May of the next year, which was repeated the following year, as can be also noted in both cases (Figures 7 and 8). This fact is also consistent with the recurrent inflow values, derived from the long-term average and the assumption that the volumes (x_j^T, $\forall j$) shall return to the same level at the end of the planning cycle.

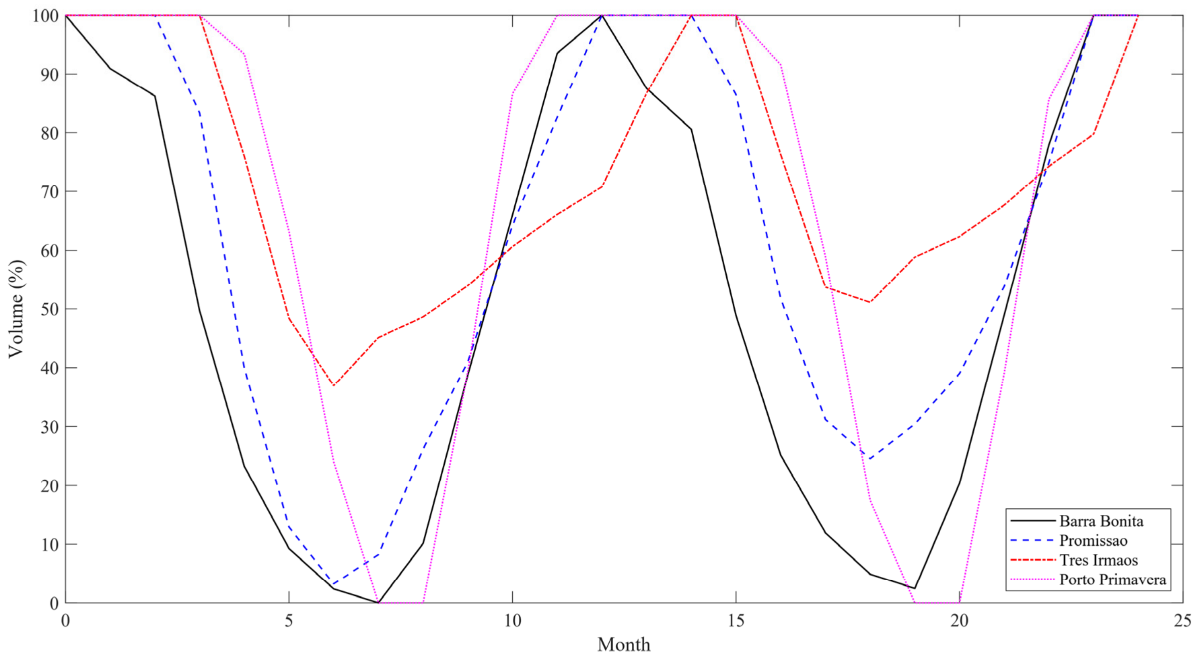

Figure 8. Relative working volumes of system reservoirs simulated with transfer to Henry Borden.

The notable differences in volumes' trajectories can be explained by the variation in water availability at the Barra Bonita reservoir due to the transfer and its consequence in the outflow downstream as well as by the fact that part of the energy demand is supplied by Henry Borden, reducing the expected production of the other hydroelectric power plants. Figure 9 illustrates the different results of the controlled outflow, u_i^t, in the operation planning of the Barra Bonita power plant compared with the water volume transferred to Henry Borden, ya_j^t, along each period of the planning horizon, T.

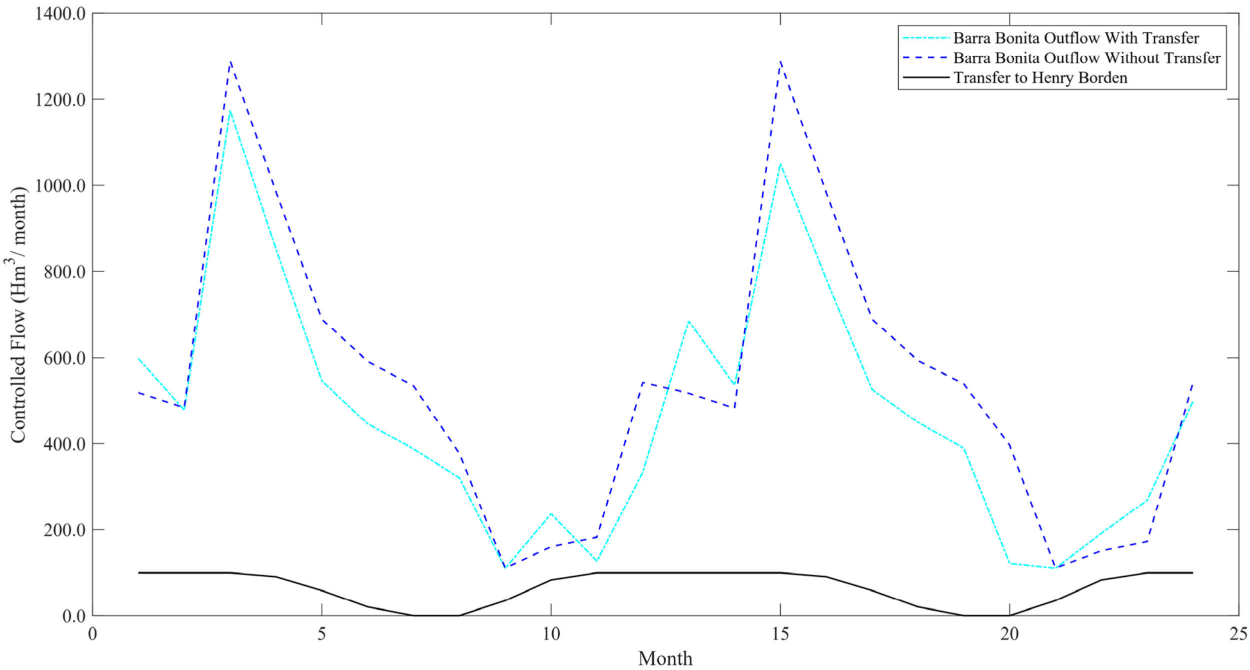

Figure 9. Outflow (u_i^t) at the Barra Bonita power plant with and without transfer compared with the water transfer (ya_j^t) from the Barra Bonita reservoir to Henry Borden.

In the case presented in Figure 9, the artificial inflow, ya_j^t, represents the amount of transferred water from the Tietê and Pinheiros rivers (from the Barra Bonita reservoir) to the Billings reservoir. It has been observed that in the period represented in the simulation, the amount of water removed upstream of the Barra Bonita power plant and transferred to the Henry Borden power plant has allowed Henry Borden to operate at full capacity, respecting the operative limits of the necessary water transfer. In this case study, this maximal power generation has been achieved with the transfer of water to the Billings reservoir up to 101.2 Hm^3 in a month.

With the extra inflow at Henry Borden, despite the reduced water availability to the other nine hydro power plants, the total hydroelectric production of the system with transfer has exceeded the benchmark case at every period of the planning horizon, as illustrated in Figure 10. For both cases, with and without transfer, the sum of the hydro and thermal power is equal to the energy consumption at each month.

The new system operation plan has been achieved by the proposed model with satisfactory results. At this stage, the advantages of optimizing the transfer along with the operation of other parts of the system, mainly the power plants affected by the transfer, can be clearly observed.

It is worth mentioning that the methodology and the computer program can be applied to any system, from any location of the world, given that the constructive and operating data of the chosen power plant are available.

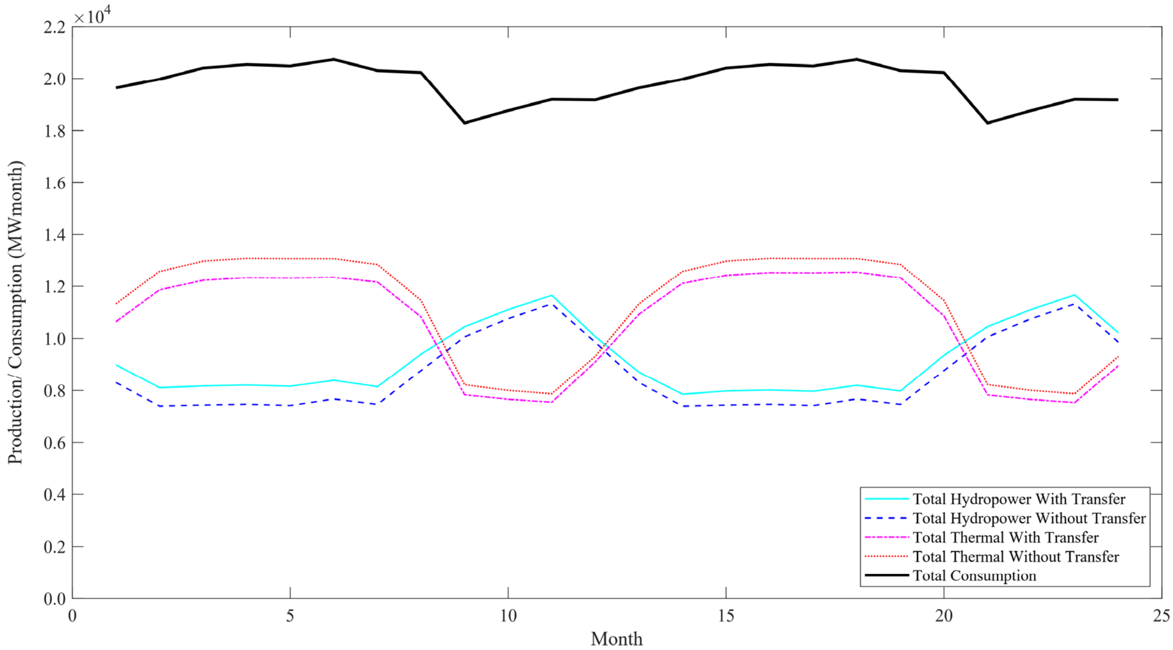

Figure 10. Comparison of hydroelectric production without and with transfer.

6. Conclusions

The studies conducted highlight the benefits of controlling the flow rates and volumes transferred between rivers or established basins, which allows for the diversion of their natural courses. Simulation results showed that transferring water between rivers enhances storage in underutilized reservoirs up to their maximum capacities.

In the case studies using this tool, it was observed that controlled and optimized water transfers—where available water resources are used efficiently—minimize the reliance on supplementary thermoelectric energy generation, which is both more expensive and polluting.

A specific example illustrates the underutilization of energy generation at the Henry Borden power plant. Here, generation potential is constrained by local water shortages, primarily due to pollution in the Billings system and the Tietê and Pinheiros rivers, which run through the metropolitan area of São Paulo. However, simulations demonstrate that once the water meets usability standards, both energy and economic gains are realized for the entire system. Therefore, it is essential to incorporate the possibility of water transfers between rivers and basins into operational methodology.

Finally, the methodology implemented in the ENERG.IA tool has shown good performance in the presented case study and can be applied to similar situations at hydroelectric plants across Brazil and worldwide, provided that the necessary construction data and water availability information are made accessible.

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Data Availability Statement: Data from dataset "Deck de Preços—Newave", with real power system parameters of the case study, were obtained from Brazilian Electricity Trading Chamber's public website and are available at https://www.ccee.org.br/precos/painel-precos [29].

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

Appendix A. Evolutionary Socio-Bio Inspired Technique (ESBIT) [11]

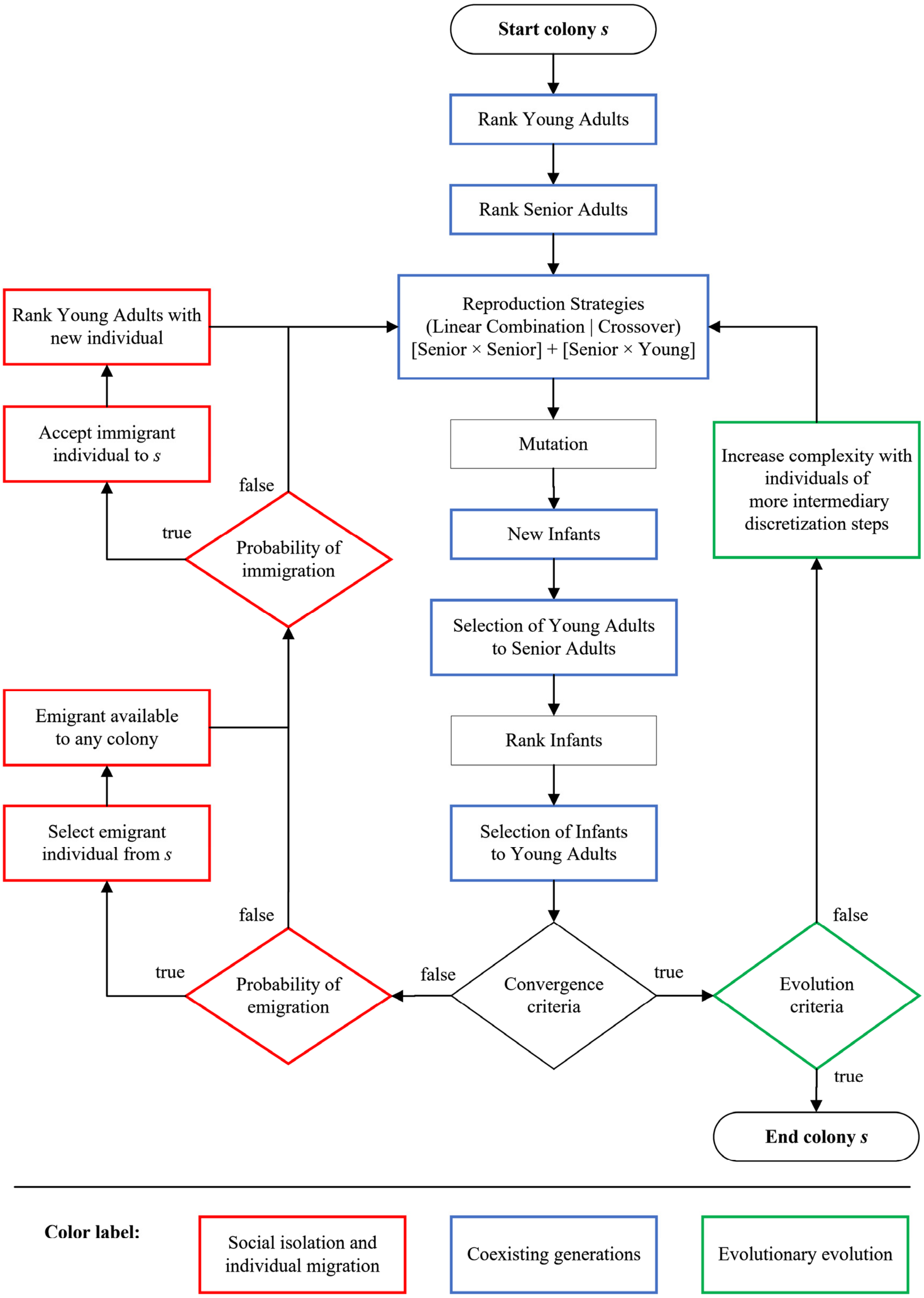

Figure A1. ESBIT flowchart.

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