MULTI-FRACTIONAL FUZZY PROGRAMMING FOR SUSTAINABLE AGRICULTURAL MULTI-CROPPING BI-SEASONAL PLANNING

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Abstract: The agricultural production system composes of several conflicting resources that must be combined to yield the desired product output. However, some goals are not conflicting in the system; therefore, this study presents a multi-objective optimization problem using a multi-fractional fuzzy programming concept. The objective is to optimize the profit ratio to cash expenditure and production of crops in different seasons under the restriction of fertilizer, machine, manpower, water consumption, and land utilization. The proposed model is illustrated with numerical examples for validation from an agricirean village in northern Nigeria. The result shows meaningful achievements and improvement in six crops out of the seven crops for both the dry and rainy seasons. Thus the concept is recommended for decision-makers for proper planning and productive yield in the agricultural industry for ensuring food security and the global sustainable developments.

Keywords: Agriculture, multi-production, fuzzy programming, fractional programming, sustainable planning, Nigeria.

MSC: 90B85, 90C26.

1. INTRODUCTION

Planning crop areas is crucial to the scarce resource management in agricultural sector. Different countries have varying cropping seasons, however, the most notable seasons are the rainy and dry seasons globally. Decision-makers (individual farmers, group or government) always have priority and crop preferences
in every season. Apart from that, certain crops can yield better than others depending on land and soil type, weather conditions and fertilizer. The nutrients requirement of these crops, such as water consumption level, fertilizers, maturity period, machine-hour, manpower, etc., varies from one product to another. Also, the cost and expenditure for farming a particular crop on a particular landmark might differ significantly. Additionally, the decision-maker always may wish to go for mixed-cropping system rather than a single cropping, as the former tends to generate more revenue to the latter and optimizes the land utilization. Most of the aforementioned goals can be hardly achieved as desired due to state of nature and unforeseen circumstances. As a result, there is a need for a technique that can integrate these goals visa-vee attained an aspirational level of decision-maker. Since most of the problems in agricultural sector involve fractions such as ratio of productivity to land, profit to expenditure, crops to yield, etc., there is a need for suitable optimization approach in handling such kind of problems.

Any optimization problem that involve a ratio of two functions is referred to as a Fractional Programming. In reality many systems comprises of more than one objective function which maybe conflicting in nature known as Multiobjective Problems. These multiobjective problems in a ratio form are known as a Multi-Fractional programming. Because real life decision-making environment has several uncertainty beyoung the reach of the decision-maker, the concept of fuzzy aspirations comes to play in order to address the uncertainty in the process of making a decision. Optimal solution to one objective may not satisfy all the conflicting goals at the same time. Hence, the challenging task before the decision-maker is to find a best compromising solution to all the objectives. In the literature, the problem described situation is termed as Multiobjective Multi-Fractional Fuzzy Programming. This article is presenting a model of this problem considering agricultural production system.

2. MANUSCRIPT PREPARATION

This article is organized as follows: Sect. 1 provides the introduction and overview of the study. The related literature on agricultural optimization problems are reviewed in Sect. 3. Sect. 4 discusses the methodology of the study. The mathematical model of the considered problem is formulated and presented in Sec. 7. Sect. 5 present the application area of the methods discussed in agricultural sector with numerical illustration. Sect. 8 present and discusses the results. Finally, the article is concluded in Sect. 9.

3. LITERATURE REVIEW

Mathematical programming have been widely used in agricultural planning problems. Over several years, researchers have been using different techniques in evaluating decision-making problems in the sector. Some authors addressed the problem using a single objective function, while others employed multiple objectives under different conditions and constraints. For instance, linear programming
(LP) has been applied to crop planning with fuzzy input parameters as an MOOP [1]. Similarly, Heady applied the LP for allocating the scarce land for agricultural cropping. A survey of the mathematical models for planning problems in agriculture has been studied extensively and documented [2, 3, 4, 5]. A systematic review for seven years period on utilization of mathematical programming models in water resource management considering uncertainty has been carried by [6]. According to the report, research trend on water consumption/management revealed that stochastic dynamic and multistage programming are the most pronounced.

[7] proposed a multiobjective structural planning to aid decision-makers for regional crops planning. The model is based on socio-economic and environmental supports. The model was demonstrated in a city of Iran. [8] considered profit to cash expenditure and crop production in a multiobjective fashion and used some aspect as fractional programming to solve the problem. [9] applied fuzzy goal programming to land use planning in agricultural system. [10] proposed a multiple objective mathematical model that optimized the net crop benefit and fertilizer utilization in agricultural settings. They further presented two heuristics algorithms for solving the model. [11] uses superiority and inferiority measures method to solve a linear fractional multiobjective optimization problem in agricultural planting system. [12] have proposed a new integer solution approach to a fractional linear programming model and they presented a numerical example to illustrate the approach. Other technique known as revised and column method was used in solving linear fractional programming problem [13]. Several studies conducted using mathematical programming concerning agricultural products for sustainable development of different nations in Africa (e.g. Nigeria), Asia (e.g. India and Saudi Arabia). For more details refer to [14, 15, 16, 17, 18].

Water supply for crop consumption is one of the crucial factors in agriculture. [19] has applied mathematical programming in examining the effect of urbanization on water consumption in agriculture, and linked to nations’ economic developments. Comparing to the based-year of the study area, they concluded that 1% increase in urbanization would reduce water consumption in agriculture by 0.639 $m^3$. [20] integrates three objectives related to economic, social and environmental aspects, and proposed a multiple objective model to improve agri-food production with minimum food waste through sustainable agri-food supply chain considering farmers cropping decision. [21] studied the aspect of imbalance between demand and supply of the crop planning problems in agricultural sector under uncertain environment, and applied the concept to fresh tomato Argentinean supply chain. [22] have proposed a framework for large-scale crop planning problem integrating sustainable climate-smart crop planning and agri-food supply chain management. [23] applied the concept of robust optimization considering the crop rotation problem with uncertainties where water supply/demand and net return regarded as uncertain with variation within the allowable rotational cycle.

One can not talk of crop planning problems without inventory and warehousing, as they are central to the agricultural products. As such, several mathematical programming models have been employed in this area. For more details, refer to [24, 25, 26, 27, 28].
4. METHODOLOGY

This section presents and discusses the general mathematical models for the MOOP, the fuzzy and the fractional programming which are subsequently used in the case study model formulation and analysis.

4.1. Multiobjective optimization (MOOP) model

Let’s define a multiobjective programming problem (MOPP) with \(j\) objectives be given as:

\[
\text{Optimize } [Z_1(X), Z_2(X), \ldots Z_j(X)]
\]

subject to:

\[
g_i(x)(\leq, =, \geq) b_i, \ i = 1, 2, \ldots, m; \ x \geq 0.
\]

(1)

Where \(Z_j\) is the set of objectives, \(g_i(x)(\leq, =, \geq) b_i\) are \(m\) set of constraints for which \(b_i\) is the \(i^{th}\) resources.

4.2. Fuzzy Goal Programming Model

Fuzzy goal programming is based on the concept of fuzzy set theory proposed by [29]. Fuzzy sets generally described imprecise goals of a decision-maker.

\[
\text{Find} \quad X = [x_1, x_2, \ldots, x_n]^T \\
\text{such that} \\
Z_k(X)(\geq, \simeq, \leq) g_k, \ k = 1, 2, 3, \ldots, K. \\
AX \leq b_i, \ i = 1, 2, \ldots, m \\
X \geq 0
\]

(2)

The fuzzy programming concept in solving multi-objective decision-making problems was initially proposed by [30].

For a Maximization type goal, the membership function is given by Eqn. (3).

\[
\mu_k(Z_k(X)) = \begin{cases} 
1, & \text{if } Z_k(X) \geq g_k \\
\frac{Z_k(X) - L_k}{g_k - L_k}, & \text{if } L_k \leq Z_k(X) \leq g_k \\
0, & \text{if } Z_k(X) \leq L_k
\end{cases}
\]

(3)

For a Minimization type goal, the membership function is given by Eqn. (4).
\[
\mu_k(Z_k(X)) = \begin{cases} 
1, & \text{if } Z_k(X) \leq g_k \\
\frac{U_k - Z_k(X)}{g_k - L_k}, & \text{if } g_k \leq Z_k(X) \leq U_k \\
0, & \text{if } Z_k(X) \leq U_k 
\end{cases}
\] (4)

4.3. Fractional Programming

From the Fuzzy goal Programming Eqn. (2), if some non zero goals (say \(i\)) can be optimize in ratio form leaving other \(k\) goals unchange, then Eqn. (5) becomes Fractional Programming problem, and can be defined as follows: let \(P, Q, H_k (k = 1, 2, \ldots, m)\) be denoted as real-valued functions which are defined on the set \(C\) of the \(n\)-dimensional Euclidean space \(\mathbb{R}^n\). Now, consider

\[
\text{Optimize } F(x) = \frac{P(x)}{Q(x)},
\]

over the set
\[
S = \{x \in C: \ H_k(x) \leq 0, k = 1, 2, \ldots, m\}.
\]

Here, it is assume that \(Q(x)\) is positive on the set \(S\). Whereas if \(Q(x)\) is negative, then \(F(x) = \frac{-P(x)}{-Q(x)}\) could be used instead. The nonlinear program

\[
\text{Program } (P) \quad \sup \{F(x): x \in S\}
\]

(6)
is called a single-ratio fractional programming. Since most of the real-life applications have more than one ratio as objective function, in such situations the minimum over the program \((P)\) is sorted as follows

\[
\sup \left\{ \min_{1 \leq i \leq r} F_i(x): x \in S \right\}
\]

(7)

and

\[
\sup \left\{ \sum_{i=1}^{r} F_i(x): x \in S \right\}
\]

(8)

Where \(F_i(x) = \frac{P_i(x)}{Q_i(x)}\), \(Q_i(x) > 0\). According to [31], Eqn. (7) is a generalized fractional programming model. Also, both Eqns. (7) and (8) are called multiobjective fractional programs, denoted as in Eqn. (9).

\[
\max \{ F_1(x), F_2(x), F_3(x), \ldots, F_r(x) : x \in S \}
\]

(9)

If the numerator function \(P\) and denominator function \(Q\) in Eqn. (5) are linear plus a constant (i.e. affine), and the set \(S\) is a convex polyhedron, then Eqn. (6)
is called a linear fractional programming model which can take the form in Eqn. (10).

\[
\sup \left\{ \frac{c^T x + \beta}{d^T x + \gamma} : Ax \leq b, \quad x \geq 0 \right\}
\]

(10)

where \(c, d \in \mathbb{R}^n\), \(\beta, \gamma \in \mathbb{R}\), the superscript \(T\) is the transpose \(A\) is an \(m \times n\) matrix, and \(b \in \mathbb{R}^m\). Generally, Eqn. (6) is known as quadratic fractional programming model, if functions \(P\) and \(Q\) are quadratic and the set \(S\) being a convex polyhedron.

Equation (6) is regarded as concave fractional programming model if \(P\) is concave on \(Q\) and \(C\), and \(h_k\) are convex on \(C\), whereby \(C\) is a convex set. Additionally, \(P(x)\) is assumed to be nonnegative on the set \(S\) if \(Q\) is unaffine. It is of interest to mention that, on a general note, the objective function of Eqn. (6) being concave does not render the function as concave, rather, it comprises of both concave and convex functions. Therefore, fractional programming models are nonconcave models generally, and thus are interested for global optimization.

5. APPLICATION OF THE METHOD IN AGRICULTURAL SECTOR

Agricultural crops are produce in different seasons of the year. Every season and each crop may require different resources. A decision-maker need to optimize the use of these resources, so that the overall goal of the farming system is achieved. Let’s consider the information given in the following Tables for the purpose of illustrating the methodology.

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Crops</th>
<th>Decision Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Season (1)</td>
<td>(1) Rice</td>
<td>(x_{11})</td>
</tr>
<tr>
<td></td>
<td>(2) Sugarcane</td>
<td>(x_{21})</td>
</tr>
<tr>
<td></td>
<td>(3) Wheat</td>
<td>(x_{31})</td>
</tr>
<tr>
<td>Rainy Season (2)</td>
<td>(4) Potato</td>
<td>(x_{42})</td>
</tr>
<tr>
<td></td>
<td>(5) Maize</td>
<td>(x_{52})</td>
</tr>
<tr>
<td></td>
<td>(6) Millet</td>
<td>(x_{62})</td>
</tr>
<tr>
<td></td>
<td>(7) Guineacorn</td>
<td>(x_{72})</td>
</tr>
</tbody>
</table>
Table 2: The Resources (Manpower, Machine hours, & Water consumption)

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>Manpower (days/ha)</th>
<th>Machine-hour/ha</th>
<th>Water consumption (inch/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{11} )</td>
<td>67.01</td>
<td>112</td>
<td>70</td>
</tr>
<tr>
<td>( x_{21} )</td>
<td>38.89</td>
<td>187</td>
<td>35</td>
</tr>
<tr>
<td>( x_{31} )</td>
<td>40.02</td>
<td>28</td>
<td>25</td>
</tr>
<tr>
<td>( x_{42} )</td>
<td>37.05</td>
<td>25</td>
<td>10</td>
</tr>
<tr>
<td>( x_{52} )</td>
<td>42.25</td>
<td>40</td>
<td>11</td>
</tr>
<tr>
<td>( x_{62} )</td>
<td>36.72</td>
<td>40</td>
<td>13</td>
</tr>
<tr>
<td>( x_{72} )</td>
<td>36.72</td>
<td>40</td>
<td>10</td>
</tr>
</tbody>
</table>

Table 3: Other Resources (Fertilizer, Production, Expenditure & Price)

<table>
<thead>
<tr>
<th>Decision Variables</th>
<th>N</th>
<th>P</th>
<th>K</th>
<th>Total Production (kg/ha)</th>
<th>Expenditure (N/ha)</th>
<th>Price (N/measure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( x_{11} )</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>2742</td>
<td>6785.27</td>
<td>1500</td>
</tr>
<tr>
<td>( x_{21} )</td>
<td>150</td>
<td>120</td>
<td>120</td>
<td>72324</td>
<td>42322.50</td>
<td>500</td>
</tr>
<tr>
<td>( x_{31} )</td>
<td>100</td>
<td>50</td>
<td>34</td>
<td>2412</td>
<td>23526.70</td>
<td>980</td>
</tr>
<tr>
<td>( x_{42} )</td>
<td>120</td>
<td>70</td>
<td>75</td>
<td>22295</td>
<td>24320</td>
<td>350</td>
</tr>
<tr>
<td>( x_{52} )</td>
<td>70</td>
<td>30</td>
<td>30</td>
<td>895</td>
<td>5242.60</td>
<td>620</td>
</tr>
<tr>
<td>( x_{62} )</td>
<td>80</td>
<td>40</td>
<td>40</td>
<td>1250</td>
<td>4892.50</td>
<td>520</td>
</tr>
<tr>
<td>( x_{72} )</td>
<td>115</td>
<td>75</td>
<td>75</td>
<td>1300</td>
<td>6200.10</td>
<td>800</td>
</tr>
</tbody>
</table>

There are restrictions that in both seasons the land to be use for the farming is 287572 ha, machine hours between 40,125.23 and 31429.80, Manpowers in days 48212.33, Water consumption in rainy season 2272.48, dry season 1280.60 inch/ha. Fertilizer nitrogen concentration 40.80, phosphate 20.70, and potashium 17.67 in metric tons. Maximum allowable cash to be spent is N5252875.20.

Note: Profit is a product of selling price and the total produce and the fuzzy aspiration amount on expenditure is given to be N500,000 in million atmost.

The minimum aspiration level of each product at each season is given in Table 4.

Table 4: The seasonal crops and associated variables

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Crops</th>
<th>Aspiration level (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Season (1)</td>
<td>(1) Rice</td>
<td>68000</td>
</tr>
<tr>
<td></td>
<td>(2) Sugarcane</td>
<td>15200</td>
</tr>
<tr>
<td></td>
<td>(3) Wheat</td>
<td>11500</td>
</tr>
<tr>
<td>Rainy Season (2)</td>
<td>(4) Potato</td>
<td>7000</td>
</tr>
<tr>
<td></td>
<td>(5) Maize</td>
<td>18000</td>
</tr>
<tr>
<td></td>
<td>(6) Millet</td>
<td>9200</td>
</tr>
<tr>
<td></td>
<td>(7) Guineacorn</td>
<td>8000</td>
</tr>
</tbody>
</table>
6. STUDY AREA

The above information are in the case of an agricultural village of Nigeria called Wurodole in Girei district. The village is located on the geographical coordinates: 9°22 North and 12°33 East with mostly dwellers as farmers. The primary occupation of the people in the area is farming and cattle rearing. The major crops during the two seasons are shown on Table 4. and the map is shown in Fig. 1.

![Figure 1: The Girei District Map Showing Study Areas](image)

7. MATHEMATICAL MODEL FORMULATION

This section presents the various conflicting objectives/goals of the problem under consideration alongside its several constraints as follows:

7.1. Goals of the Problem

The problem is made up of three conflicting goals, related to ratio of profit-to-expenditure, and crop productivity at each season. The individual formulation of the goals are presented below:

**Goal 1:** This objective is to optimize profit to expenditure ratio.

\[ Z_1 = \frac{4113000x_{11} + 3616000x_{12} + 2363700x_{13} + 7898250x_{14} + 554000x_{52} + 650000x_{62} + 780000x_{72}}{6785.27x_{11} + 4232.50x_{12} + 23525.70x_{13} + 24328.72x_{14} + 5242.60x_{52} + 4982.50x_{62} + 62000.10x_{72}} \]
Goal 2: This objective is to optimize each crop productivity in the rainy season.

\[ Z_2 = \frac{(2742x_{11} + 72324x_{21} + 2412x_{31})}{\sum_{i=1}^{3} x_{i1}} \]  

(12)

Goal 3: This objective is to optimize each crop productivity in the dry season.

\[ Z_3 = \frac{(22295x_{42} + 895x_{52} + 1250x_{62} + 1300x_{72})}{\sum_{i=4}^{7} x_{i2}} \]  

(13)

7.2. Constraints of the problem

The constraints are comprised of several items related to manpower per day per hectare, machine hour per hectares, water consumption per crop type per hectare, expenditure in Naira (Nigerian currency) per crop per hectare, productivity in kilogram per crop per hectare, and fertilizers (in different proportions of nitrogen, phosphate and potassium) also per crop per hectare. The complete formulation of these constraints is given in (14).

Constraints of the Model

\[ \sum_{i=1}^{3} x_{i1} \leq 287.527; \]
\[ \sum_{i=1}^{7} x_{i2} \leq 287.527; \]
\[ 67.01x_{11} + 38.89x_{21} + 40.92x_{31} + 37.05x_{42} + 42.25x_{52} + 36.72(x_{52} + x_{72}) \geq 40125.23; \]
\[ 112x_{11} + 187x_{21} + 28x_{31} + 25x_{42} + 40(\sum_{i=4}^{7} x_{i2}) \geq 48212.33; \]
\[ 70x_{11} + 35x_{21} + 25x_{31} \geq 2272.48; \]
\[ 10(x_{42} + x_{72}) + 11x_{52} + 13x_{62} \geq 1280.60; \]
\[ 30x_{11} + 150x_{21} + 100x_{31} + 120x_{42} + 70x_{52} + 80x_{62} + 80x_{72} \geq 40800; \]
\[ 30(x_{11} + x_{52}) + 120x_{21} + 50x_{31} + 70x_{42} + 40x_{62} + 75x_{72} \geq 20700; \]
\[ 30(x_{11} + x_{52}) + 120x_{21} + 40(x_{31} + x_{62}) + 75(x_{42} + x_{72}) \geq 17670; \]
\[ 6785.27x_{11} + 42322.50x_{21} + 23526.70x_{31} + 24320x_{42} + 5242.60x_{52} + 4892.50x_{62} + 62000.10x_{72} \leq 5252875.20; \]
\[ 2742x_{11} \geq 68000; \]
\[ 72324x_{21} \geq 15200; \]
\[ 2412x_{31} \geq 11500; \]
\[ 22295x_{42} \geq 7000; \]
\[ 895x_{52} \geq 18000; \]
\[ 1250x_{62} \geq 9200; \]
\[ 1300x_{72} \geq 8000; \]
\[ 411300x_{11} + 3616200x_{21} + 2363760x_{31} + 7803250x_{42} + 554900x_{52} + 650000x_{62} + 780000x_{72} \geq 500000; \]
\[ \sum_{i=1}^{7} x_{ij} \geq 0; \quad j = 1, 2. \]  

(14)
The productivity values of various crops in the farming seasons are shown in Table 5.

Table 5: The seasonal crops and associated productivity

<table>
<thead>
<tr>
<th>Seasons</th>
<th>Crops</th>
<th>Productivity (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Season (1)</td>
<td>(1) Rice</td>
<td>70000</td>
</tr>
<tr>
<td></td>
<td>(2) Sugarcane</td>
<td>14200</td>
</tr>
<tr>
<td></td>
<td>(3) Wheat</td>
<td>11800</td>
</tr>
<tr>
<td>Rainy Season (2)</td>
<td>(4) Potato</td>
<td>85000</td>
</tr>
<tr>
<td></td>
<td>(5) Maize</td>
<td>20000</td>
</tr>
<tr>
<td></td>
<td>(6) Millet</td>
<td>11200</td>
</tr>
<tr>
<td></td>
<td>(7) Guineacorn</td>
<td>9500</td>
</tr>
</tbody>
</table>

8. RESULTS ANALYSIS AND DISCUSSION

After solving the mathematical formulation of the problem in Eqn. (11)-(14), using the optimization package Lingo version 21.0, the compromised solutions has been found to be $Z_1 = 364.1681054$, $Z_2 = 129937.75kg/ha$, $Z_3 = 154282.0207kg/ha$ Also, the various productivity yeilds has been optimized and presented in Table 5. From the above results anyalysis, it can be seen that the crops in both seasons have been optimized as follows:

In the dry season, the productivity of rice has improved from sixty-eight thousand to seventy thousand (68000-70000) tonnes, wheat from eleven thousand five hundred to eleven thousand eight hundred (11500-11800) tonnes while the sugar-cane has drop slightly from fifteen thousand two hundred to fourteen thousand two hundred (15200-14200) tonnes respectively.

However, in the rainy season, all the four crops yield are improved. The productivity of potato has been optimized from seventy thousand to eighty five thousand (70000-85000) tonnes per hectare, the maize crop is improved from eighteen thousand to twenty thousand (18000-20000) tonnes per hectare, the millet increased from ninety thousand two hundred to eleven thouan two hundred (9200-11200) tonnes per hectare, and the guineacorn from eight thousand to nine thousand five hundred (8000-9500) tonnes per hectare.

Furthermore, these improvement can be achieved with just an expenditure 364.168 million naira as against the proposed amount which is 500 million naira, with the total productivity of 129937.75kg/ha, and 154282.0207kg/ha for both dry and rainy seasons. Therefore, the results of this study is promising for which every farmer will admire to go for it. Since, it cut cost and yeild higher crops productivity.

The future scope of this research is enormus. (i) One can compare different aspect of these combinations, by alternating the crops in different seasons. (ii) Another comparision can be made acording the amount of fertilizer used (iii) Also, a situation where some or all parameters assume certain probability distributions can be explore. The researcher hope to explore all the aforementioned
and several other aspects of this work as an extension to benefit policymakers (farmers/government) in this regards.

9. CONCLUSION AND FUTURE SCOPE

Decision-making is an integral part of human endeavours. Food production is bedrock of human existence, without sufficient and affordable food security, no meaningful achievement can be made in any sector of life. Therefore, agriculture has a paramount important for sustainable development goals of every nations. Any decision-making tools that can foster the yeild and growth of the agricultural sector are the must to do by the policymakers and researchers. This study formulated a multiojective fractional optimization problem and applied to the agricultural crop planning and yeild improvement under fuzzy environment. The application of this method can help the decision-makers (farmers and government) to make a proper plans and have better farm produce with reasonable profit using the scarce resources.

The concept is useful in real-life applications and can be extended to different sectors other than Agriculture.

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