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Location and Routing Problems of Debris Collection Operation After Disasters with Realistic Case Study

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Abstract

Debris removal after disasters presents challenges unique to each disaster. The transportation routing as well as disposal sites issue will be the subject of this study. The uniqueness of debris collection operation is due to the limited access from one section to the other, as a result of the blocked access by debris. Therefore a new constraint i.e. access possibility constraint was added to the classical L-CARP. Case studies on a test network and on realistic instances based on estimates of debris due to likely large scale natural disaster in Tokyo Metropolitan Area have also been reported under various scenarios.

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Keywords: LRP; debris collection; disaster management; blocked access; access possibility

1. Introduction

Management of debris is a concern after any major disaster. In particular, debris removal after a disaster presents challenges unique to that disaster. Often, the debris removal process takes months or even years to finish. It is likely to be a concern for some time to come since there exists many factors that make it such a costly and complex operation. The cost is mostly arising from the cost of collection and transportation to the disposal sites. Technical factors which form the cost of this process are firstly limited space to establish appropriate temporary or

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final disposal sites. The second factor is the cost of providing necessary heavy vehicles and tools to execute the debris collection operation. The third factor is the transportation cost of debris disposal that depends on vehicle's route choice to transport the debris to the temporary or final disposal sites.

Routing problems are one of the important issues in cost efficiency considering that route choice greatly affect total travel costs that is incurred in the debris collection operation. As well as disposal sites issue, whereby determining of the number, the location and the capacity are considered very important due to affect the vehicle routing in the operation. The combination of the disposal sites location problem and the vehicle routing problem will be the subject of our study. In the context of the location and routing problem, the following research questions can arise: What is the correlation among location, routing and travel costs? How to formulate this kind of problem with appropriate mathematical models? How to solve such mathematical models? (i.e. which solution algorithm shall be used to obtain the optimum cost?).

To address these research questions, a variant of the undirected Location-Capacitated Arc Routing Problem (L-CARP) was chosen. The location-routing problem (LRP) is a research area within location analysis, with the distinguishing property of paying special attention to underlying issues of vehicle routing. The phrase "location-routing problem" is misleading, as location-routing is not a single well defined problem like the travelling salesman problem. It can be thought of as a set of problems within location theory. However (Nagy & Salhi, 2007) preferred to think of the LRP as an approach to modeling and solving location problems. Their definition stemmed from a hierarchical viewpoint, whereby the aim was to solve a facility location problem as the master problem, however in order to achieve this, vehicle routing problem as the sub problem needed to be solved simultaneously. From a practical viewpoint, location-routing formed part of distribution management; while from a mathematical point of view, it could usually be modeled as a combinatorial optimization problem.

Arc routing problems consist of determining a least cost traversal of some specified arcs of a graph, subject to side constraints. Such problems are encountered in variety of practical situations such as road or street maintenance, winter gritting operation, waste collection, mail delivery, school bus routing, utility meter reading, etc. Many surveys can be found explaining many arc routing problem variants, however the three main variants are the Chinese Postman Problem (CPP) in which it is required to traverse all arcs of a graph, the Rural Postman Problem (RPP) in which only a subset of arcs must be traversed, and the CARP which is a capacity constrained version of the two earlier variants with multiple real life applications, as reviewed in detail by Cordeau & Laporte (2002), Dror (2000), Eiselt, Gendreau & Laporte (1995a, 1995b), Assad & Golden (1995).

The problem in this study is motivated from debris collection operation after disasters.For this a modification to the classical L-CARP is required. In this new L-CARP variant, roads are treated as a set of arcs. A set of required arcs consists of arcs that are covered by debris, thus they have demands to service. The objective function of the L-CARP is to service all required arcs in the graph with least cost with feasible vehicle routes as a result of feasible location of disposal sites. To solve this problem, analysis will be performed into two phases i.e. location-allocation phase as reviewed by Wu, Low & Bai (2002), Nagy & Salhi (2007) and routing phase as reviewed in (Dror, 2000); and (Assad & Golden, 1995).

Locating disposal sites and allocating debris to each disposal site will be performed in the location-allocation phase, followed by the routing phase. In the routing phase of debris collection operation, the sequences fvisiting and servicing arcs are very important, because one section may block other sections. Initially, only adjacent arcs can be connected with each other, while for distant arcs there may be no way to be connected before removing the blocked access first. Another matter that should be paid attention to is that routes also can only be operated in a particular sequence, considering that one completed route will affect the access possibility for the other routes. This constraint was developed in this study as a binary matrix termed as the access possibility matrix, where an entry is equal to 1 if a vehicle can possibly move from one arc to another; 0 otherwise. This is illustrated in Fig. 1 to better understand the problem. At stage 1, the access possibility from 0 to 1 is equal to 1 (i.e. p_{01}=1); and p_{02}=0 because the access is still blocked. In stage 2, after arc no.1 has been serviced, p_{02} becomes 1. This means that vehicle should service arc no.1 first, before being allowed to service arc no.2 through the shortest path. The access possibility from one point to the others changes every time a single arc has been serviced by a vehicle. Here, we can also see the existence of three candidate disposal sites, i.e. A, B and C. , Determining which candidates disposal sites should be established and the capacity of each will greatly affect the route choice of vehicle in the operation of collecting all demand on the graph

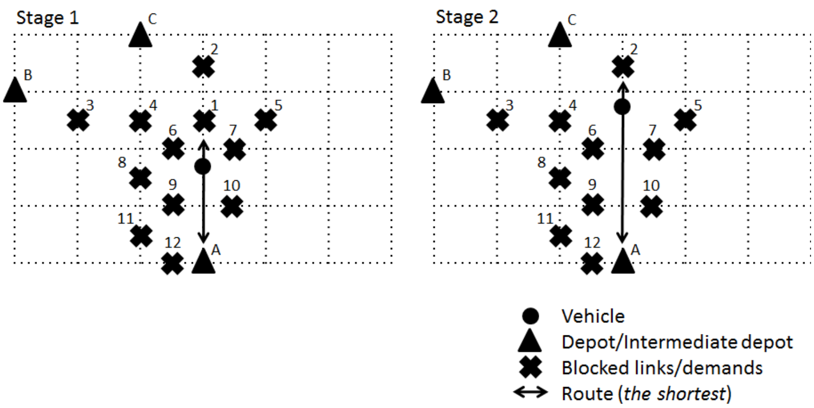

Fig. 1. Problem illustration

Similar to the various L-CARP-related research (as mentioned in the next section) the underlying L-CARP to our debris collection operation in this study was transformed into the Location-Capacitated Vehicle Routing Problem (L-CVRP). Both the L-CARP and the L-CVRP are in fact closely related, the main difference being that in the L-CARP customers are set of arcs while in the L-CVRP customers are set of nodes. The resulting model formulation was applied to solve a realistic problem based on disasters debris estimation data resulting from large scale earthquake and flood disasters scenarios in Tokyo Metropolitan Area by Hirayama, Shimaoka, Fujiwara, Okayama & Kawata (2010). In addition to that spatial and statistical data of Tokyo Metropolitan Area was also used based on the Japanese Standard Grid Square and Grid Square Code used for the Statistics (Announcement No.143 by the Administrative Management Agency Japan, on July, 12, 1973).

The remaining sections of this paper are organized as follows. The mathematical formulation of the problem is presented in Section 2. Then, meta-heuristics solution techniques and problem instances are reported in Section 3. Application of model formulation to a realistic case study of Tokyo Metropolitan Area disasters debris problem is presented in Section 4. Finally, the conclusionfollows are presented in Section 5.

2. Model Formulation

The L-CARP can be defined on an undirected graph $G = (V, A)$, in which V is the set of nodes and A is the set of arcs. Set A is partitioned into a subset of required arcs A_1, which must be serviced, and another subset of arcs A_2 required to maintain connectivity. Each required arc $a \in A_1$ is associated with a demand $z(a)$, a travel cost $tc(a)$ which refers to the distance travelled, and a service cost $sc(a)$. The other arcs, in subset A_2, have a travel cost $tc(a)$ only. Usually, the service cost is greater than the travel cost because it takes more effort to service an arc than to only simply travel along it.

There exists a depot as a route starting point as well as a final destination point after all required arcs are completely serviced. In addition, intermediate depots can also be considered which serve as vehicles destination points to empty their loads. As soon as an arc or a road is serviced by the vehicle, it will open and can be used, without waiting until the vehicle which services it completes its route. In some practical cases, where roads are wide enough, the debris could be removed from the point to the road side. Considering that our objective is to collect the debris and open the blocked access, therefore the method whether to transport the debris to the intermediate depot or just remove it to the road side does not affect the progress. However in this paper, the roads are assumed to be quite narrow and to respect the capacity of vehicle and labor, it is assumed as necessary to transport the debris to the intermediate depot. The fixed cost for establishing such intermediate depot h is represented by G_h. The idea of intermediate depot came from (Angelelli & Speranza, 2002), whereby it was termed as the intermediate facility which serves as point for vehicles to renew their capacity. Since the objective of this study is to find the best location as well as optimum number of intermediate depots, multiple intermediate depots will also be considered. Some literature about multiple depots in terms of waste collection operation were reviewed by Beasley & Benjamin (2010), Laporte, Cordeau & Crevier (2007), Angelelli & Speranza (2002).

A set of identical vehicles $K = \{1 \dots m\}$ are placed at the central depot node. Every vehicle has a fixed capacity Q_k and vehicle cost F_k which can be included in cost whenever the vehicle is used. Each vehicle serves a single route that must start and end at the depot. While doing so, vehicles can visit one of the intermediate depots whenever their loads exceed Q_k. As mentioned earlier, the vehicles are allowed to move from or to the adjacent arcs, whereas for distant arcs with blocked access, vehicles are not allowed to visit them before removing the blockage first (i.e. regulated by the access possibility constraint). This access possibility constraint belongs to the family of dynamic constraints, considering that the blocked access conditions in the entire network will change immediately every time a blockage is opened. The objective is to service all required arcs in the graph at least cost with feasible routes, where the cost is related to the number of vehicles used, the number and location of intermediate depots established, travel costs and the service costs.

A transformation from L-CARP in graph $G = (V, A)$ into an equivalent L-CVRP in a transformed graph $G' = (V', A')$ is performed in a well-known transformation by (Longo et al., 2006). Therein, the type of arc transformation into node with making two nodes for each required arc. An arc (i, j) in A_1 is associated with two nodes s_{ij} and s_{ji}, thus the resulting L-CVRP instance is defined on a complete undirected graph $G' = (V', A')$. An illustration of the transformation process from (Longo, De Aragao & Uchoa, 2006) is presented in Fig. 2a and Fig. 2b.

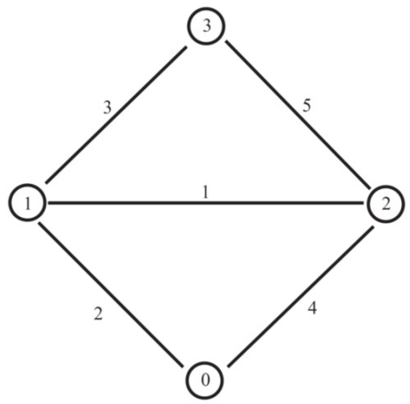

Fig. 2a. Original L-CARP graph

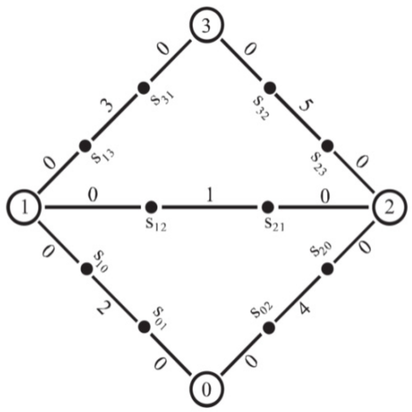

Fig. 2b. Transformed L-CVRP graph

The transformation fixes the flow variable (x_{ij}^k) on all undirected arcs $\{(s_{ij}, s_{ji}) \in A' \mid (i, j) \in A\}$ to 1. It means that L-CVRP solutions are only feasible where pairs of nodes s_{ij} and s_{ji} are visited in sequence, either s_{ij} from or to s_{ji}. It could be said that sum of z on s_{ij} and s_{ji} is a single quantity because they were obtained from the same single arc. As the impact, the vehicle must have sufficient load capacity to service the pair of nodes s_{ij} and s_{ji} simultaneously, otherwise, vehicle must visit one of the intermediate depots to empty the load or look for other pair of nodes. After the above mentioned transformation applied on debris collection operation problem, a L-CVRP with blocked access is obtained.

Notations used in this study are mostly the same used by Tagmouti, Gendreau & Potvin (2007), where $N' \subset V'$, is the set of required nodes that must be serviced. The depot is a single node, however it is also duplicated into an origin depot o and a destination depot d in V'. In addition, there exists a set of potential intermediate depots $I = \{V'n + 1 \dots\}$, where $I \subset V'$ and n is the number of nodes that must be serviced. Even though the best location among a set of potential intermediate depots will be chosen, however one of the intermediate depot is always established right at the depot location because of the efficiency reason. This situation is acceptable in conditions where it is difficult to provide an empty space in a particular area to establish other intermediate depots. Therefore, the depot will be also duplicated into an intermediate depot $V'n+1$ in V'. Once load of vehicles exceed Q_k, vehicles can choose one of the intermediate depots to empty the load. On the last tour, when all required nodes have completely serviced, vehicles must return to the depot.

The operation of multiple vehicles will increase costs due to fixed cost (F_k) of every additional vehicle. Moreover, operating multiple vehicles may not decrease the total travel cost (*tc*), considering that working in a network with blocked access imposes the condition that routes must be operated in a particular sequence. Technically, every time a vehicle completes service on one node, it will update information of the access possibility to all other vehicles. Therefore, operating multiple vehicles will still be tested in this study, because some vehicles with varying routes which start simultaneously may decrease the total required time (*tt*). Such operation can be applied to solve the debris collection problem with time restriction, such as depot closing time or time windows at the demand nodes. It should be noted that the classical CVRP itself can be considered a single vehicle routing operation without any time constraints as demonstrated in detail byYang, Mathur & Ballou, (2000).

As a new idea for the debris collection operation, an access possibility constraint is introduced on the nodes, which is represented by p_{ij}^k, $i \in V', j \in V', k \in K$, which is equal to 1 if vehicle k from node i can possibly visit or service node j, 0 otherwise. The access possibility matrix is always changed from the original and previous positions, every time a vehicle completes or services a required node and every time a blockage is opened. Therefore, it can be classified as a dynamic constraint. The transformed L-CVRP's decision variables are: (1) the binary flow variables on the arcs x_{ij}^k, $(i,j) \in A', k \in K$, which are equal to 1 if vehicle k travels from node i to service node j, 0 otherwise; (2) The binary intermediate depot variables y_h, $h \in I$ which are equal to 1 if intermediate depot h is established, 0 otherwise; (3) The binary demand allocated $e_{hj}, j \in N', h \in I$ which are equal to 1 if demand j is allocated to intermediate depot h, 0 otherwise; and (4) the non-negative variables Q_i^k, $i \in V'$ which specify the remaining capacity of vehicle k just after servicing node i. Note that $Q_o^k = Q_k, k \in K; Q_h^k = Q_k$, $k \in K, h \in I$; the inter node travel cost (c_{ij}) is based on the shortest distance $d(i,j)$, which in turn depends on travel cost $tc(i,j)$ and service cost $sc(i,j)$ of arc (i,j). The demands at depot and intermediate depots are zero, i.e. $z_o = z_d = z_h = 0$, $h \in I$; the maximum number of vehicles is limited to m; and g is the maximum number of intermediate depots, that can be established. The transformed L-CVRP can be formulated as follows:

Min

$$\sum_{k \in K} \sum_{(i,j) \in A'} c_{ij} x_{ij}^k + \sum_{h \in I} G_h y_h \tag{1}$$

Subject to

$$\sum_{k \in K} \sum_{i \in N' \cup I \cup \{o\}} x_{ij}^k = 1 \quad ; j \in N' \tag{2}$$

$$\sum_{k \in K} \sum_{j \in N'} x_{oj}^k \leq m \tag{3}$$

$$\sum_{h \in I} y_h \leq g \tag{4}$$

$$\sum_{j \in N' \cup \{d\}} x_{oj}^k = 1 \quad ; k \in K \tag{5}$$

$$\sum_{j \in N' \cup \{d\}} x_{ij}^k - \sum_{j \in N' \cup \{o\}} x_{ji}^k = 0 \quad ; k \in K,\ i \in N' \tag{6}$$

$$\sum_{i \in N' \cup \{o\}} x_{id}^k = 1 \quad ; k \in K \tag{7}$$

$$x_{ij}^k - p_{ij}^k \leq 0 \quad ; i \in V', j \in V', k \in K \tag{10}$$

$$x_{jh}^k - y_h \leq 0 \quad ; h \in I, j \in N', k \in K \tag{11}$$

$$0 \leq Q_i^k \leq Q_k \quad ; k \in K,\ i \in V' \tag{12}$$

$$x_{ij}^k \in \{0,1\} \quad ; (i,j) \in A',\ k \in K \tag{13}$$

$$p_{ij}^k \in \{0,1\} \quad ; i \in V', j \in V', k \in K \tag{14}$$

$$y_h \in \{0,1\} \quad ; h \in I \tag{15}$$

$$\sum_{j \in N'} z_j e_{hj} - q_h y_h \leq 0 \quad ; h \in I \qquad (8)$$

$$x_{ij}^k \left(Q_i^k - z_j - Q_j^k \right) \geq 0 \quad ; (i,j) \in A',\ k \in K \qquad (9)$$

$$e_{hj} \in \{0, 1\} \quad ; h \in I,\ j \in N' \qquad (16)$$

The objective function (1) minimizes the sum of travel costs (*tc*) which refers to travelled distance and the sum of cost of establishing intermediate depots. Instead of travel cost, travel time can also be considered in the objective function if one wants to minimize the sum of total travel and service times (i.e. the total operation time) instead of total costs. The fixed vehicle cost (F_k) can also be added to all out going vehicles from depot $o \in V'$ if one wants to penalize the use of an additional vehicle. Constraint (2) requires that each node in N' must be serviced once. Constraint (3) is for the maximum number of vehicles used. Constraint (4) is for the maximum number of intermediate depots established. Constraint (5) - (7) are the flow conservation constraints. Constraint (8) is capacity constraint for the intermediate depot established. Constraint (9) ensures that vehicles are allowed to move from node i to node j only if the remaining capacity after servicing node i is still feasible to load demand at node j. Constraint (10) ensures that vehicles are allowed to move from node i to node j only if the access between node i and node j is open, i.e. p_{ij}^k=1. Constraint (11) ensures that vehicles are allowed to move from node i to intermediate depot h to dispose debris only if intermediate depot h is already established, i.e. y_h=1. Constraint (12) ensures load values that do not exceed Q_k and are positive. Constraint (13) is for binary values for the flow variables. Constraint (14) is for binary values for access possibility. Constraint (15) is for binary values for establishing intermediate depots. Constraint (16) is binary values for allocating demands to the intermediate depots.

3. Meta-heuristics Solution Technique

3.1. Tabu search meta-heuristics

L-CVRP is NP-hard (non-deterministic polynomial-time hard). CVRP itself was first addressed with relatively simple heuristics, such as the construct strike (Christofides, 1973), path-scanning (Golden, De Armmon & Baker, 1983) and greedy heuristics (Costa, Hertz & Mittaz, 2002). The solution methodologies have been improved over time using meta-heuristics such as the tabu search as reviewed in detail in (Gendreau, 2003), (Mastrolilli, 2001) and (Hertz, Laporte & Mittaz, 2000). In this study as well, a tabu search meta-heuristics method is developed as a solution technique to solve the underlying L-CVRP for our debris collection operation. In this study, theoretically the L-CVRP is analyzed in two phases (location-allocation and routing), however technically both are processed simultaneously. The process begins with making a list of all possible combinations of the intermediate depots to be established. It then proceeds to calculate the best route of each combination using tabu search and compares one result with the others to search for the best solution as well as the decision of the optimum number, location, and allocation of demands for each intermediate depot established which is also associated with the capacity of intermediate depot.

3.2. Problem instances

Before applying the formulation of the debris collection problem (i.e. its underlying modified L-CVRP) on the realistic case study from the Tokyo Metropolitan Area, the model formulation is tested on a small problem instance, which was also given by Pramudita, Taniguchi & Qureshi (2012). In the test instance, the service cost (*sc*) and the fixed vehicle cost (F_k) have been assumed as 0, thus the cost involved is only the travel cost (*tc*) (i.e. c_{ij}=$tc_{ij} + G_h$). The service cost can be taken into consideration by assuming that *sc* is included in *tc*.

In our case, the objective is to service all required nodes, and due the fact that the considered debris collection operation is not time constrained, therefore the amount of service cost is always fixed and it will not affect the optimization process. Similarly, as mentioned earlier the fixed cost of a vehicle can be added to all outgoing arcs from the origin depot but for this particular test instance just a single vehicle is considered. Another assumption taken in this case is that the shortest path from node i to node j in the graph is the only path that exists for every node pair. Accordingly, the connection between i and j depends on whether $d(i,j)$ is blocked or not, however if j is depot or intermediate depot, the vehicle can always move from i to j through the shortest path. The L-CARP graph of test instance in Fig. 3a is transformed into the corresponding L-CVRP graph in Fig. 3b.

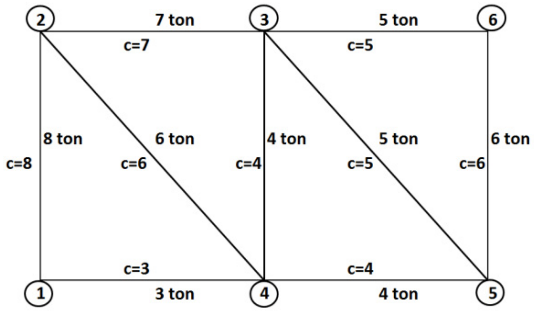

Fig. 3a. L-CARP test instance

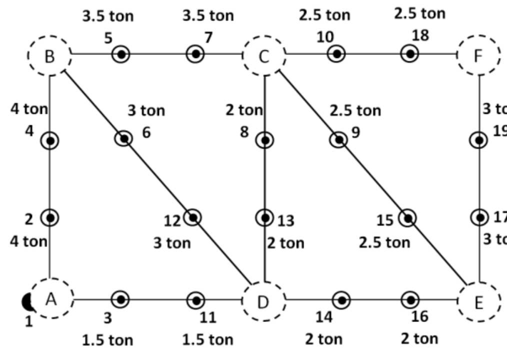

Fig. 3b. Transformed test instance in L-CVRP

After transformation, the graph turns into L-CVRP with number of nodes V'=25, which consists of node no.1 as a depot), node no.2-19 as required nodes and node A-B-C-D-E-F as candidate locations of intermediate depot. The vehicle capacity (Q_k) is 20 ton, fixed intermediate depot cost (G_h) is 8 as well as the travel cost c_{ij} between nodes and was also presented in Pramudita, Taniguchi & Qureshi (2012).

Fig. 4a shows the best cost obtained from the best combination scenario of intermediate depot establishment for each possible number. The dashed line is travel costs (tc) only (without considering G_h), which shows the conditions of tc reduction from 69 to 58 when scenario AD is used (i.e. the second intermediate depot at node D is established besides the first one at node A). The subsequent intermediate depot establishments by others scenario do not affect the travel costs which are stagnant at the same amount. The solid line is travel costs (tc) aggregate with G_h, which shows that the optimum solution obtained when scenario AD is used, i.e. two intermediate are depots established at node A (qi≥14 ton) and D (qi≥34 ton). The best total cost is 74 and with route 1/A – 3 – 11 – 14 – 16 – 15 – 9 – 7 – 5 – D – 13 – 8 – 10 – 18 – 19 – 17 – D – 12 – 6 – 4 – 2 – 1/A.

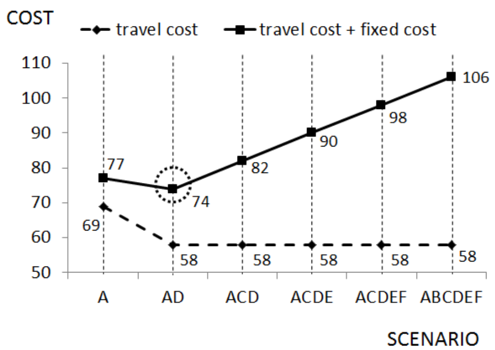

Fig. 4a. Solution for the best cost

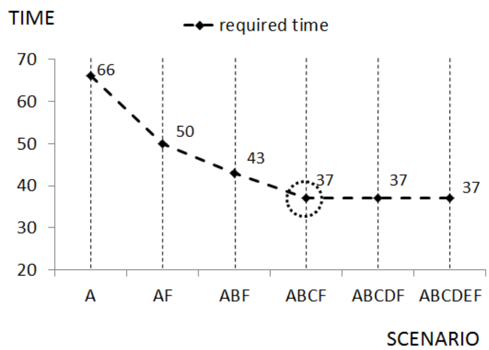

Fig. 4b. Solution for the best time

Similar to the previous figure, however Fig. 4b shows the best required time from the best combination scenario of intermediate depot establishment for each possible number. The next test instance is a modification of the earlier problem by operating multiple vehicles (i.e. k_1 and k_2) are also given in Pramudita, Taniguchi & Qureshi (2012). As mentioned earlier in multiple vehicles operation the objective function minimizes total travel time ($\sum tt$), therefore, F_k and G_h can still be ignored. As seen that the addition of a second intermediate depot until the fourth one affect the reduction of *tt* significantly (i.e. 66 → 50 → 43 → 37), however next become stagnant. Therefore, the optimum solution obtained when scenario ABCF is used, i.e. four intermediate depots established at node A ($qi \geq 15$ ton), B ($qi \geq 17$ ton), C ($qi \geq 7$ ton) and F ($qi \geq 9$ ton). The best total required time (*tt*) is 37 and with routes $k1$: 1/A – 2 – 4 – B – 5 – 7 – C – 9 – 15 – 16 – 14 – 1/A and $k2$: 1/A – 3 – 11 – 12 – 6 – B – 13 – 8 – 10 – 18 – F – 19 – 17 – 1/A.

4. Application on Tokyo Metropolitan Area Case Study

An estimation procedure was established by Hirayama, Shimaoka, Fujiwara, Okayama & Kawata, (2010) to assess the amount of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area. It was shown that the procedure of disaster debris estimation in disaster management and operation systems could be established for not only emergency response in the aftermath, it can also be used in pre-disaster planning. In that case study, the amount of debris from earthquake and catastrophic flood disasters in Tokyo Metropolitan Area was estimated according to the hazard maps.

In this section, the model formulation of the debris collection problem will be applied to solve the realistic case study which was assessed by Hirayama, Shimaoka, Fujiwara, Okayama & Kawata, (2010). Considering the large size of entire Tokyo Metropolitan Area, the model formulation will be tested in two spot locations only, representing eastern and western part of Tokyo.

4.1. Tokyo eastern area (location 1)

Location 1 is an area of 6,537,657 square meters in eastern part of Tokyo (139°48′0″E - 139°49′53″E and 35°40′45″N - 35°42′0″N). It consists of 22 roads which are also treated as the required arcs in our model formulation. After developing the graph transformation, the Location 1 area can also be treated as a L-CVRP graph. Now the transformed graph consists of 44 required nodes and 3 candidate locations of depots as well as intermediate depot (nodes A, B and C), as shown in Fig. 5.

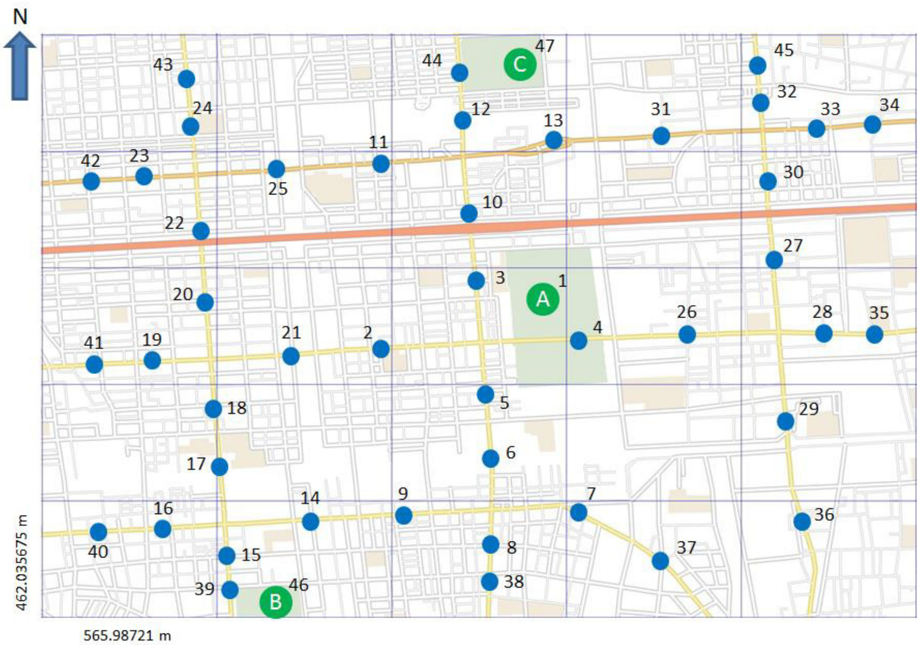

Fig. 5. Application of L-CVRP in Tokyo eastern area (location 1)

At this stage, the location of the depot and intermediate depots has not yet been decided. However, there exist three candidates of depot locations as well as intermediate depots, i.e. nodes A, B and C. The determination of these candidate locations considering that there are huge open spaces (*to be named*) close to the locations which could serve as vehicle parking areas and disposal sites. The road network in Location 1 is assumed as a simple network with respect to relatively small number of roads that exist. Therefore, only a single intermediate depot as well as a depot at the same location will be established (among nodes A, B or C); and then G_h could be ignored. After decided, node no.1 serves as depot, where vehicle starts and ends their tour; and the other nodes are debris collection points or the required nodes. Besides serving as depot, node no.1 is duplicated into the chosen node (among nodes A, B or C) which serves as an intermediate depot. There exist distances between nodes called as *tc*.

Based on the assessment of debris resulting from earthquake and flood disasters in Tokyo Metropolitan Area (Hirayama et al., 2010), the amount of debris information was obtained. It was spread over 5 by 5 grid areas or 25 grid areas of 261,506 square meters each. Since the data result is not detailed, therefore the amount of debris which is spread on every road in each grid area needs to be calculated. In this paper, such calculation was performed by dividing the road area by the grid areas, and then multiplying it by the sum of debris in corresponding grid area. In order to get data of the road area, the road lengths are measured from existing map of Tokyo. The road widths are assumed to be on average 3.25 m/lane and a total of 4 lanes were assumed for each road.

The objective function of this operation is opening the blockage at least cost with feasible routes as a result of feasible location of disposal sites; therefore the debris could be removed from the road to a near vacant space, such as near the road side. However in this case study, vehicles still need to load and transport some part of the debris to the disposal site due to the limited space and due to the assumption that some debris material cannot be left anyway in the public space. The assumption is that 50% of total amount of debris on the road needs to be loaded and transported to the disposal sites. It may be noted that the percentage figure (i.e. of 50%) is just an arbitrary assumption, since exact proportion may highly be dependent on specific site condition, the nature of debris and the urgency of the debris removal operation.

In this case study, because of lack of available data, another assumption is taken that all considered arcs are blocked due to the debris; or every arc is treated as a required arc; or the p_{ij}^k constraint is set to a maximum closed state. Therefore, as mentioned earlier in the test problem instances, p_{ij}^k sets that only adjacent arcs can be connected with each other, while for distant arcs it was assumed that there may be no way to connect them before removing the blocked access first.

In the real life situations, demands (i.e. the amount of debris to be removed) in some arcs could very possibly exceed the vehicle capacity, so was the case also in this Tokyo Metropolitan Area case study. Hence, in anticipating such situation, instead of a single vehicle some specified number of vehicles may be operated considering that they will work together in a group with the same route. Therefore, in this case study, it is assumed that there are eight standard dump truck vehicles involved in this debris collection operation with an individual capacity of 25 tons each. Furthermore, it is also assumed that those vehicles will be operated as one unit and thus will be treated as a single group of vehicles with unified capacity of 200 tons. In some cases, the number of vehicles could be reduced so that fixed vehicle cost may decrease. However as a consequence, the frequency of vehicles commuting to the disposal site to empty loads as well as travel cost will increase.

Even after assuming a reasonable size of a unit group of vehicles, still because of limited capacity, the group of vehicles may not necessarily be able to service a single arc completely without returning to intermediate depot to empty the load. This condition can give rise to additional costs, therefore, a fixed travel cost (tc') is also considered, besides *tc.* Here tc' is defined as the commuting cost of the group of vehicles from and to the nearest intermediate depot because of the limited capacity in servicing single required arc. If one wants to minimize the total travel time, tc' can also be changed into tt' (i.e. the total commuting travel time to and from an arc with a demand greater than the capacity of the group of vehicles), which will be referred as the fixed required time. The amount of the tc' can be calculated before the transformation from arcs into nodes using equation (17) & (18).

$$tc' = \sum_{(i,j)\in A_1} min\left(2c_{hj}\left\lfloor\frac{z(i,j)}{Q_k}\right\rfloor\right);\ h \in I \qquad (17)$$

$$z'(i,j) = z(i,j) - Q_k\left\lfloor\frac{z(i,j)}{Q_k}\right\rfloor;\ (i,j) \in A_1 \qquad (18)$$

By considering the tc', it is assumed that the original demands $(z(i,j), (i,j) \in A_1)$ can be reduced until the amount equal or less than the capacity of group of vehicles $(z'(i,j) \leq Q_k,\ (i,j) \in A_1)$. Therefore, the model formulation is optimized by considering that the remaining demands $(z'(i,j), (i,j) \in A_1)$ can be loaded by vehicle and then vehicle continues its tour to the other nodes without returning to intermediate depot if the capacity is still available. The amount of remaining debris exists at each node or the remaining demands are presented in Appendix A.

Similar to the test instance and due to the reasons discussed in earlier section (§3.2) the service cost (sc) is assumed to be zero here as well. Some fixed costs can be determined before running the optimization process i.e. total fixed vehicle cost (F_k) as well as total fixed travel cost (tc') which was calculated as 641.34 distance units. Subsequently, the total travel cost (tc) was calculated by applying the model formulation with the reduced demands; using tabu search, the best total travel cost (tc) obtained was 46.19 distance units with route as shown in Appendix B. Such optimum solution was obtained if the depot as well as the intermediate depot was established at node A.

4.2. Tokyo western area (location 2)

Location 2 is an area of 6,537,657 square meters in western part of Tokyo (139°40′52″E - 139°42′45″E and 35°40′45″N - 35°42′0″N). It has a more complicated road network structure than the eastern part, in terms of larger number of existing arcs i.e. 98 arcs. The location 2 area can also be treated as a graph. After developing the graph transformation, now the final transformed graph consists of 196 required nodes and 3 candidate locations for depots as well as intermediate depot (nodes A, B and C), as shown in Fig. 6. Determining these candidate locations involved assuming that there are a huge open space (*to be named*) close to these locations.

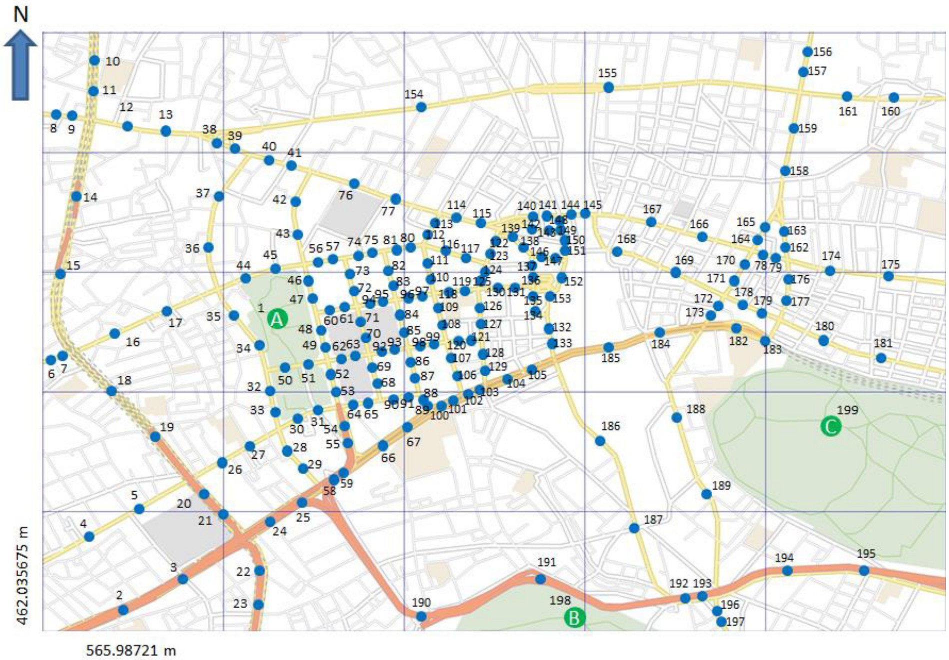

Fig. 6. Application of L-CVRP in Tokyo western area (location 2)

In case 1, only single intermediate depot as well as depot at the same location will be established (among nodes A, B or C); and then G_h could be ignored. After deciding node no.1 serves as depot, and it is duplicated into the chosen node (among nodes A, B or C) which serves as intermediate depot. Similar to the Location 1, the amount of remaining debris exist or the remaining demands in each node were calculated and are presented in Appendix C. In this case also, it is assumed that there are eight standard dump truck vehicles involved in this operation with an individual capacity of 25 tons each working as a single group of vehicles with unified capacity of 200 ton. The total fixed travel cost (tc') was calculated as 6.95 distance units before running the optimization process. Subsequently, total travel cost (tc) is calculated by applying the model formulation; using tabu search, the best total travel cost (tc) obtained was 74.51 distance units with route as shown in Appendix D. Such optimum solution was obtained if the depot as well as the intermediate depot established at node A.

Because of the complexity of road network structure in location 2 with respect to more roads existing, another strategy is evaluated in case 2, i.e. with establishing multi intermediate depots. The depot has been decided to be established at node A, as well as the first intermediate depot at the same location because of the efficiency reason according to the result from previous case. However there are still two candidates of intermediate depot locations at nodes B and C. The number of subsequent intermediate depots that should be established, the best location and the minimum capacity each in order to minimize cost of the debris collection operation are the objective function in this case. After completing the calculation process, the cost obtained of each possible combinations of intermediate depots establishment is shown in Fig. 7a. It can be seen that the best decision is to establish an intermediate depot is using scenario ABC i.e. at node A (qi≥6606.08 ton), B (qi≥766.74 ton) and C (qi≥2289.94 ton) at once, in order to obtain the cost optimum solution as 59.46 (tc'=55.48 and tc=3.98) and with routes as shown in Appendix E. However in such condition G_h is not considered yet or assumed G_h to be 0.

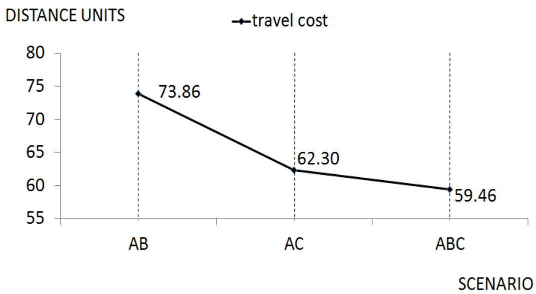

Fig. 7a. The scenario options without G_h

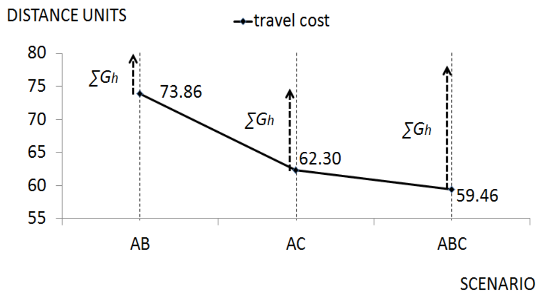

Fig. 7b. The scenario options with G_h

In the meantime, Fig. 7b shows condition G_h is considered due to there will be costs involved in setting up and closing a disposal site. Therefore, the optimum cost solution is not only determined by the travel cost, but also the costs to establish the disposal site, such as cost for leasing public or private land, clearing area, building infrastructure, etc. After the amount of G_h agreed upon, every additional number of intermediate depots should add G_h into the total cost. In this case, the scenario ABC still can be accepted if the total cost after added by G_h is still a minimum; or otherwise the scenario can be changed to respect the minimum cost.

In case 3, the problem is modified by considering multiple groups of vehicles operating. This means that all groups of vehicles may not move together as an unit, however it depends whether that group is involved in debris collection from a specific node with large enough demand. Therefore, in this operation, it is assumed that there are four groups of vehicles with capacity of 50 ton each and all may have varying routes. Since the capacity of vehicles is reduced, the remaining demands should be less than they were in the previous cases (cases 1 and 2) as in Appendix C.

As mentioned earlier, multiple vehicles operation has the objective function to find the best required time (tt). In order to deal with this kind of problem, the L-CVRP was optimized by considering the time of operation instead of travel distance. After completing the calculation process, the total fixed required time (tt') is 24.91 time units and the best total required time (*tt*) is 33.27 time units with route for each vehicle group shown in Appendix F. Such optimum solution was obtained if the depot was established at node A and the intermediate depot established at node A (qi≥6163.24 ton), B (qi≥483.06 ton) and C (qi≥3016.46 ton) at once.

5. Conclusion

The debris collection operation after a disaster is a new L-CARP problem that has not received much research attention yet. The uniqueness of this kind of L-CARP problem is due to the limited access from one section to the other, as a result of the blocked access by debris. Therefore a modification in the classical L-CARP is required to solve this kind of problem. It is performed by adding a new constraint, which is developed in this study as access possibility constraint. This constraint determines whether a vehicle can move from one node to another in a particular network, or not. Depending on the field conditions, p_{ij}^k constraint can be flexibly modified. In this case study, the p_{ij}^k was set to a maximum closed where only adjacent arcs can be connected with each other, while for distant arcs it was assumed that there may be no way to be connect them before removing the blocked access first. However, in real life problems as long as there exist other paths from node i to node j, vehicle k still can move from node i to node j even without traversing the blocked shortest path. Therefore, the setting of p_{ij}^k constraint can be modified and developed in accordance with the conditions of the problem in the field and the objective of the operation.

Routing is one of the most important aspects of finding a optimum cost solution in debris collection operation. In addition, it has been demonstrated in this study that the location of the disposal sites also greatly affects the cost. The calculation in finding the best solution has been done for all candidate locations of disposal sites related to the number, the location as well as the minimum capacity, as main part of this study. Hence the debris collection operation problem is solved by taking into account a combination of routing and location aspects would obtain a better solution than solving it from single aspect only.

In order to estimate the feasibility of the formulation and its solution algorithm, a practical case study of Tokyo Metropolitan Area was conducted. Dividing the area in Location 1 and Location 2 according to the complexity of the associated road network in terms of number of arcs, the problems in the case study were successfully solved. The optimized routes were improved significantly over the initial feasible solutions. It was shown that the problem formulation and the tabu search meta-heuristics algorithm can solve large scale, realistic and complicated instances with a reasonable computation time.

Based on both the test problem instances and the realistic case study of Tokyo Metropolitan Area tested in this research, it can be concluded that locating intermediate depots with good decisions relating to the number, the location, as well as the minimum capacity, greatly affects the total travel cost (*tc*) and total required time (*tt*).

Acknowledgements

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Appendix A.

1/A/B/C = 0; 2 = 81.1; 3 = 83.5; 4 = 21.1; 5 = 65.9; 6 = 65.9; 7 = 84.6; 8 = 1.8; 9 = 94.4; 10 = 83.5; 11 = 70.3; 12 = 49.2; 13 = 59.3; 14 = 94.4; 15 = 44.8; 16 = 91.6; 17 = 1.4; 18 = 1.4; 19 = 8.6; 20 = 99.6; 21 = 81.1; 22 = 99.6; 23 = 36.5; 24 = 79.2; 25 = 70.3; 26 = 21.1; 27 = 27.5; 28 = 44.6; 29 = 26.2; 30 = 27.5; 31 = 59.3; 32 = 98.5; 33 = 24.2; 34 = 24.2; 35 = 44.6; 36 = 26.2; 37 = 84.6; 38 = 1.8; 39 = 44.8; 40 = 91.6; 41 = 8.6; 42 = 36.5; 43 = 79.2; 44 = 49.2; 45 = 98.5 (Ton)

Appendix B.

1/A-3-10-A-2-21-19-41-18-17-A-4-26-29-36-27-30-33-34-A-5-6-8-38-A-7-37-A-9-14-A-11-25-A-12-44-23-42-

A-13-31-A-20-22-A-28-35-15-39-A-16-40-A-24-43-A-32-45-1/A

Appendix C.

1/A/B/C = 0; 2 = 23.7; 3 = 23.7; 4 = 30.7; 5 = 30.7; 6 = 11.3; 7 = 11.3; 8 = 18.4; 9 = 18.4; 10 =42.1; 11 =42.1; 12 =46; 13 =46; 14 =92.2; 15 = 92.2; 16 = 60.8; 17 = 60.8; 18 = 64.8; 19 = 64.8; 20 = 21.1; 21 = 21.1; 22 = 20.9; 23 = 20.9; 24 = 21; 25 = 21; 26 = 29.3; 27 = 29.3; 28 = 23.7; 29 = 23.7; 30 = 18.6; 31 =18.6; 32 = 22.1; 33 = 22.1; 34 = 41.5; 35 = 41.5; 36 = 55.2; 37 = 55.2; 38 = 21.7; 39 = 21.7; 40 = 23.6; 41 = 23.6; 42 = 46.3; 43 = 46.3; 44 = 35.7; 45 = 35.7; 46 = 22.9; 47 = 22.9; 48 = 21.6; 49 = 21.6; 50 = 23.7; 51 = 23.7; 52 = 20; 53 = 20; 54 = 21.4; 55 = 21.4; 56 = 15.5; 57 = 15.5; 58 = 10.1; 59 = 10.1; 60 = 15.4; 61 = 15.4; 62 = 16.3; 63 = 16.3; 64 = 11.3; 65 = 11.3; 66 = 31.3; 67 = 31.3; 68 = 19; 69 = 19; 70 = 23.4; 71 = 23.4; 72 = 22.7; 73 = 22.7; 74 = 14.6; 75 = 14.6; 76 = 40.9; 77 = 40.9; 78 = 9.4; 79 = 9.4; 80 =12.3; 81 = 12.3; 82 = 21.7; 83 = 21.7; 84 = 22.8; 85 = 22.8; 86 = 14.5; 87 = 14.5; 88 = 9.4; 89 = 9.4; 90 =11.9; 91 = 11.9; 92 = 15.1; 93 = 15.1; 94 = 14.6; 95 = 14.6; 96 = 12.3; 97 = 12.3; 98 = 9.7; 99 = 9.7; 100 =11.8; 101 = 11.8; 102 = 7.3; 103 = 7.3; 104 = 19.6; 105 = 19.6; 106 = 17.2; 107 = 17.2; 108 = 14.9; 109 = 14.9; 110 = 13.8; 111 = 13.8; 112 = 8.7; 113 = 8.7; 114 = 12.9; 115 = 12.9; 116 = 13.8; 117 = 13.8; 118 = 10.8; 119 = 10.8; 120 = 8.1; 121 = 8.1; 122 = 8.7; 123 = 8.7; 124 = 6.8; 125 = 6.8; 126 = 15.7; 127 = 15.7; 128 = 14.7; 129 = 14.7; 130 = 12.9; 131 = 12.9; 132 = 14.9; 133 = 14.9; 134 = 11.1; 135 = 11.1; 136 = 7.5; 137 = 7.5; 138 = 10.7; 139 = 10.7; 140 = 12.6; 141 = 12.6; 142 = 9.3; 143 = 9.3; 144 = 7.8; 145 = 7.8; 146 = 6.8; 147 = 6.8; 148 = 5.1; 149 = 5.1; 150 = 6.9; 151 = 6.9; 152 = 18.8; 153 = 18.8; 154 = 19.5; 155 = 19.5; 156 = 16; 157 = 16; 158=38; 159=38; 160=31.1;161=31.1; 162=23.1; 163=23.1; 164=17.7; 165=17.7; 166 =43.6; 167 = 43.6; 168 = 41.1; 169 = 41.1; 170 = 15.5; 171 = 15.5; 172 = 8.8; 173 = 8.8; 174 = 53.7; 175 = 53.7; 176 = 24.7; 177 = 24.7; 178 = 15.9; 179 = 15.9; 180 = 56.6; 181 = 56.6; 182 = 19.1; 183 = 19.1; 184 = 34.9; 185 = 34.9; 186 = 77.7; 187 = 77.7; 188 = 67.5; 189 = 67.5; 190 = 94.3; 191 = 94.3; 192 = 6.3; 193 = 6.3; 194 = 39.6; 195 = 39.6; 196 = 7.3; 197 = 7.3 (Ton)

Appendix D.

1/A-62-63-69-68-65-64-31-30-27-26-A-49-48-47-46-43-42-A-51-50-32-33-28-29-58-59-53-52-A-70-71-61-60-72-73-57-56-74-75-A-92-93-85-84-83-82-81-80-111-110-97-96-A-54-55-66-67-89-88-100-101-102-103-129-128-A-34-35-36-37-A-86-87-91-90-98-99-107-106-104-105-121-120-108-109-A-94-95-118-119-125-124-117-116-112-113-77-76-A-45-44-17-16-A-127-126-130-131-135-134-132-133-153-152-147-146-137-136-138-139-A-25-24-3-2-21-20-5-4-A-190-191-A-19-18-7-6-22-23-A-41-40-39-38-13-12-151-150-A-123-122-115-114-140-141-144-145-167-166-78-79-A-142-143-149-148-168-169-171-170-164-165-172-173-A-185-184-182-183-177-176-179-178-A-186-187-192-193-196-197-A-15-14-A-154-155-157-156-159-158-163-162-A-188-189-161-160-A-9-8-11-10-A-180-181-194-195-A-174-175-1/A

Appendix E.

1/A-62-63-69-68-65-64-31-30-27-26-A-49-48-47-46-43-42-A-52-53-54-55-59-58-29-28-33-32-A-51-50-34-35-56-57-74-75-A-70-71-61-60-72-73-81-80-111-110-97-96-A-92-93-98-99-107-106-101-100-67-66-89-88-A-85-84-83-82-112-113-77-76-A-86-87-91-90-102-103-104-105-185-184-173-172-C-177-176-79-78-164-165-158-159-120-121-A-94-95-109-108-127-126-119-118-125-124-117-116-114-115-122-123-A-45-44-17-16-A-128-129-186-187-192-193-B-191-190-A-25-24-22-23-3-2-21-20-7-6-A-36-37-39-38-154-155-C-179-178-169-168-145-144-141-140-139-138-137-136-A-130-131-135-134-132-133-153-152-147-146-151-150-143-142-149-148-196-197-B-189-188-182-183-C-180-181-171-170-162-163-C-174-175-166-167-C-157-156-161-160-13-12-A-5-4-19-18-A-41-40-9-8-11-10-A-15-14-A-194-195-1/A

Appendix F.

Group_1 = 1/A-52-53-A-69-68-A-60-61-120-121-A-34-35-36-37-A-43-42-A-107-106-102-103-A-96-97-118-119-

A-190-191-187-186-C-179-178-172-173-C-183-182-174-175-C-162-163-C-164-165-150-151-C-158-159-161-160-C-155-154-A-132-133-A-13-12-1/A

Group_2 = 1/A-49-48-A-70-71-A-31-30-27-26-A-85-84-A-94-95-67-66-A-108-109-59-58-A-127-126-125-124-A-110-111-112-113-A-19-18-142-143-C-177-176-C-79-78-184-185-149-148-C-166-167-C-141-140-146-147-C-157-156-C-152-153-A-9-8-1/A

Group_3 = 1/A-51-50-A-92-93-98-99-A-64-65-90-91-A-72-73-A-45-44-17-16-A-28-29-A-128-129-A-100-101-130-131-A-104-105-C-180-181-169-168-C-171-170-145-144-C-188-189-193-192-B-194-195-196-197-B-22-23-A-39-38-A-15-14-1/A

Group_4 = 1/A-62-63-A-47-46-A-54-55-A-32-33-A-86-87-88-89-A-56-57-5-4-A-83-82-A-74-75-A-25-24-A-81-80-123-122-A-20-21-A-116-117-139-138-A-41-40-A-76-77-137-136-A-3-2-A-135-134-115-114-A-7-6-A-11-10-1/A

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