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Modeling Optimum Logistic For Multi-day Climbing In Tropical Mountain By Considering Geometrical Constraint

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ABSTRACT

We propose here a set of mathematical model used to predict optimum logistic preparation for multi-day climbing in a tropical mountain. The model is developed based on energy cost paid for the climbing and its corresponding optimum logistic demand where both depend on climbing track profile and necessity to stay overnight. To calculate the energy cost, we need to formulate energy expenditure (EE) based on the track profiles and climber heart rates during the climbing. Moreover, the logistic demand is optimized by using objective functions which are dedicated to fulfill the energy cost with logistic weight and volume of climbing backpack as their main constraints. Additionally, novel geometrical constraint from climbing backpack dimension is proposed and involved to the optimization model. We demonstrate the use of our proposed model to predict optimal number of logistic items for a particular climbing track in the Java Island of Indonesia.

Keywords: Climbing track; Energy expenditure; Geometrical constraint; Mathematical model; Optimum logistic

1. Introduction

Mountaineering activity in particular climbing is not commonly considered as an ordinary outdoor activity. Good preparation for climbing logistics in order to avoid unnecessary incidents or accidents is not only important but also mandatory. Maintaining energy supplies to balance energy expenditure (EE) paid by a person in multi-day climbing is challenging because it is commonly constrained by requirements to minimize weight and simultaneously to adapt with limited capacity of climbing backpack volume. There have

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been several studies related to calculations of EE and logistic demand in mountaineering tourism for example in [1–3]. Unfortunately, none of them have provided specific calculation of optimal logistic preparation in connection directly with EE in multi-day climbing.

Meanwhile, climbing in tropical climate such as in Indonesia is often exposed to intense sun-ray and identical to frequent rain which has significant impact in proper logistic preparations. Although such conditions have less significant influence to EE as stated, for example, by [4–7], they still produce different responses to human body compared to climbing in subtropical climate. For example, muddy tracks which are normally found in tropical mountains have been responsible for additional energy consumed in order to compensate slow movements in slippery conditions [8–11].

In this contribution, we propose a mathematical model to predict optimum logistic preparation for multi-day climbing which can be suitable for tropical climate such as in Indonesia. The model consists of two parts, i.e. an equation to calculate EE and sets of constrained optimization model. In the first part, we aim to combine the EE equation based on climbing track profile and person heart rate proposed by [12] and [13], respectively. It is then followed by construction of knapsack problems in the second part where objective functions are designed to give maximum energy supplied from climbing logistics to compensate energy cost from EE with logistic weight and climbing backpack volume as constraints. To demonstrate our proposed model, we use the climbing track located in the Mount of Sindoro, Central Java, Indonesia, similar to [14] as our basis to collect track coordinates and heart rate data up to its summit with the height of 3136 meter above sea level.

Additionally, we also propose geometrical constraint by considering dimension of logistic items and climbing backpack instead of using only their volumes. In this case, we use statistical approach to determine a so-called mean of cross sectional area. Simple cases are used to demonstrate the capability of the geometrical constraint to tackle fitting of logistic item orientation to the dimension of climbing backpack. Comparison with and without using the geometrical constraint for the previous optimization procedures is also presented.

We split this work into six sections including this part. The second section presents the selection of EE equation which is suitable for our goal in this work. It is then followed by the construction of knapsack problem to find optimum logistic for multi-day climbing in the third section. Meanwhile, the fourth section is dedicated to present the derivation of formulation for the geometrical constraint. We then demonstrate in the fifth section the capabilities of our proposed model. Finally, we summarize our work in the last section.

2. Energy expenditure (EE) equations

As stated before, there are two equations used here to calculate EE independently. The first equation is based on climbing track profile proposed by [12] with the physical unit of Wg^{-1}. It is derived from the load carriage decision aid (LCDA) proposed by the United States (US) Army in the form of

$$\begin{aligned} W_T = &1.44 + 1.94v^{0.43} + 0.24v^4 \\ &+ 0.34vG\left(1 - 1.05^{1-1.1^{G+32}}\right), \end{aligned} \tag{2.1}$$

where v and G are the speed $\left(\mathrm{ms}^{-1}\right)$ and the surface grade in percent $(\%)$, respectively. Moreover, we are interested to compare (2.1) with respect to its corresponding EE from the second equation which directly calculates from the heat rate v_h with the unit of beat per-minute (bpm). As given by a physical unit of kJ.min^{-1}, the formulation proposed by [13] is written as

$$\begin{aligned} W_H =& g\big(-55.0969 + 0.6309 v_h \\ & + 0.1988 w_p + 0.2017 A_g\big) \\ & + (1-g)\big(-20.4022 + 0.4472 v_h \\ & - 0.1263 w_p + 0.74 A_g\big), \end{aligned} \tag{2.2}$$

with g, w_p and A_g denoting gender index, i.e. 1 for men and 0 for women, the person weight in kg, and the person age in years, respectively.

Both equations can be described further as follows. Eq. 2.1 is based on the track profile by taking into account geometrical data, i.e. distance and elevation, and walking speed but without considering human physiological responses. This type of EE equation gives an advantage that it can be applied directly to any types of climbing tracks as long as one knows their profiles without necessity to collect physical data from individual person except their climbing speed. On the other hand, Eq. 2.2 depends mainly on human physiological responses during climbing without a demand for information on the profile of climbing tracks.

Since we aim to use energy in calorific unit for our knapsack problems, both W_T^* and W_H shall be converted first into the energy cost E_c with the unit of kilocalori (kcal). We do the conversion simply by using physical unit multiplications that fit with the corresponding unit given each in (2.1) and (2.2).

As both equations may produce different results for E_c, we decide to consider only the first equation as the reference be-

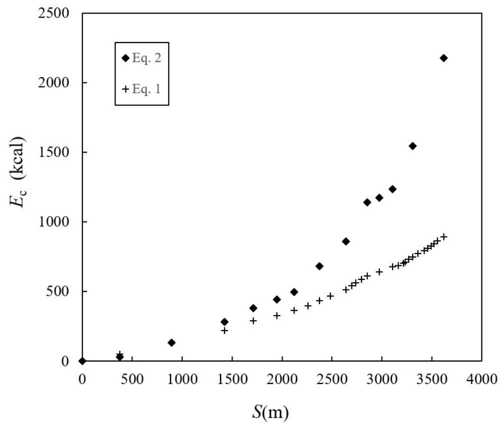


Fig. 1. The cumulative energy cost E_c calculated from the data given in [14] by using Eqs. (2.1) and (2.2).

cause it has more flexibility to be applied for different climbing tracks without high difficulties in direct measurements of v_h during climbing. As a consequence, if the first equation gives more E_c compared the second one, we will use the first equation to solve the knapsack problem. Otherwise, we need to modify the first equation to reach the same level of E_c as the second one by curve fitting.

We use the previous data obtained from a track given by [14] to evaluate E_c as the function of the climbing track total length S from (2.1) and (2.2) for a comparison shown in Fig. 1. In the figure, we use cumulative E_c from the contribution of every segment, i.e. locations for coordinate measurements of the track and the heart rate. One can observe that there is significant gap between both results where the first equation gives lower prediction of E_c compared to the second one. Thus, we need to fit the first equation to the second one by changing the constants in (2.1).

To perform fitting, we shall rewrite (2.1) in its general form according to [12] as

$$\begin{aligned} W_T^* =& 1.44 + 1.94v^{0.43} + 0.24v^4 \\ &+ c_1 v G\left(1 - {c_2}^{1-{c_3}^{G+c_4}}\right), \end{aligned} \tag{2.3}$$

where the constants c_1 to c_4 will be determined simultaneously to capture the result from (2.2). We demonstrate later the fitting by using the climbing track in a tropical mountain in the Java Island Indonesia, i.e. the Mount of Sindoro, up to its summit in a two days trip with camping in between.

3. Construction of knapsack problems

In this part, we construct two knapsack problems similar to [15] which is dedicated to find optimum number of each logistic items as independent variables. First, we are interested to use the energy density v_i for each logistic items denoted by the ratio between the energy supplied by a logistic item and its corresponding weight, i.e. $e_i = E_{L,i}/m_i$, as the first objective function. The index i here is an integer referring to each logistic item. In such case, we define volume capacity of climbing backpack and total weight of logistic items as constraints. Moreover, the second objective function is dedicated to minimize the gap between E_c and $E_L = \sum E_{L,i}x_i$ with the same constraints as the first one.

We construct two knapsack problems from two sets of optimization problems under the objective functions $r = \sum e_i x_i$ and $\Delta W = E_c(W_T^*) - \sum E_{L,i}$. At the first set, we try to find maximum of $r\left(x_i, E_{L,i}, m_i\right)$ from the contribution of each number of logistic item x_i which is constrained simultaneously according to their total weight and volume namely

$$\begin{aligned} &\max\left[r\left(x_i, E_{L,i}, m_i\right)\right] \\ &\text{with} \\ &x_{i,\min} \le x_i \le x_{i,\max} \\ &\sum_{i=1}^{N} E_{L,i}x_i \ge E_c \\ &\sum_{i=1}^{N} m_i x_i \le M_L \\ &\sum_{i=1}^{N} V_i x_i \le V_C, \end{aligned} \tag{3.1}$$

with N, M_L and V_C denoting the total number of logistic item, the maximum allowable weight of all logistic items and the maximum volume of the climbing backpack, respectively. We note here that a physical related variable given with the index i corresponds to its value for each logistic item i. The maximum and the minimum numbers of logistic items, respectively, as $x_{i,\max}$ and $x_{i,\min}$ can be set according to demand. Second, we can also propose an optimization problem to minimize the $\Delta W = E_c(W_T^*) - E_L$ as

$$\begin{aligned} &\min\left[\Delta W\left(x_i, E_c, E_L\right)\right] \\ &\text{with} \\ &x_{i,\min} \le x_i \le x_{i,\max} \\ &\sum_{i=1}^{N} m_i x_i \le M_L \\ &\sum_{i=1}^{N} V_i x_i \le V_C. \end{aligned} \tag{3.2}$$

One can basically obtain from (3.1) and (3.2) two recommendations for optimum number of logistic items for multi-day climbing activities. Here, the first recommendation is intended to fulfill the demand of $E_c(W_T^*)$ implicitly by maximizing the energy density e_i under allowable weight from the total logistic item and maximum volume of the climbing backpack. It is a typical situation where people need recommendation on how many logistic items can be brought in their climbing activities by anticipating overweight and to find an appropriate climbing backpack. On the other scenario, we search for the number of recommended logistic item to fulfill $E_c(W_T^*)$ as close as possible with the same constraints as the first recommendation. We use the same initial values and solver type for solving both problems stipulated in (3.1) and (3.2).

4. Geometrical constraint

Since dimensions and shapes of logistic items for climbing are normally random, we propose a novel method to better fit such logistic items into space inside a climbing backpack. First, we shall define the dimension of a climbing backpack, i.e. with its volume V_C, its height H_C, and by assuming constant cross section area A_C along its height. Second, with total height from all logistic items N given by

$$H_L = \sum_{i=1}^{N} h_i x_i, \tag{4.1}$$

one can obtain the height ratio R_h by dividing (4.1) with the H_C namely

$$R_h = \frac{H_L}{H_C}. \tag{4.2}$$

Here, R_h represents the number of logistic item stacks required in order not to exceed H_C. By formulating (4.2), we assume that a logistic item must be cut exactly at the location with $h_i = H_C$ if its height is larger than H_C. Furthermore, we need also to check if A_C is surpassed by the total area given by summation of the stack areas. In this case, it is necessary to assume that area of each stack must be equal.

In order to determine an effective area of each stack, statistical approach is introduced here. It is because area of each logistic item A_i is different and random. Thus, we propose to use a mean value from the total area of all chosen logistic item namely

$$\bar{A}_s = \frac{\sum_{i=1}^{N} A_i x_i}{\sum_{i=1}^{N} x_i}. \tag{4.3}$$

The reason of using the mean value $\bar{A}_s$ comes from the fact that if there is area of one logistic item surpassing $\bar{A}_s$, it will be compensated by another logistic item with its area less than $\bar{A}_s$. Moreover, in reality, one actually can rearrange logistic items inside a climbing backpack by maximizing the use of every possible empty space.

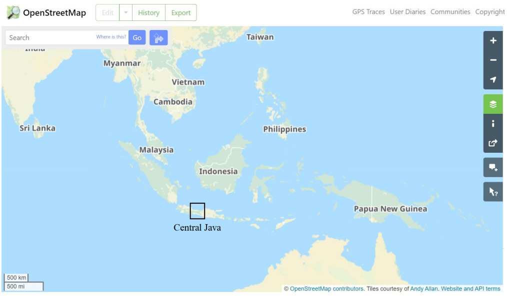
With (4.2) and (4.3) in hand, we can determine the total mean area of stack $\bar{A}_s^T$ by using $\bar{A}_s$ as

$$\bar{A}_s^T = R_h \bar{A}_s. \tag{4.4}$$

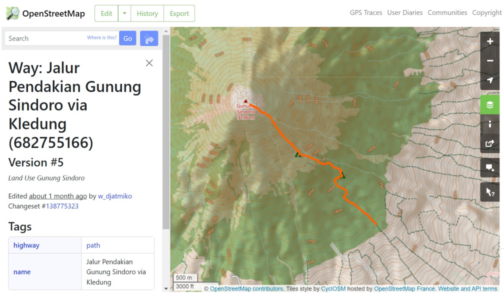
Therefore, in case of $\bar{A}_s^T \leq A_C$, all logistic item theoretically can be inserted to a climbing backpack having that given A_C. Otherwise, $\bar{A}_s^T > A_C$ means that there is a probability that such climbing backpack cannot accommodate all logistic items.

5. Results and discussions

We demonstrate here the calculation of E_c, the curve fitting to obtain our proposed EE model based on (2.3), the corresponding knapsack problems and the implementation of the geometrical constraint by using data collected from the Mount Sindoro climbing track from the Kledung Basecamp shown in Fig. 2. In this work, we assume that ambient temperature has insignificant influence to E_c for human as stated



(a)



(b)

Fig. 2. Located at the Central Java Province Indonesia shown by a small box (a), the Kledung Basecamp of the Mount Sindoro and the climbing track to its summit (b) are shown by using the OpenStreetMap [17].

by [16]. As outcomes, there will be recommendations related to the optimum number of logistic items.

5.1 Energy cost calculations

There were two measurements used as the basis to develop our proposed model. The first measurement was dedicated to record global coordinate of the climbing track by using the global positioning system (GPS) recievers. We used outdoor standard GPS recievers from Garmin [18], i.e. 62s and 78s series, which were capable to access at least 4 satellites to identify a particular position. The coordinates both in latitude and longitude position could be recorded manually including their corresponding elevations in meter. Next, the

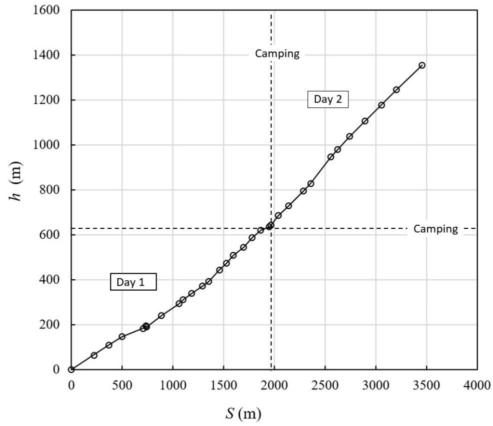


Fig. 3. Measured elevation h from the Mount Sindoro climbing track by using the GPS receivers up to the summit. Our camping area was located approximately at h = 636 meter above starting point of the measurements.

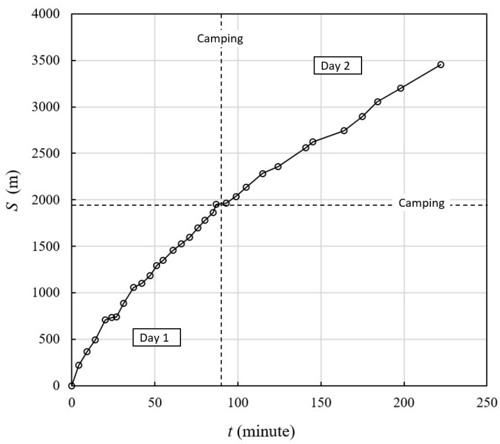


Fig. 4. The cumulative time t required to climb without considering time spent for taking rests and in the camping area.

heart rate v_h was measured from our respondents at the same location as the global coordinate measurements by using common finger clip oximeter due to its rapid and simple measurement procedures.

We perform global coordinate tracking for one of the climbing tracks in the Mount Sindoro, i.e. via the Kledung Basecamp, starting from the height of 1791 me-

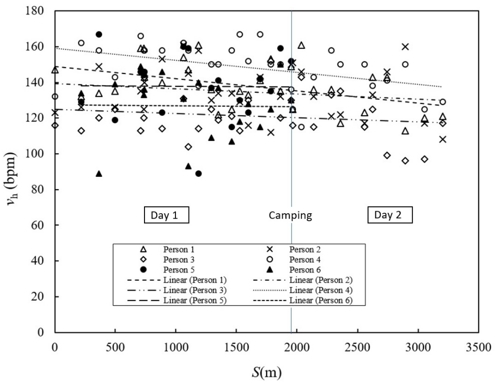


Fig. 5. Heart rates v_h measured along the track in Fig. 3 from 6 persons, i.e. 4 males and 2 females, with each corresponding trend-line. There are no v_h measurement during camping to accommodate sleeping time.

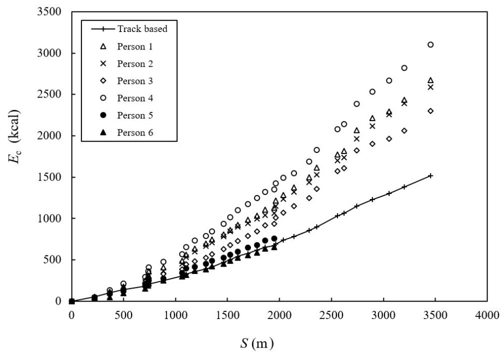


Fig. 6. The results of E_c based each on the climbing track represented by the continuous line with marker and on v_h given by different markers without lines.

ter above sea level up to its summit by using the GPS receivers. The results for elevation of the track as a function of the total climbing distance S and the cumulative time to travel t are shown in Figs. 3 and 4, respectively. We introduce S to measure the climbing activities only without considering rest time during climbing and camping to adapt with (2.1). Thus, there will be energy correction explained in the next section to take into account the rest time.

Simultaneously, the heart rate v_h of our respondents are measured by involving 6 persons to follow the track as well as measuring their average walking speeds without considering different time, i.e. day or night, to avoid further complexities. The results of v_h presented in Fig. 5 show decrements with respect to S. Unfortunately, since we focus only to calculate E_c, detail analysis of such decrements is not in the scope of this work.

By using (2.1) and (2.2), we can now calculate E_c based on the data given by Figs. 3, 4, and 5 as well as information for respondent ages and weights from Table 1 to come with the results shown in Fig. 6. It is clear from Fig. 6 that variations of the results are high mainly due to large different in the measured v_h in Fig. 5.

Table 1. Respondent data for the calculation of E_c.

Person	Gender	Age (years)	Weight (kg)
1	male	36	68
2	male	32	72
3	male	40	74
4	male	39	73
5	female	22	50
6	female	21	50

With the results in Fig. 6, we decide to choose the result either from the person 1 or 2 for fitting the constants in (2.3) because both curves are almost coincide and located approximately in the middle of the other respondent results. Fortunately, it means also that our fitted constants represents at least two persons instead of only one person. The results from the fitting can be seen in Fig. 7 and used to rewrite (2.3) as

$$W_T^* = 1.44 + 1.94v^{0.43} + 0.24v^4 + 0.79vG\left(1 - 1.03^{1-1.07^{G+35.20}}\right). \tag{5.1}$$

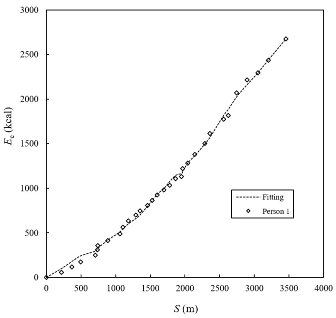


Fig. 7. The results of fitting to (2.3) by using E_c from the person 1 providing the values of $c_1 = 0.79$, $c_2 = 1.03$, $c_3 = 1.07$, and $c_4 = 35.20$.

5.2 Solving the knapsack problems

With (5.1) in hand, we can compute E_c required to walk at a specific distance for any climbing tracks without necessity to measure v_h which is used as an input to solve the optimization problem defined before. In this demonstration, we use available logistics such as foods, drinks, and climbing equipment in the local market around the Kledung Basecamp to define logistic items.

From the identified items, we construct 4 criteria as combinations from the items which consist each with drinking, snacks, main foods, and equipment shown in Table 2 for the number of item i, respectively, given by 1-4, 5-8, 9-12, and 13-20. The required number of items $x_{i,\min}$ and $x_{i,\max}$ are also shown in Table 2. In this case, we do not consider a freedom choice yet, which needs advanced optimization algorithms, to focus more on the connection of optimum logistic and E_c. It is essential to note that the calorific, the volume, and the weight of the logistic items shown in Table 2 are given as basis information to solve the knapsack problems to obtain each item number based each on the optimization problems stipulated in (3.1) and (3.2). We use the same constraint for both (3.1) and (3.2) namely $M_L = 10$ kg and $V_C = 18$ dm^3 and assume that the total E_c is proportional to $2W_T^*$ plus energy required to rests and to stay overnight at the camping area in amount of 1250 kcal to come with the total of 7878 kcal. We use the factor 2 to account for equal energy to walk up and down.

We use a modest computational tool for solving the knapsack problems in hand, i.e. the Solver in MS-EXCEL [20]. The results by using the GRG Nonlinear method and by defining initial number for all logistic items x_i equal to 1 are presented in Tables 3 and 4 each for (3.1) and (3.2), respectively. Since we have different objective functions, the results give different numbers of item. Thus, to control the number of required item one needs to activate $x_{i,\min}$ and $x_{i,\max}$ properly. From computational aspect, the first optimization set can use integer as a constraint to define the number of logistic item as independent variable. However, for the second set of optimization we have found that the use of integer for item number produces unconverged computational results probably due to ill conditions influenced by such integer constraint. Since the targeted variables in Table 2 are only 20 items, the solver can produce results in very short time.

The recommendations for optimum number logistic items obtained here serve as important information for tourists to better plan their climbing activities. Such plan can be illustrated as follows. One can decide to walk only up to a specific height in a tropical mountain anywhere. With that height, the energy E_c can be calculated from (5.1). By using that value of E_c, the corresponding optimum logistic similar to previously demonstrated can be calculated. Thus, we consider that all the calculations described here are generic because they can be used

Table 2. The energy $E_{L,i}$ (kcal), the weight m_i (g), and the volume V_i (litre) for each logistic item $i = 1, 20$. While $E_{L,i}$ and m_i depicted here are obtained from [19], V_i is measured.

Logistic items						
item	$E_{L,i}$	m_i	V_i	name of the item	$x_{i,\min}$	$x_{i,\max}$
x_1	110	200	0.4	mineral water	1	5
x_2	370	107	0.3	energy drink	1	3
x_3	0.01	600	0.26	milk	1	9
x_4	150	25	0.18	others	1	8
x_5	150	25	0.09	peanut	1	4
x_6	150	25	0.09	chocolate	1	5
x_7	100	25	0.052	wafer	1	5
x_8	150	30	0.075	biscuit	1	5
x_9	150	50	0.06	ketchup	1	5
x_{10}	150	50	0.072	sausage	1	8
x_{11}	500	250	0.3	rice	1	5
x_{12}	450	250	0.225	potato	1	4
x_{13}	0	2100	1.5	tent	1	1
x_{14}	0	500	1.5	sleeping bag	1	1
x_{15}	0	2000	0	carrier	1	1
x_{16}	0	25	1.0	cloths	1	1
x_{17}	0	25	0.22	plate	1	1
x_{18}	0	500	1.125	stove and gas	1	1
x_{19}	0	450	1.125	pan/frying	1	1
x_{20}	0	25	0.15	other	1	1

for different climbing tracks and logistic item sets. In a more complex situation such as several days adventures with more complex logistic item sets, one can also follow the steps demonstrated here.

It is important to note that the values of E_L given here are not directly related with energy consumed during a climbing activity because we normally consumed energy converted from foods from the past. Therefore, our optimum logistic recommendation obtained here are dedicated to replace the energy earned by a person from previous day walking.

5.3 Implementation of geometrical constraint

Here, we demonstrate implementation of our proposed geometrical constraint. In the first demonstration, we use regular geometries to show its working principle and to identify its limitations by considering container with height, cross section area, and volume represented, respectively, by H_C, A_C, and V_C. It is then followed by computing an alternative logistic recommendation with the geometrical constraint implemented by using the same input data to obtain the results in Table 3 .

Simple examples on the implementation of the geometrical constraint in three dimensional (3D) cases are presented by using regular objects, projected in two dimensional, as shown in Fig. 8. To extent the objects in 3D, we set their thickness equal to the diameter of the sphere, i.e. 3 cm. The dimension of all objects are provided in Table 5. The task is to compare the results based on the calculation of (4.4) with respect to the container cross section area varied in different dimensions. The results from 4 scenarios are presented in Table 6

Table 3. The optimum number of each item x_i given by solving the optimization problem based on $r(e_i, x_i)$.

Based on the maximum of $r(e_i, x_i)$				
i	x_i (-)	$x_i m_i$ (g)	$x_i V_i$ (litre)	$x_i E_{L,i}$ (kcal)
1	1	20	0.4	110
2	1	107	0.3	370
3	2	1200	0.5	0.0
4	1	25	0.2	150
5	3	75	0.3	450
6	5	125	0.5	750
7	4	100	0.2	400
8	5	150	0.4	750
9	5	250	0.3	750
10	8	400	0.6	1200
11	5	1250	1.5	2500
12	1	250	0.2	450
13	1	2100	1.5	0.0
14	1	500	1.5	0.0
15	1	2000	0.0	0.0
16	1	25	1.0	0.0
17	1	25	0.2	0.0
18	1	500	1.1	0.0
19	1	450	1.1	0.0
20	1	25	0.2	0.0
Total =	49	9577	17.9	7880

Table 4. The optimum number of each item x_i given by solving the optimization problem based on $\Delta W(E_c, E_L)$

Based on $\Delta W(E_c, E_L)$				
i	x_i (-)	$x_i m_i$ (g)	$x_i V_i$ (litre)	$x_i E_{L,i}$ (kcal)
1	1.0	20	0.4	110
2	3.0	321	0.9	1110
3	1.0	600	0.3	0.0
4	1.96	49	0.4	294.3
5	2.46	61.5	0.2	369.3
6	2.46	61.5	0.2	369.3
7	1.99	49.8	0.1	199
8	2.49	74.7	0.2	373.6
9	2.52	126	0.2	378.0
10	2.5	124.8	0.2	374.5
11	5.0	1250	1.5	2500
12	4.0	1000	0.9	1800
13	1.0	2100	1.5	0.0
14	1.0	500	1.5	0.0
15	1.0	2000	0.0	0.0
16	1.0	25	1.0	0.0
17	1.0	25	0.2	0.0
18	1.0	500	1.1	0.0
19	1.0	450	1.1	0.0
20	1.0	25	0.2	0.0
Total =	38.4	9363.4	18.0	7878

with the help of equations from (4.2) to (4.4) with the differences of the area ΔA and the volume ΔV computed. The results from Table 6 can be visualized in Fig. 9 where the excess volumes are detected based on the constraints provided by H_C. According to Table 6, we can arrange all the objects based on the number of stacks R_h equal to 2, 4, and 2 each for the scenario 1, 3, and 4, respectively. All three stack formations are shown in Fig. 9 where the remaining empty spaces, i.e. indicated as well by positive value of ΔV, available in the scenario 1, 3, and 4 will compensate the excess volumes due to the constraint provided by H_C. Importantly, the values of ΔA indicate compactness with respect to the constraint A_C. Hence, the negative values of ΔA mean that the objects must have good enough flexibility in order to force the objects to fit with the container and vice versa.

A further validation for the proposed geometrical constraint can be done by using blocks with T_i, L_i, and W_i representing each of its thickness, length, and width, respectively, as shown in Fig.10. It is important to note that such validation is much inspired by similar tests performed by [21]. The bigger block consists of seven smaller blocks in Fig.10 where each dimension of them is given in Table 7. The validation results are presented in Table 8 where the first scenario gives exactly the same area with the bigger block, i.e. $\Delta A = 0$. Unfortunately, the other two scenarios produce non zero $\Delta A > 0$ indicating empty spaces in very small per-

Table 5. Dimensions of the object in Fig. 8 and their corresponding total height, area, and volume. Again, all units are measured and based on centimeter (cm).

Object name	h_i	w_i	t_i	x_i	$h_i x_i$	$A_i x_i$	$V_i x_i$
block	9	1	3	1	9	3	27.0
sphere ($A_i = \pi w_i^2/4$)	3	3	3	1	3	7.1	9.4
triangular prism	2	3	3	1	2	9	18.0
cube	2	2	3	1	2	6	12.0
Total ($\sum$)					16	25.1	66.4

Table 6. Results from 4 scenarios with constant thickness $t_C = 3$ cm representing rectangular cross section area for A_C . All units are based on centimeter (cm) with each number of object x_i equals to 1.

Scenario	H_C	W_C	A_C	V_C	R_h	$\bar{A}_s$	$\bar{A}_s^T$	$^1\Delta A$	$^2\Delta V$
1	8	4	12	96	2	6.3	12.53	-0.5	29.63
2	4	4	12	48	4	6.3	25.07	-13.1	-18.4
3	4	8	24	96	4	6.3	25.07	-1.1	29.6
4	8	8	24	192	2	6.3	12.53	11.5	125.6

[1] $\Delta A = A_C - \bar{A}_s^T$
[2] $\Delta V = V_C - \sum_{i=1}^{4} V_i x_i$

centage compared to A_C which shall not exist in this case.

Since the method proposed here is based on an analytical approach, we cannot directly compare to standard bin packing problems relied on iterative and heuristic methods such as [21–23] to find optimum configurations to fulfill particular given containers. Hence, our proposed method can be considered as a rapid predictor in the context of climbing activites to determine if a backpack can accomodate all recommended logistic items or not.

Furthermore, we apply the geometrical constraint to the knapsack problem by still relied on the data in Tabel 2 with the dimension of the climbing backpack as $H_C = 60$ cm, $A_C = 300$ cm^2, and $V_C = 18000$ cm^3. Here, we simultaneously solve the knapsack problem previously used to produce the results in Table 3 but now with the geometrical constraint produced by (4.2) to (4.4) and stipulated by targeting a small enough of ΔA. The result is shown in Table 9. There are significant differences in the combinations of logistic item number compared to the result in Table 3 which are mainly due to the role of geometrical constraint instead of produced from iteration

Table 7. Dimension of smaller blocks, defined without unit, used for the validation computed based on the reference values of $t_b = 8$, $l_b = 10$, and $w_b = 12$. The number of each smaller block i is given by $N_{b,i}$ with its thickness, length, and width denoted by T_i, L_i, and W_i, respectively.

Block type (i)	$N_{b,i}$	T_i	L_i	W_i
1	2	t_b	l_b	$2\,w_b$
2	1	t_b	$2\,l_b$	$2\,w_b$
3	4	t_b	l_b	w_b

Table 8. Validation results with scenarios 1, 2, and 3 each based on the dimension represented by Table 7 with total volume of the bigger block represented by H_C, A_C equal to V_b = 11520.

Scenario	H_C	A_C	V_C	R_h	$\bar{A}_s$	$\bar{A}_s^T$	$^3\Delta A$	$^4\Delta V$
1	24	480	11520	2.33	205.7	480	0	0
2	20	576	11520	4	137.1	548.6	27.4	0
3	24	480	11520	5	91.4	457.1	22.9	0

[3] $\Delta A = A_C - \bar{A}_s^T$
[4] $\Delta V = V_C - V_b$

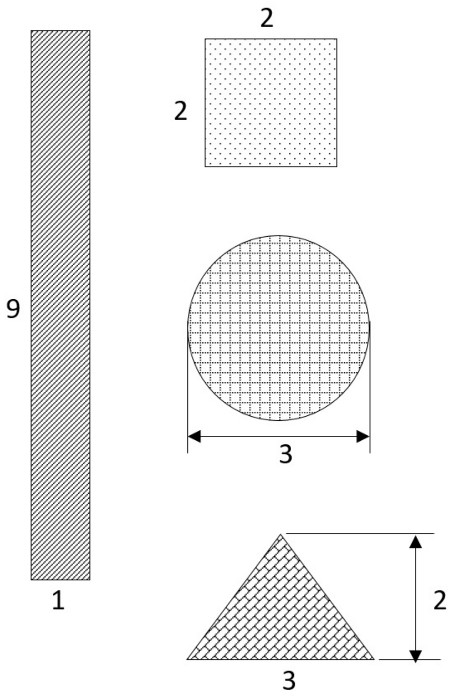


Fig. 8. The regular 3D objects, projected in 2D way, used to show the working principle of the geometrical constraint. The thickness for the square, the rectangular, and the triangle objects equal to the diameter of the sphere. All objects have been drawn in a proportional way with their units in centimeter (cm).

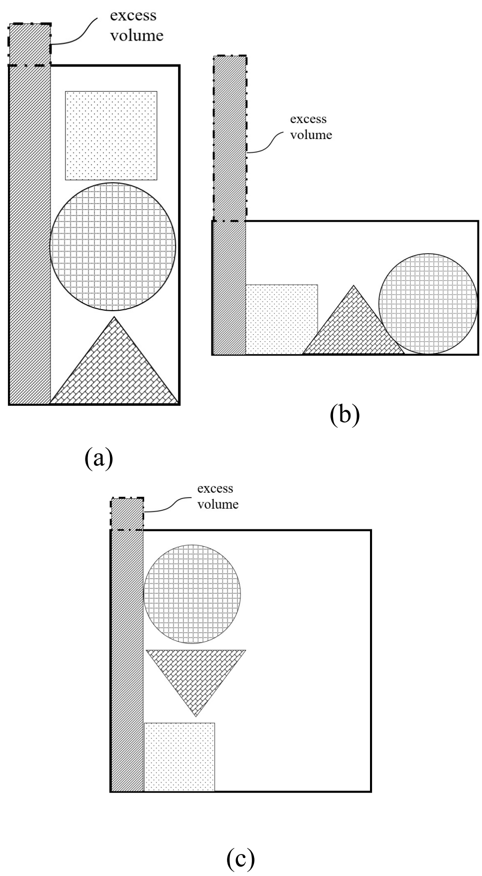


Fig. 9. Visualization of geometrical arrangement for the scenarios 1, 3, and 4 from Table 5.

process. In our case where the objective function and the constraints are the same, the latter typically gives only small deviation to both results.

Finally, to identify the behaviours of (3.1), we run additional scenarios based on changes of the item with the highest calorific values. From the result in Fig. 11 with $M_T = \sum_{i=1}^{20} m_i x_i$, the opti-

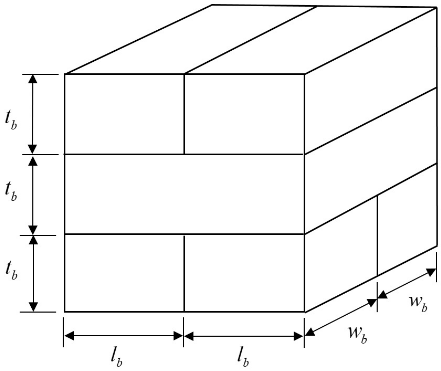


Fig. 10. A block constructed from seven smaller blocks with different sizes used to verify the method represented by Eqs. 4.1 to 4.4.

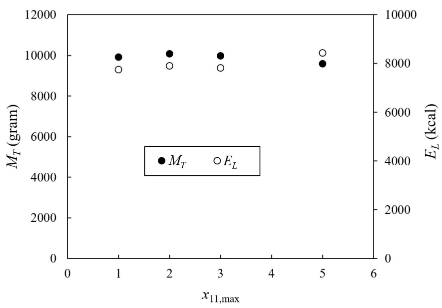


Fig. 11. Sensitivity analysis with respect to calorific value under influence of the item with maximum calorie content.

Table 9. The results by using the geometrical constraint for the optimum number of each item x_i from the objective function $r(e_i, x_i)$. The geometrical parameters are given as $R_h = 11.22$, $\bar{A}_s = 26.8\,\mathrm{cm}^2$, $\bar{A}_s^T = 300.05\,\mathrm{cm}^2$, $\Delta A = 0.0\,\mathrm{cm}^2$, and $\Delta V = 4.0\,\mathrm{cm}^3$. The values of x_i can be set as integers for implementation in the Solver.

Based on the maximum of $r(e_i, x_i)$				
i	x_i (-)	$x_i m_i$ (g)	$x_i V_i$ (litre)	$x_i E_{L,i}$ (kcal)
1	4	80.0	1.6	440
2	2	214.0	0.6	740
3	2	1200	0.5	0.0
4	7	175	1.3	1050
5	3	75	0.3	450
6	4	100	0.4	600
7	9	225	0.5	900
8	3	90	0.2	450
9	2	100	0.1	300
10	4	200	0.3	600
11	4	1000	1.2	2000
12	2	500	0.5	900
13	1	2100	1.5	0.0
14	1	500	1.5	0.0
15	1	2000	0.0	0.0
16	1	25	1.0	0.0
17	1	25	0.2	0.0
18	1	500	1.1	0.0
19	1	450	1.1	0.0
20	1	25	0.2	0.0
Total =	54	9584	14	8430.1

mizations under the geometrical constraints show slight changes on the optimum results. By changing the maximum number of allowable item 11 x_{11}, our proposed algorithm for (3.1) can redistribute the contribution of calorific values to other items with the optimization indicator values, i.e. M_T and E_L, changing slightly. It indicates stability of the algorithm to avoid random results.

6. Concluding Remarks

A connection between energy cost and optimum logistic preparation for a tropical mountain climbing has been proposed in this work. We demonstrate such connection by using the climbing track in the mount of Sindoro via the Kledung Basecamp. Here, the energy cost is calculated from the climbing track profile and the heart rate of persons walking on the tracks. With that energy cost in hand, we construct mathematical models for our own energy cost equation and corresponding knapsack problems. The models are then used to determine the optimum number of logistic items to match the energy cost by considering each logistic item weight and volume. Additionally, we also propose a novel approach to fit the logistic items with the climbing backpack geometry by involving the geometrical constraint to the model. Our work can be used by tourists as supporting information to better manage their climbing activities in the future.

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