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Integer Programming Formulations For The Frobenius Problem

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***Abstract:* - The Frobenius number of a set of relatively prime positive integers $a_1, a_2, \dots, a_n$ such that $a_1 < a_2 < \dots < a_n$, is the largest integer that can not be written as a nonnegative integer linear combination of the given set. Finding the Frobenius number is known as the *Frobenius problem*, which is also named as the *coin exchange problem* or the *postage stamp problem*. This problem is closely related with the equality constrained *integer knapsack problem*. It is known that this problem is NP-hard. Extensive research has been conducted for finding the Frobenius number of a given set of positive integers. An exact formula exists for the case $n = 2$ and various formulas have been derived for all special cases of n = 3. Many algorithms have been proposed for $n \geq 4$.**

As far as we are aware, there does not exist any integer programming approach for this problem which is the main motivation of this paper. We present four integer linear programming formulations about the Frobenius number of a given set of positive integers. Our first formulation is used to check if a given positive integer is the Frobenius number of a given set of positive integers. The second formulation aims at finding the Frobenius number directly. The third formulation involves the residue classes with respect to the least member of the given set of positive integers, where a residue table is computed comprising all values modulo that least member, and the Frobenius number is obtained from there. Based on the same approach underlying the third formulation, we propose our fourth formulation which produces the Frobenius number directly.

We demonstrate how to use our formulations with several examples. For illustrative purposes, some computa-tional analysis is also presented.

***Key-Words:* - Frobenius problem; Frobenius numbers; integer programming; modelling.**

I. INTRODUCTION

Let $a_1, a_2, \dots, a_n$ be fixed positive integers (PIs) such that $a_1 < a_2 < \cdots < a_n$ and the greatest common divisor of them is equal to 1. A non-negative integer linear combination (NILC) of $a_1, a_2, \dots, a_n$ is written as,

$$N = \sum_{i=1}^{n} x_i\, a_i \qquad (1)$$

where $x_1, x_2, \dots, x_n$ are nonnegative integers. It is well known that there are only finitely many positive integers which can not be expressed as a NILC of $a_1, a_2, \dots, a_n$.

Ferdinand Georg Frobenius (1849-1947) used to ask to the students in his lecture to find the largest integer that can not be expressed as a NILC of $a_1, a_2, \dots, a_n$ (Alfonsin [2]). For this reason, the largest integer that cannot be expressed as a NILC of $a_1, a_2, \dots, a_n$ is named as the Frobenius number (FN) of $a_1, a_2, \dots, a_n$ and it is denoted by F$(a_1, a_2, \dots, a_n)$.
Thus, all the integers greater than the Frobenius number $F = F(a_1, a_2, \dots, a_n)$ can be expressed as a NILC of $a_1, a_2, \dots, a_n$. That is to say the equation

$$\sum_{i=1}^{n} x_i a_i = F + j \qquad (2)$$

has nonnegative integer solutions for each $j \geq 1$.

Finding the FN of a given set of PIs is named as the *Frobenius problem* which is also known as the *coin exchange problem* or the *postage stamp problem* (Tripathi [26]). This problem is also related to the equality constrained *integer knapsack problem* (Böcker and Liptak [7]). Sylvester [23] showed that

$$F(a_1, a_2) = a_1 a_2 - a_1 - a_2 \qquad (3)$$

Since 1884, extensive researches have been conducted for finding exact formulas for the FN of a set of three or more integers. Brauer [8] found the Frobenius number for consecutive integers. Roberts [20] developed a formula for arithmetic sequences. There are few cases for which the Frobenius number has been exactly determined.

Curtis [10] showed that no closed formula can be found for all $n > 2$. Formulas covering all cases for three integers have been given recently by Tripathi [26]. Alfonsin [3] proved that the Frobenius problem is NP-hard for $n > 2$.

Research on the Frobenius problem has mainly been on finding bounds for the Frobenius number and algorithmic aspects. In 1975, Lewin [15] proposed an algorithm for finding the FN of a given set of PIs. Later, Owens [19] showed that Lewin's algorithm produces wrong results. Since then, considerable amount of algorithms and approaches have been developed for various cases (Böcker and Liptak [7]; Trimm [25]; Einstein et al [12]). Beihoffer et all [6] developped graph theory based algorithms and conducted detailed computational analysis in 2005. Later, Roune [21] developed an algorithm that produces the Frobenius numbers of some sets of thousand-digit PIs. Ong and Ponomarenko [18] developed some formulas for the FN of geometric sequences.

Applications of the Frobenius problem occur in several areas like number theory, automata theory, sorting algorithms, petry nets, etc. Alfonsin [2] surveys all the related references, outlines most of the applications and indicates open questions about the Frobenius problem.

The Frobenius problem is still attracting researchers. Recently, two Ph.D.thesis appeared on this subject (Mohammed [16]; Navarro [17]). There is a web site [24] named as "The On-Line Encyclopedia of Integer Sequences" whose address is http://oeis.org.
In this site, one can find the Frobenius numbers of some special sets of positive integers such as "Frobenius numbers of arithmetic sequences up to 8 successive numbers", "Frobenius numbers of three successive primes" etc. There is a GAP package (Delgado et al [11]) which can be used to compute the FN of any set of PIs. The program is extremely fast.

From the mathematical programming point of view, the Frobenius problem is closely related with integer programming. Vizvari [27] produces upper bounds and gives exact solutions for some subproblems by applying integer programming. Krawczyk and Paz [14] propose close bounds by solving a series of integer linear programs. Aardal and Lenstra [1] use Frobenius numbers to create infeasible instances for integer knapsack problems. Aliev and Henk [4, 5] discover the average behaviour of the Frobenius number based on integer knapsacks. There is also a close relationship between integer knapsack feasibility and Frobenius numbers (Hansen and Ryan [13]; Ryan [22]).

The remarkable improvement in hardware and software technology and widespread availability of commercial optimisation software will allow us to solve many models easily in the near future. To the best of our knowledge, there is no approach and/or algorithm for finding the FN directly by using integer programming formulations which is the main motivation of this study. Our aim has been to develop some user friendly mathematical models for finding the FN of a given set of positive integers that can be executed by using any optimizer. Hopefully, we developed very useful mathematical models. Our contributions may be summarized as follows:

1. We propose integer linear programming formu-lations for checking the necessary and sufficient conditions for a positive integer to be the FN of a given set of PIs.
2. We present a general integer linear prog-ramming model for finding the FN of a given set of relatively prime positive integers.
3. In order to reduce the solution time of the general model, we rearranged the model with rgard to the smallest integer in the given set. So then, we are able to find the FN very easily.

In the following section, we propose two formulations, discuss their usage and give some examples. In section 3, we generalize our approach by proposing two more formulations so that one can find the FN of a given set of three or more PIs very
easily by using an optimizer. In the last section, we summarize our findings and express some remarks for further researches.

II. TEST FOR THE FROBENIUS NUMBER

In what follows, $a_1, a_2, \ldots, a_n$ denote PIs such that $a_1 < a_2 < \cdots < a_n$ and the greatest common divisor of them is equal to 1.

Given a positive integer α, the following integer linear programming model can be used to check if the equation

$$x_1a_1 + x_2a_2 + \cdots + x_na_n = \alpha \qquad (4)$$

has a solution in the set of nonnegative integers.

M_1:
$\min p$
$s.t.$
$a_1x_1 + a_2x_2 + \cdots + a_nx_n - p = \alpha$
$x_i \geq 0$ and integer; $i = 1, \ldots, n; p \geq 0$ and integer.

Since the equation (4) has a solution when α is large enough, the model M_1 has an optimal solution. Thus we can state the following proposition.

Proposition 2.1. Let the optimal solution of M_1 be denoted as $\bar{x}_1, \bar{x}_2, \ldots, \bar{x}_n, \bar{p}$. Then the equation (4) has a solution in the set of nonnegative integers if and only if $\bar{p} = 0$.

All the examples given in this paper are solved with CPLEX 12.8 by using an Intel Core i7-3630QM CPU 2.40 GHz and 16 GB RAM computer.

Example 2.2. Consider the integers 11, 882, 1017, 1218 and let α = 3359. The corresponding model M_1 is

$\min p$
$s.t.$
$11x_1 + 882x_2 + 1017x_3 + 1218x_4 - p = 3359$
$x_i \geq 0$ and integer; $i = 1, 2, 3, 4; p \geq 0$ and integer

This model gives the optimal solution

$$\bar{x}_1 = 145, \bar{x}_2 = 2, \bar{x}_3 = \bar{x}_4 = 0, \bar{p} = 0 .$$

Hence 3359 can be expressed as a NILC of 11, 882, 1017, 1218.

Example 2.3 (Owens [19]). Consider the integers 34, 37, 38, 40, 43 and let α = 163. The correspond-ing model M_1 is:

$\min p$
$s.t.$
$34x_1 + 37x_2 + 38x_3 + 40x_4 + 43x_5 - p = 163$
$x_i \geq 0$ and integer; $i = 1, 2, 3, 4, 5; p \geq 0$ and integer

The value of p in the optimal solution of the above model is $\bar{p} = 0$. Therefore, 163 can be expressed as a NILC of 34, 37, 38, 40, 43 and thus it is not the FN of 34, 37, 38, 40, 43. As mentioned before, Lewin[15]'s algorithm produces incorrectly 163 as the Frobenius number of 34, 37, 38, 40, 43 (Owens [19]).

An immediate corollary to Proposition 2.1 is the following.

Corollary 2.4. If α is the Frobenius number of $a_1, a_2, \dots, a_n$, then the value of p in the optimal solution of M1 is $\bar{p} \geq 1$.

The above corollary gives a necessary condition for α to be the FN of a given set of PIs. Obviously, this condition is not sufficient for p to be the FN. For instance, if one takes the right hand side constant of the model given in Example 2.3 above as equal to 165, the value of p in the optimal solution will be equal to 1. Thus 165 can not be written as a NILC of 34, 37, 38, 40, 43, but as Owens [19] shows and as we will show in Example 3.1, the Frobenius number of the set {34, 37, 38, 40, 43} is 175 not 165. So, we need more tests for finding the FN.

To get a sufficient condition for an integer to be the FN of $a_1, a_2, \dots, a_n$, we use the following theorem.

Theorem 2.5. Let α be a positive integer such that $\alpha + j$ can be expressed as a NILC of $a_1, a_2, \dots, a_n$ for each $j = 1, 2, \dots, a_1$. Then the Frobenius num-ber of $a_1, a_2, \dots, a_n$ is not larger than α.

Proof of Theorem 2.5. It suffices to prove that every integer larger than α can be expressed as a NILC of $a_1, a_2, \dots, a_n$. In fact, let k be an integer such that $k \geq \alpha + 1$. Divide $k - (\alpha + 1)$ by a_1:

$$k - (\alpha + 1) = qa_1 + r, q \geq 0, 0 \leq r \leq a_1 - 1$$

Then

$$k = qa_1 + (\alpha + 1 + r)$$

where $1 \leq 1 + r \leq a_1$. This shows that k can be expressed as a NILC of $a_1, a_2, \dots, a_n$.

The next corollary leads to develop another integer linear programming model (M_2 below) which gives the Frobenius number directly.

Corollary 2.6 If α is the smallest integer satisfying the conditions in Theorem 2.5, then α is the Frobenius number of $a_1, a_2, \dots, a_n$.

Hence the value of α in the optimal solution of the following model M_2 gives the Frobenius number of $a_1, a_2, \dots, a_n$.

M_2:
$\min \alpha$
$\sum_{i=1}^{n} a_i x_{ij} - \alpha = j$
$x_{ij} \geq 0$ and integer; $i = 1, \dots, n; j = 1, \dots, a_1$
$\alpha \geq 0$ and integer

Note that the number of decision variables in the model M_2 is $na_1 + 1$ while the number of constraints is a_1.

Example 2.7 We apply M_2 to the set {4, 63, 73, 111}. The explicit form of the corresponding M_2 model is written as

$\min \alpha$
$s.t.$
$4x_{11} + 63x_{21} + 73x_{31} + 111x_{41} - \alpha = 1$
$4x_{12} + 63x_{22} + 73x_{32} + 111x_{42} - \alpha = 2$
$4x_{13} + 63x_{23} + 73x_{33} + 111x_{43} - \alpha = 3$
$4x_{14} + 63x_{24} + 73x_{34} + 111x_{44} - \alpha = 4$
$x_{ij} \geq 0$ and integer; $i, j = 1, 2, 3, 4$
$\alpha \geq 0$ and integer

The optimal value of α turns out to be 122. Thus, the Frobenius number of the given set of PIs is 122. When we delete 111 from the set {4, 63, 73, 111} and solve the model for the set {4, 63, 73}, we get the same number 122 as the FN of the set {4, 63, 73}. So F(4, 63, 73, 111) = F(4, 63, 73) = 122. This is because 111 can be expressed as a NILC of 4, 63, 73: 111 = 12 · 4 + 63.

As the above example shows, if any of the integers $a_1, a_2, \dots, a_n$, say a_k, can be expressed as a NILC of the remaining ones, then $\{a_1, a_2, \dots, a_n\}$ and the set obtained by deleting a_k from it have the same FN. We have used the model M_2 to find the FN of various choices of $a_1, a_2, \dots, a_n$ where a_1 is not very large. Since dimension of the model depends directly upon the value of a_1, it may take a lot of time to find the FN when a_1 gets larger. The state of the art of the software for integer linear programming and hardware facilities of the present day computers may allow us to solve M_2. However, the combinatorial nature of the problem may not allow to find the Frobenius number of $a_1, a_2, \dots, a_n$ when a_1 becomes larger and larger. Therefore, we need more user friendly models that require less CPU time of the optimizer that is used for their solutions.

III. RESIDUE APPROACH

Let α be the Frobenius number of $a_1, a_2, \dots, a_n$. In what follows we drop the subscript 1 from a_1 and put $a_1 = a$. Consider the partition of the set of nonnegative integers into residue classes modulo a. Let $C_0,\ C_1, \dots, C_{a-1}$ be the residue classes repre-sented, respectively, by $0, 1, \dots, a-1$; that is

$$C_j = \{ka + j : k \geq 0 \ and\ integer\}, j = 0, 1, ., a-1$$

We note that α belongs to one of these residue classes. Note also that α can not belong to C_0, because otherwise α would be a multiple of $a = a_1$, hence a NILC of $a_1, a_2, \dots, a_n$. So, α must belong to one of the classes C_1, $C_2, \dots, C_{a-1}$. Now for each $j = 1, \dots, a-1$, let α_j be the smallest element that can be expressed as a NILC of $a_1, a_2, \dots, a_n$. Say

$\alpha_j = k_j a + j$. Then $\alpha_j - a$ can not be expressed as a NILC of $a_1, a_2, \dots, a_n$, but any element β_j of C_j with $\beta_j \geq \alpha_j$ can be expressed as such. In fact, we have $\beta_j = h_j a + j$ with $h_j \geq k_j$ so that

$$\beta_j = h_j a + j = k_j a + j + (h_j - k_j)a = \alpha_j + (h_j - k_j)a$$

is a NILC of $a_1, a_2, \dots, a_n$.

The above discussion shows that (see also, Brauer and Shockley [9]),

$$\alpha = \max\{\alpha_1 - a, \alpha_2 - a, \dots, \alpha_{a-1} - a\} \quad (5)$$

Various special algorithms are proposed for obtaining $\alpha_1, \alpha_2, \dots, \alpha_{a-1}$. (see for instance, Owens [19]; Beihoffer et al [6]; Böcker and Liptak [7]). We propose the following model for finding α_j for each $j = 1, \dots, a-1$.

$M_3(j)$:

$$\begin{aligned}
&\min \alpha_j \\
&s.t. \\
&a_2x_2 + \cdots + a_nx_n - ay_j = j \\
&\alpha_j - ay_j = j \\
&x_i \geq 0, y_j \geq 0, \alpha_j \geq 0 \text{ and integer}, i = 2, \dots, n
\end{aligned}$$

For each $j = 1, \dots, a-1$, this formulation has two constraints and $n + 2$ decision variables. By writing a computer code that uses any integer programming solver, like CPLEX, as a subroutine, one can obtain the numbers $\alpha_1, \alpha_2, \dots, \alpha_{a-1}$ easily. Then one gets the Frobenius number by the relation given in (5).

Example 3.1. Let us use M_3 to find F(34, 37, 38, 40, 43). $M_3(j)$ becomes:

$$\begin{aligned}
&\min \alpha_j \\
&s.t. \\
&37x_2 + 38x_3 + 40x_4 + 43x_5 - 34y_j = j \\
&\alpha_j - 34y_j = j \\
&x_i \geq 0, y_j \geq 0, \alpha_j \geq 0 \text{ and integer}, i = 2, 3, 4,
\end{aligned}$$

for each $j = 1, \dots, 33$. Optimal solution of the above model for each j is given in Table 1 below.

j	y_j	α_j	j	y_j	α_j	j	y_j	α_j
1	6	205	2	5	172	3	1	37
4	1	38	**5**	**6**	**209**	6	1	40
7	2	75	8	2	76	9	1	43
10	2	78	11	3	113	12	2	80
13	2	81	14	3	116	15	2	83
16	3	118	17	3	119	18	2	86
19	3	121	20	4	156	21	3	123
22	3	124	23	4	159	24	3	126
25	4	161	26	4	162	27	3	129
28	4	164	29	5	199	30	4	166
31	4	167	32	5	202	33	4	169

Table 1. Optimal solutions of $M_3(j)$, $1 \leq j \leq 33$

We see from Table 1 that

$$\max\{\alpha_j : 1 \le j \le 33\} = 209.$$

So F(34, 37, 38, 40, 43) = 209 − 34 = 175. The mean CPU of the 33 cases has been found as 0.03 seconds.

Note that if $\alpha_j = ay_j + j$ and $y = \max\{\alpha_j : 1 \le j \le a - 1\}$, then $y - a = F(a_1, a_2, \dots, a_n)$ and $ay_j + j \le y$ for all $j = 1, \dots, a - 1$.

In order to avoid solving $a - 1$ models separately or to prepare a special code, we propose the following model for finding the FN directly.

M_4:

$$\begin{aligned}
&\min F\\
&s.t.\\
&\quad a_2x_{2j} + \cdots + a_nx_{nj} - ay_j = j, j = 1, \dots, a-1\\
&y - ay_j \ge j, j = 1, \dots, a-1\\
&y - F = a\\
&x_{ij} \ge 0, y_j \ge 0, F \ge 0 \text{ and integers}, \quad i = 2, \dots, n, \\
&j = 1, \dots, a-1
\end{aligned}$$

If the value of F in the optimal solution of M_4 is $\bar{F}$ then F$(a_1, a_2, \dots, a_n)$ = $\bar{F}$. The formulation M_4 has $n(a - 1) + 2$ integer decision variables and $2a - 1$ contstraints. The dimension of M_4 increases very rapidly depending upon the value of $a = a_1$.

Therefore, when the solution time is important, the researcher may prefer the model M_3.

Example 3.2. Frobenius numbers of various combinations of positive integers have been calculated by using M_4. Our findings are given in Table 2 below. CPU time of each instance has been

PIs	FN
10, 195, 218	1057
10, 195, 218, 272	729
10, 195, 218, 272, 287	621
10, 195, 218, 272, 287, 324	601
10, 195, 218, 272, 287, 324, 341	509
10, 195, 218, 272, 287, 324, 341, 353, 499	489
11, 882, 1693, 2749, 3727	5210
11, 893, 1017	3809
11, 893, 1017, 1217	3440

Table 2. Frobenius Number of various sets of PIs

PIs	FN	Time(sec)
5123, 5692, 6055	972404	685.045
5123, 5692, 6055, 6371	267783	353.396
5123, 5692, 6055, 6371,6899	150698	386.683
5123, 5692, 6055, 6371,6899,7300	106857	580.19
5123, 5692, 6055, 6371,6899,7300,8472	85227	676.356
5123, 5692, 6055, 6371,6899,7300,8472,8619	72179	794.273
5123, 5692, 6055, 6371,6899,7300,8472,8619,9001	67678	925.803
5123, 5692, 6055, 6371,6899,7300,8472,8619,9001,9544	60851	1002.52
5123, 5692, 6055, 6371,6899,7300,8472,8619,9001,9544, 9809	56274	1113.33
5123, 5692, 6055, 6371,6899,7300,8472,8619,9001,9544, 9809,10012	54921	1219.73
5123, 5692, 6055, 6371,6899,7300,8472,8619,9001,9544, 9809,10012,11207	51648	1316.25

Table 3. Frobenius Number of various sets with larger a_1s

seconds. This model allows us to compute the Fro-
less than 5 seconds. The model allows us to compute the Frobenius number of a given set of positive integers $a_1 < a_2 < \cdots < a_n$, very easily, for small values of a_1.

We observe from Table 2 that, as we expect, there is
An inverse relation between the FN and the number of elements of the given set of PIs.

The dimension of the model M_4 depends merely upon a_1. Therefore, as it is seen in Table 2, it has been convenient to choose sets of integers with small a_1s.

Our computational analysis showed that, CPU time rapidly increases as a_1 gets larger. In order to reduce the computation time, we prepared a code with C++ CPLEX Concert Technology which solves M_3 for each j by using CPLEX 12.8 as a subroutine and finally produces the FN of the given set of integers. Our code is able to reach the FN of a given set within seconds.

Computational results of some sequences with a_1s at levels of several thousands are given in Table 3.

IV. CONCLUSION

We presented four integer linear programming formulations (M_1, M_2, M_3, M_4) regarding the Frobenius problem. The formulations M_1 and M_2 can be used to get necessary and sufficient conditions for a positive integer to be the Frobenius number of a given set of relatively prime positive
integers. The formulations M_3 and M_4 are used to find the Frobenius number of a given set of relatively prime positive integers directly. Several examples are worked out with each formulation for demonstrative purposes.

The dimension of the proposed formulations are closely related with the smallest integer a_1 in the given set. To get M_3 work more effectively for larger a_1 s, we wrote a computer code which uses our M_3 with CPLEX 12.8; with that code we get the ability to compute the FN of any set of integers within seconds.

Our approach in this work is completely different from the existing algorithmic approaches. Anyone who wants to compute the Frobenius number of a given set of relatively prime positive integers can use our formulations easily. There are free optimizers in the internet, while the existing algorithms need special computer codes which can not be reached easily.

We hope that, this paper will open a new window for the computation of the Frobenius number by using integer programming techniques.

Adaptations of the proposed formulations for special classes of PIs are under construction.

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