Supplying Goods and Materials to the Offshore Islands Using ILP

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Abstract: - Many of problems are proved to be NP-complete or NP-hard problems. To solve these problems and to obtain the optimal solutions, it is usual to transfer the problems to Integer Linear Programming formulations. Coast Guard Administration (CGA), an agency intermingles jurisdiction over both coastal and oceanic affairs, CGA is in charge of harbor security check, resolving fishery conflict, investigating smuggling, and illegal immigration or emigration on various outlying islands, including Kinmen, Mazu, Penghu, Pengjiayu, Guishandao, Xiaoliuqiu, Ludao and Lanyu. To supply livelihood materials, including drinking water, rice, and oil, for those officers station on different outlying islands, becomes a critical issue. In the paper, we will discuss the demand of the rice and the drinking water for the supply of the people on the set of large islands. This research is to explore and assess the model of supply of livelihood material to those outlying islands. By calculating and fitting an optimally supplying model, this research expects that such supplying model can decrease the budget or cost of supply and improve the quality of livelihood materials for the stationing officers on outlying islands.

Key-Words: - Integer Linear Programming, Supplying, Coast Guard Administration, Offshore islands

1 Introduction

The Coast Guard Administration (CGA)[11] has been responsible for the safety and security of Taiwan's coastline and waters since its inception in February 1, 2000. The CGA's missions are to maintain open access to the ocean, patrol the coast round-the-clock for protecting and serving the people of Taiwan. CGA is in charge of harbor security check, resolving fishery conflict, investigating smuggling, and illegal immigration or emigration on various outlying islands, including Kinmen, Mazu, Penghu, Pengjiayu, Guishandao, Xiaoliuqiu, Ludao and Lanyu. The area of CGA Mission is as shown in Fig. 1. To supply livelihood materials, including drinking water, rice, and oil, for those officers station on different outlying islands, becomes a critical issue. The cost to supply the necessary foods and water for people living on islands is usually expensive because the demand of foods for people living on island is huge and complex. If the cost of supplying foods and water is well-managed, the total cost can be reduced. Otherwise, the cost of supplying the necessary foods and water is huge. How to manage the assignment of foods and water is an important issue, especially for the limited budget.

Some researches provided the ILP-based approach to solve many applications, such as the vehicle routing problem, supply chain management, and the high-level synthesis scheduling and power reduction problem for computer-aided design. Huang et al, provided the ILP-based approach to re-manage the turning time to reduce the maximal current values at high level synthesis [3]. Nguyen et al. gave the multi-stage approach to minimize the total power by the ILP formulation for the multiple supply voltage problems [4]. Lin et al presented the integer linear programming-based approach to optimize the total power consumption for the gate level netlist [10]. Roberto et al, presented the ILP-based refined approach to solve the problem and their reallocation model did not rely on the lingo code [5]. The authors presented the robust approach to formulate the ILP constraints for the uncertain information. Most of the researches study how to transfer the problem into the ILP formulations and solve them by using the linear/nonlinear commercial tools (or their own lingo code)[1][2][6][9]. However, most of them do not consider the supply and demand problem for people living on some islands. Hence, the total cost of supplying the necessary demand of foods and water is usually huge.

The main contributions for the paper are as follows. First, the Integer Linear Programming based approach which transfers the rice and drinking water into the ILP formulations is given to minimize the cost of supplying the rice and drinking water to the people in the islands. Second, the daily foods being necessary to the people form the demand constraints. The cost of the boats with many supplying foods forms the supply constraints. Finally, to supply the necessary demand of the people living on islands can effectively formulate into the transportation problem and to efficiently obtain the optimal assignment by solving the ILP formulations.

The rest of the paper is as follows. Section 2 describes notations and the problem formulations. Section 3 discusses the basic knowledge of Integer Linear Programming. Section 4 discusses the ILP-based approach to minimize the cost of supplying. Experimental result and the conclusion are attached in Sections 5 and 6.

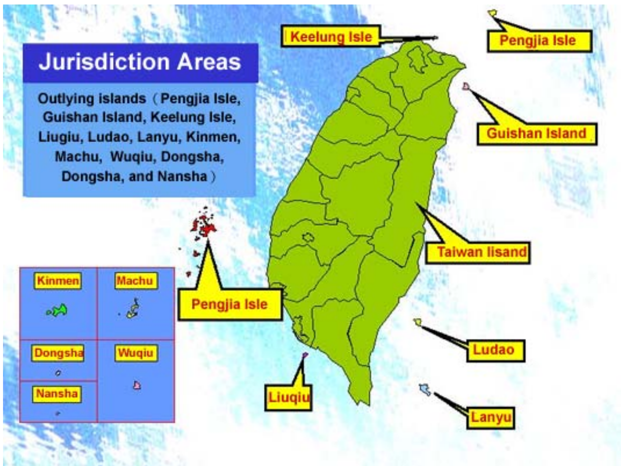

Fig. 1 The Area of CGA Mission

2 Problem Formulation

In this section, the notations used in the paper and the problem formulation are described in detailed. We first describe the notation in the following section. The notations used in the paper are defined as follows.

ru_i :the minimal demand of rice in the *i-th* month.

rx_i :the supplying of rice in in the *i-th* month.

ry_i :the price of rice in the *i-th* month.

rc_i :the cost of rice in the *i-th* month.

rx_{i_j}:the amount of rice coming in the *i-th* month and consuming in the *j-th* month.

rU :discounted threshold of rice.

rM :the upper bound of values of rice.

wu_i :the minimal demand of drinking water in the *i-th* month.

wx_i :the supply of drinking water in the *i-th* month.

wy_i :the price of drinking water in the *i-th* month.

wc_i :the cost of drinking water in the *i-th* month.

wx_{i_j}:the amount of drinking water coming in the *i-th* month and consuming in the *j-th* month.

wU_1 :the first discounted threshold of drinking water.

wU_2 :the second discounted threshold of drinking water.

wM :the upper bound of values of drinking water.

Summary, the above notations are defined to handle the demand and supply for the rice and the drinking water. The problem defined in the paper is as follows: Given the demand of the rice and drinking water for people living on the set of islands, the backup demand of the rice and drinking water during a year, the supply capacity of rice and drinking water of the boats, and the prices of the rice, drinking water and the boats. By meeting the demand of the rice and drinking water, the objective of the paper is to minimize the total cost the rice and drinking water for people in the set of islands.

3 Integer Linear Programming

Mathematical programming is a mathematical procedure for determining optimal allocation with resources constraints. The most popular special form of Mathematical Programming is Linear Programming or LP for short. LP deals with problems in which linear functions are to be optimized subject to constraints specified by linear inequations and equations. The linear function to be optimized (maximized or minimized) is called the objective function. The linear inequations and equations are called the linear constraints. In many applications of optimization, the variables of LP formulation would be restricted to integer values. The methods for formulating and solving LP problems with integrality requirements are called integer linear programming or ILP for short.

There are many problems such as placement, routing, partition and technology mapping which are difficult to solve. Many of these problems are proved to be NP-complete or NP-hard problems. To solve these problems and to obtain the optimal solutions, it is usual to transfer the problems to ILP formulations. In this Section, we propose some useful formulating methods, which can be divided into four operations; they are basic logic operations, conditional logic operations, mathematics operations (functional analysis) and other operations.

3.1 Basic Logic Operations

It may be convenient for some applications to state requirements using basic logic expressions. There are five major operators, "NOT(~)", "AND($\wedge$)", "OR($\vee$)","XOR($\oplus$)" and "IMPLICATION($\rightarrow$)". They are useful in basic logic expressions. Let the binary logical variable TRUE be represented by 1 and FALSE be represented by 0. If b_1, b_2, b_3, b_4 and b_5 are 0/1 variables, then we can use the ILP constraints as shown in Table 1 to represent the various logical expressions.

Table 1 Basic Logic Operations

Logical Expression	ILP Constraints
$b_5 = \sim b_1$	$b_5 = 1-b_1$
$b_5 = b_1 \wedge b_2$	$b_5 \le b_1$ $b_5 \le b_2$ $b_5 \ge b_1+b_2-1$
$b_5 = b_1 \vee b_2$	$b_5 \ge b_1$ $b_5 \ge b_2$ $b_5 \le b_1+b_2$
$b_5 = b_1 \oplus b_2$	$b_5 \ge b_1-b_2$ $b_5 \ge b_2-b_1$ $b_5 \le b_1-b_2+2^* b_3$ $b_5 \le b_2-b_1+2^*(1- b_3)$
$b_1 \rightarrow b_2$	$b_1 \le b_2$

In fact, there may be more than one formulating method. For example, according to the property of XOR, the logical expression $b_5 = b_1 \oplus b_2$ in Table 1 can be rewrote as $b_5 = (b_1 \vee b_2) - (b_1 \wedge b_2)$.

Therefore, we have ILP constraints as shown in Table 2 which can also represent the logical expression $b_5 = b_1 \oplus b_2$. However, the formulating method in Table 2 takes more CPU time than the formulating method in Table 1 during the solving procedure.

Table 2 Another Formulating Method for XOR

Logical Expression	ILP Constraints
$b_5 = b_1 \oplus b_2$	$b_3 \ge b_1$ $b_3 \ge b_2$ $b_3 \le b_1 + b_2$ $b_4 \le b_1$ $b_4 \le b_2$ $b_4 \ge b_1 + b_2 -1$ $b_5 = b_3 - b_4$

3.2 Conditional Logic Operations

When we formulate an ILP problem, it would be usable to apply the conditional statement like the If-Then-Else statement of the general programming language. But the conditional statement in ILP is very difficult to formulate. Let's consider a conditional statement as follows.

If ($x_1 > x_2$)
Then b_1=0
Else b_1=1
where *x's* are integral variables and *b's* are 0/1 variables.

To formulate the conditional statement, we need to add an upper bound M which is a constant larger than $|x_1-x_2|$. Then, the ILP constraints as shown in Table 3 can be used to represent the conditional statement.

Table 3 Conditional Logic Operations

Logical Expression	ILP Constraints
If ($x_1 > x_2$) Then b_1=1 Else b_1=0	$M^*b_1+(x_2 - x_1) \ge 0$ $M^*(1-b_1)+(x_1 - x_2)>0$

3.3 Mathematics Operations

In the mathematical programming, some of the mathematical functions are very important, such as the maximum, the minimum, and the absolute value functions. The package, which solves the mathematical programming, usually provides these functions, but functions that the package provides may make the linear property of mathematical programming loose. Such being the case, we try to propose some ILP constraints to represent these mathematical functions.

In Table 4, we add a 0/1 variable b_1, and a constant value M that is the upper bound of x_1 and x_2.

Table 4 Conditional Logic Operations

Logical Expression	ILP Constraints
x_3=max(x_1,x_2)	$x_3 \geq x_1$ $x_3 \geq x_2$ $x_3 \leq x_1+M*b_1$ $x_3 \leq x_2+M*(1- b_1)$
x_3=min(x_1,x_2)	$x_3 \leq x_1$ $x_3 \leq x_2$ $x_3 \geq x_1+M*b_1$ $x_3 \geq x_2+M*(1- b_1)$
x_3=abs(x_1-x_2)	$x_3 \geq x_1 - x_2$ $x_3 \leq x_2 - x_1$ $x_3 \geq x_1 - x_2+M*b_1$ $x_3 \geq x_2 - x_1+M*(1- b_1)$

3.4 Other Operations

Though we have introduced several formulating methods in the previous sections, there are still many other formulating methods. Sometimes, we would need the expression "$x_1 \neq x_2$" to ensure that both variables x_1 and x_2 are not equal. It's obvious that "$x_1 \neq x_2$" can be replaced by "$x_1 > x_2$ or $x_1 < x_2$". Therefore, we can obtain the ILP constraints as shown in Table 5 to represent the expression "$x_1 \neq x_2$".

Table 5 Inequality Operations

Logical Expression	ILP Constraints
$x_1 \neq x_2$	$x_2 < x_1 + M*b_1$ $x_1 < x_2 + M*(1-b_1)$

The formulating methods in Table 6 are helpful in lots of cases. Although the logical expressions in Table 6 look like non-linear, they still can be represented by correlative ILP constraints.

Table 6 Special Multiplication Operations

Logical Expression	ILP Constraints
$x_2 = x_1 * b_1$	$x_2 \leq x_1$ $x_2 \leq M*b_1$ $x_2 \geq x_1 - M*(1 - b_1)$ where x's are variables, b's are 0/1 variables and M is the upper bound of x's
$x_2 = x_1 * c_1$ where $c_1=\alpha$ or β	$x_2 \geq \alpha * x_1$ $x_2 \leq M*(c_1 - \alpha) + \alpha * x_1$ $x_2 \leq \beta * x_1$ $x_2 \geq M*(c_1 - \beta) + \beta * x_1$ where x's are variables, b's are 0/1 variables, $\alpha,\beta(\alpha \leq \beta)$ are constants, and M is the upper bound of x's

4 The ILP-based Solution

In the paper, to simplify, we only discuss the demand of the rice and the drinking water for the supply of the people on the set of large islands. The objective is to minimize the cost of the rice and the drinking water while satisfying the demand of rice and drinking water of the people in the large islands. The following is the objective function of the paper.

The total cost of the rice and the drinking water are described as follows,

$$total = total\_rice + total\_water \quad (1)$$

Formula (2) denotes the total cost of rice for the 12 months.

$$total\_rice = \sum_{i=1}^{12} rc_i \quad (2)$$

For each month, the unused rice can be saved to the next two months. Hence, we have

$$\begin{aligned} & rx_{i,i} \geq 0, rx_{i,i+1} \geq 0, rx_{i,i+2} \geq 0 \text{ for } i=1,2,...10 \\ & rx_{11,11} \geq 0, rx_{11,12} \geq 0 \\ & rx_{12,12} \geq 0 \end{aligned} \quad (3)$$

For each month, to meet the minimal demand of rice, we have $ru_i \geq 0$. Besides, the supplying amount of rice should be less than the total amount of the previous three months. Hence we have

$$\begin{aligned} & rx_i = rx_{i\_i} + rx_{i\_i+1} + rx_{i\_i+2} \text{ for } i=1,2,...10 \\ & rx_{11} = rx_{11\_11} + rx_{11\_12} \\ & rx_{12} = rx_{12\_12} \end{aligned} \quad (4)$$

To keep the health of the rice, we suppose the rice should be eaten during 3 month. Hence, we have

$$\begin{aligned} & rx_{1\_1} \geq ru_1 \\ & rx_{1\_2} + rx_{2\_2} \geq ru_2 \\ & rx_{i-2\_i} + rx_{i-1\_i} + rx_{i\_i} \geq ru_i \text{ for } i=3,4,...12 \end{aligned} \quad (5)$$

Similarly, the total cost of water is as the following formula,

$$tatal\_water = \sum_{i=1}^{12} wc_i \quad (6)$$

For each month, the unused water can be saved for next four months. Hence, we have

$$\begin{aligned} & wx_{i,i} \geq 0, wx_{i,i+1} \geq 0, wx_{i,i+2} \geq 0, wx_{i,i+3} \geq 0, wx_{i,i+4} \geq 0 \ i=1,2,...8 \\ & wx_{9,9} \geq 0, wx_{9,10} \geq 0, wx_{9,11} \geq 0, wx_{9,12} \geq 0 \\ & wx_{10,10} \geq 0, wx_{10,11} \geq 0, wx_{10,12} \geq 0 \\ & wx_{11,11} \geq 0, wx_{11,12} \geq 0 \\ & wx_{12,12} \geq 0 \end{aligned} \quad (7)$$

For each month, to meet the minimal supply of water, we have $wx_i \geq 0$. Besides, the supplying amount of water should be less than the total amount of the previous five months. Hence we have

$$\begin{aligned} & wx_i = wx_{i\_i} + wx_{i\_i+1} + wx_{i\_i+2} + wx_{i\_i+3} + wx_{i\_i+4} \text{ for } i=1,2,...8 \\ & wx_9 = wx_{9\_9} + wx_{9\_10} + wx_{9\_11} + wx_{9\_12} \\ & wx_{10} = wx_{10\_10} + wx_{10\_11} + wx_{10\_12} \\ & wx_{11} = wx_{11\_11} + wx_{11\_12} \\ & wx_{12} = wx_{12\_12} \end{aligned} \quad (8)$$

The total supplying water is larger than the minimal demand water, we have

$$\begin{aligned} & wx_{1\_1} \geq wu_1 \\ & wx_{1\_2} + wx_{2\_2} \geq wu_2 \\ & wx_{1\_3} + wx_{2\_3} + wx_{3\_3} \geq wu_3 \\ & wx_{1\_4} + wx_{2\_4} + wx_{3\_4} + wx_{4\_4} \geq wu_4 \\ & wx_{i-4\_i} + wx_{i-3\_i} + wx_{i-2\_i} + wx_{i-1\_i} + wx_{i\_i} \geq wu_i \text{ for } i=5,6,...12 \end{aligned} \quad (9)$$

Besides, we also consider the relationship between the price and the amount of rice. Generally, the price of rice is about 35 NTD (New Taiwan Dollar) and the price can be reduced to 34 NTD when the amount of rice is over the given threshold. Hence, according to [8], the if-else statement for the relationship of price and amount of rice is as follows.

if $(rx_i > rU)$
  then $ry_i = 34;$
  else $ry_i = 35;$
(10)

The statement is also transferred into the ILP formulations.

$$\begin{aligned} & rM \times rb_i + (rU - rx_i) \geq 0 \\ & rM \times (1 - rb_i) + (rx_i - rU) \geq 0 \\ & ry_i = 34 + 1 \times (1 - rb_i) \end{aligned} \quad (11)$$

where rb_i is a binary variable.

To estimate the total cost of rice, we should compute the cost of each month.

$$rc_i = ry_i \times rx_i \quad (12)$$

The statement is a non-linear formula. It is clear that only two possible values for ry_i (34 or 35), hence it could be transferred into the ILP formulations as follows.

$$\begin{aligned} & rc_i \geq 34 \times rx_i \\ & rc_i \leq 35 \times rx_i \\ & rc_i \leq rM*(ry_i - 34) + 34 \times rx_i \\ & rc_i \geq rM*(ry_i - 35) + 35 \times rx_i \end{aligned} \tag{13}$$

Because the formulation of drinking water is similar to rice, we omit the remainder of the formulation.

5 Experimental Result

The ILP formulation were automatically produced by using the C++ language on the ASPIRE 5920G, using Intel Core 2 Duo T7300 (2 GHz) with 3GB RAM. The linear commercial tool Lingo 8.0 is used to solve the ILP formulation [7]. Due to the security, the benchmarks used in the Tables 7, 8, 9 and 10 are randomly generated within the user-defined range.

Table 7 shows the number of people and the daily minimal demand of rice for each island. Similarly, Table 8 shows the number of people and the daily minimal demand of drink water for each island.

First, we investigate the improvement on the rice. The first, second columns denote the benchmarks of island and the original rice demand. The third, fourth and fifth columns denote the new demand by our approach, the improved demand of rice and the improved ratio of rice. Table 9 shows that the 2.7% of the rice is improved by using the ILP-based approach. Summary, the ILP-based approach improved the rice demand.

Second, we observe the improvement on the drinking water. The first, second columns denote the benchmarks of island and the original drinking water demand. The third, fourth and fifth columns denote the new drinking water demand by our approach, the improved demand of drinking water and the improved ratio of drinking water. Table 10 shows that the 8.7% of the drinking water is improved by using the ILP-based approach. Summary, the ILP-based approach improved the demand of drinking water.

Finally, we observe the relationship between *rU* and *total_rice* in Table 11, and draw the trend between *rU* and *total_rice* in Fig.2. In Table 12, we fix wU_1 as 10000 to show the relationship between wU_1 , wU_2 and *total_water*, and draw the trend between wU_1 ,wU_2 and *total_water* in Fig.3.

6 Conclusion

In the paper, the ILP-based approach is presented to solve the problem of supplying the necessary demand of foods and water for people living on the island. The supply of water and foods forms the supply constraints. Similarly, demand of water and foods forms the demand constraints. The optimal cost is obtained by solving the ILP formulations which denotes the supply of budget and the demand of the diving water and foods. Experimental results show that the proposed ILP-based approach minimizes the improvement on rice and diving water by 2.77 and 8.7% compared to the traditional results.

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Table 7 The Minimal Demand of Rice

	Number of people	Daily minimal demand of rice	Daily minimal package number
Island 1	767	352 kg	11.73
Island 2	460	211 kg	7.033
Island 3	613	281 kg	9.366
Island 4	115	53 kg	1.766
Island 5	383	176 kg	5.866
Island 6	46	21 kg	0.7
Island 7	92	42 kg	1.4
Island 8	77	35 kg	1.166
Island 9	290	133 kg	4.433
Island 10	387	178 kg	5.933
Island 11	97	45 kg	1.5

Table 8 The Minimal Demand of Drink Water

	Number of people	Daily minimal demand of drink water	Daily minimal bottle number
Island 1	767	15340000 ml	1023
Island 2	460	920000 ml	614
Island 3	613	1226000 ml	818
Island 4	115	230000 ml	154
Island 5	383	766000 ml	511
Island 6	46	92000 ml	62
Island 7	92	184000 ml	123
Island 8	77	154000 ml	103
Island 9	290	580000 ml	387
Island 10	387	774000 ml	516
Island 11	97	194000 ml	130

Table 9 Improvement on the Rice

	Original cost	New cost	Reduced cost	Imp (%)
Island 1	4496800	4370700	126100	2.80
Island 2	2695525	2618340	77185	2.86
Island 3	3589775	3483420	106355	2.96
Island 4	2248400	2184840	63560	2.83
Island 5	677075	658920	18155	2.68
Island 6	268275	263160	5115	1.91
Island 7	536550	518160	18390	3.43
Island 8	447125	433500	13625	3.05
Island 9	574875	562020	12855	2.24
Island 10	1699075	1650360	48715	2.87
Island 11	2273950	2209320	64630	2.84
Avg.	-	-	-	2.77

Table 10 Improvement on the Drinking Water

	Original cost	New cost	Reduced cost	Imp (%)
Island 1	111982000	102670560	9311440	8.32
Island 2	67160000	56802720	10357280	15.42
Island 3	89498000	80424480	9073520	10.14
Island 4	55918000	48303840	7614160	13.62
Island 5	16790000	15303600	1486400	8.85
Island 6	6716000	6399840	316160	4.71
Island 7	13432000	12369120	1062800	7.91
Island 8	11242000	10662480	579520	5.15
Island 9	14162000	13457760	704240	4.97
Island 10	42340000	38477280	3862720	9.12
Island 11	56502000	52527840	3974160	7.03
Avg.	-	-	-	8.7

Table 11 Relationship between *rU* and *total_rice*

rU	0	50	100	150	200	300	397	398	399	400
total_rice	54910	54910	54910	54910	54910	54910	54910	54944	54978	55012
rU	401	402	403	404	405	406	407	408	409	410
total_rice	55046	55080	55148	55216	55284	55304	55406	55508	55610	55712
rU	411	412	413	414	415	416	417	418	500	600
total_rice	55814	55916	56018	56120	56222	56324	56426	56525	56525	56525

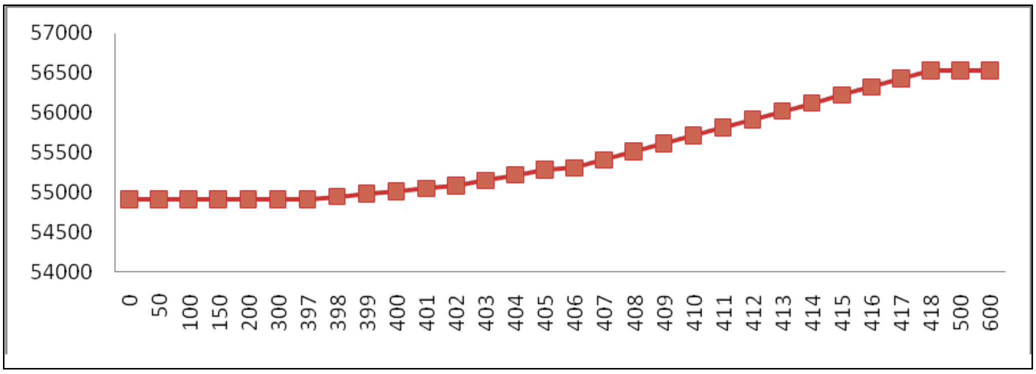

Fig. 2 The Trend between *rU* and *total_rice*

Table 12 Relationship between wU_1 , wU_2 and *total_water*

wU_1	10000	10000	10000	10000	10000	10000
wU_2	3435	4000	5000	6000	7000	10000
total_water	407784	412304	420304	428304	436304	460304

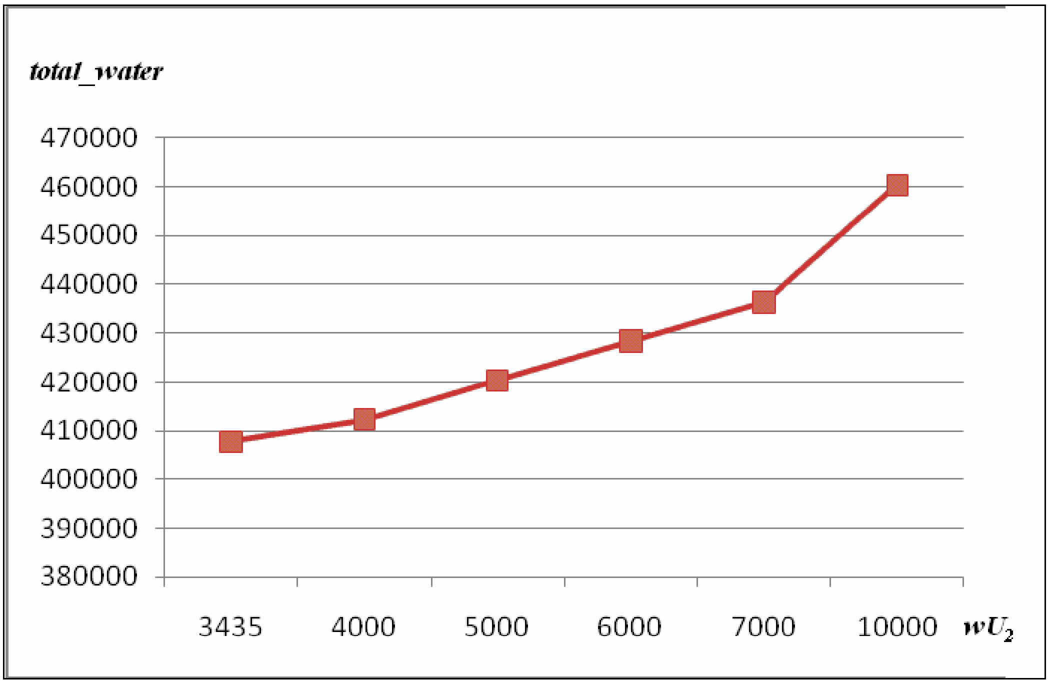

Fig. 3 The Trend between wU_1 ,wU_2 and *total_water*