CARGO LAYOUT OPTIMIZATION IN SPACECRAFT: EXPLORING HEURISTICS FOR BRANCH-AND-BOUND METHOD

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ABSTRACT

This paper focuses on *cargo layout optimization* in a spacecraft such an H-IIA Transfer Vehicle (HTV), an Automated Transfer Vehicle (ATV), and a Multi-Purpose Logistics Module (MPLM), and proposes its optimization method by exploring the branch-and-bound method. Concretely, a heuristic relaxation for the branch-and-bound method is proposed to minimize the gap between the CG of a spacecraft and its actual center. To investigate the effectiveness of the proposed relaxation, intensive simulations were conducted and the following implications were found: (1) the proposed heuristic relaxation, based on both objective function relaxation and cargo placement relaxation, finds an optimal solution with the shortest calculation time, and it creates the mostly smallest number of nodes in comparison with the full-search method and two other branch-and-bound methods based on linear and quadratic programming problems; and (2) the proposed objective function relaxation contributes to not only heuristic relaxation but also to LP relaxation in terms of improving both calculation time and the number of nodes.

Keywords: cargo layout optimization, operations research, branch-and-bound method, relaxed problem

1 INTRODUCTION

For a spacecraft such an H-IIA Transfer Vehicle (HTV), a Automated Transfer Vehicle (ATV), and a Multi-Purpose Logistics Module (MPLM), *cargo layout optimization* is the important problem of placing all cargos to satisfy several strict conditions. When focusing on the center of gravity (CG) of a spacecraft, for example, the CG should be as close to the actual center of the spacecraft as possible due to the fact that such placement of cargos is critical for its orbit and amount of fuel. However, this problem has the following two difficulties that derive *combinatorial explosion* when optimizing solutions by conventional operations research methods: (1) *non-linear objective functions* (*i.e.*, quadratic expression is required to express the distance between the CG of a spacecraft and its actual center); and (2) *discrete constraints* (*i.e.*, cargos of different size should be placed in discrete locations).

To tackle these difficulties, this paper focuses on the *branch-and-bound method* [7] as a combinatorial optimization [12] and explores its *heuristic relaxation* to minimize the gap between the CG of a spacecraft and its actual center. Although other methods like *meta-heuristics methods* [11] – such as genetic algorithms (GA) [6] or simulated annealing (SA) [1] – can be employed, we focus on the branch-and-bound method because this method can find an optimal solution (*i.e.*, a minimization of the CG gap) that contributes to reducing the amount of fuel needed for a spacecraft.

However, the precision of the lower bound is critical for the branch-and-bound method and such precision depends heavily on the addressed problem. Therefore, in this paper, we aim to propose heuristic relaxation for the branch-and-bound method that calculates good precision of the lower bound and investigate its capability and applicability to solve cargo layout problems for real missions.

This paper is organized as follows. The next section starts by briefly introducing a cargo layout problem and its problem class from the viewpoint of optimization. Section 3 proposes heuristic relaxation for the branch-and-bound method. Section 4 presents our simulation results and Section 5 discusses the re-

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lationship between our proposed approach and other proposed approaches. Finally, our conclusions are presented in Section 6.

2 CARGO LAYOUT PROBLEM and ITS PROBLEM CLASS

2.1 Cargo Layout Problem

The cargo layout problem for a spacecraft is a combinatorial optimization problem that requires placements of all cargos in a designated area (*e.g.*, a pressurized logistics carrier in HTV) in order to minimize the gap between the CG of a spacecraft and its target location. Based on such characteristics, an objective function in this problem is represented by min $\|x-t\|$, where x and t indicate the CG of a spacecraft and the target location, respectively. This equation indicates that the problem has a *non-linear objective function*. Furthermore, a placement of cargos is discretely divided and all cargos should be placed without an overlap each other. This indicates that this problem has a *discrete constraint*.

Fig. 1 indicates one rack-bay that consists of four racks in a spacecraft, each of which consists of several types of cargo. Note that one rack is presented by three dotted line rectangles that indicate the partitioned placement of cargos. As the figure illustrates, the CG of a spacecraft (pink circle) should be made close to its actual center (blue circle) by chaining placements of several cargos (*e.g.*, yellow, blue, green, and red cargos) in discrete places to minimize the above non-linear objective function.

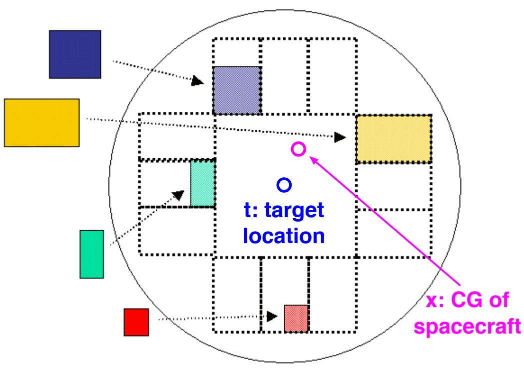


Fig. 1: **Cargo Placement Problem**

What is important here is that this case represents a simple situation but it is mostly *common* in HTV, ATV, and MPLM. For example, HTV has two rack-bays located in the pressurized logistics carrier; four HTV Resupply Racks (HRRs) are located in one rack-bay; and six types of Cargo Transfer Bags (CTBs) corresponding to cargos are placed in HRRs. These cargos should be placed so as not to make the center of gravity of the HTV exceed 25 *mm* from its actual center. This is a difficult constraint to meet in HTV.

2.2 Problem Class

Fig. 2 shows a problem class for optimization. The vertical and horizontal axes indicate an objective function and a constraint, respectively. In particular, the former axis is divided into linear and non-linear objective functions, while the latter one is divided into continuous and discrete constraints. Concretely, continuous constraints in this figure means continuous with linear constraints.

In this figure, (1) the linear programming (LP) problem is categorized as the class that has a *linear* objective function and *continuous* constraint; (2) the quadratic programming (QP) problem is categorized as the class that has a *non-linear* objective function and *continuous* constraint; (3) the combinatorial optimization problem I, like the knapsack problem, is categorized as the class that has a *linear* objective function and *discrete* constraint; and (4) the combinatorial optimization problem II, like the traveling salesman problem, is categorized as the class that has a *non-linear* objective function and *discrete* constraint. The problems in classes (1) and (2) can be solved by simplex or interior-point methods, and interior-point or sequential quadratic programming methods, respectively. The problems in classes (3) and (4), on the other hand, can be solved by the branch-and-bound, branch-and-cut, or metaheuristics methods.

From this categorization, the cargo layout problem addressed in this paper corresponds to class (4).

3 RELAXATION FOR BRANCH-AND-BOUND METHOD

3.1 Relaxation

To tackle the cargo layout problem categorized in class (4) of Fig. 2, we propose or employ the following three types of *relaxation* shown in Fig. 3.

(1) **Objective function relaxation:** The following three relaxation methods are proposed.

- *Method A:* Linear relaxation by ignoring the second term of the distance between the CG of the spacecraft and the target location.

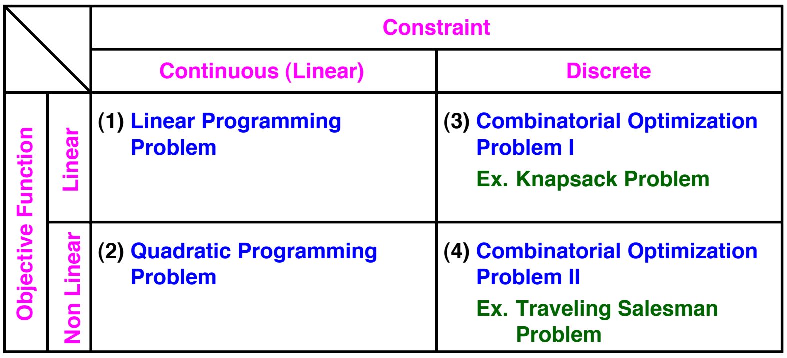


Fig. 2: **Problem Class**

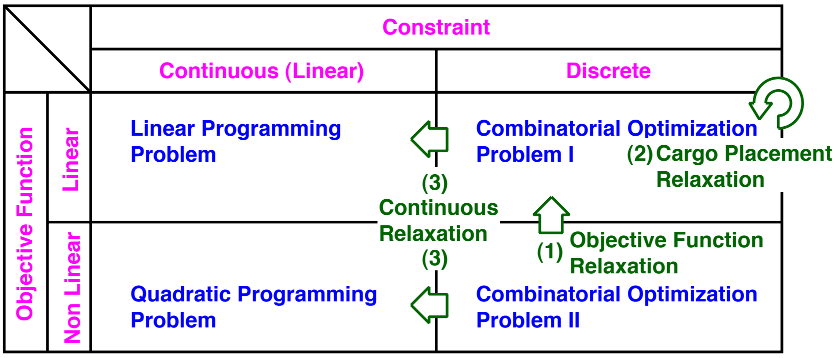


Fig. 3: **Problem Relaxation**

- *Method B:* Linear relaxation by employing the projection direction of the opposite CG vector (red line) instead of the distance between the CG of a spacecraft and the target location. The red line is created by the placed cargos, as shown in Fig. 4 (i).
- *Method C:* Linear relaxation by employing the projection direction of the opposite modified CG vector (blue line) instead of the distance between the CG of a spacecraft and the target location. The blue line is created by both placed cargos and not-yet-placed cargos (light green boxes) that have the same weight (*i.e.*, the average weight of all not-yet-placed cargos), as shown in Fig. 4 (ii).

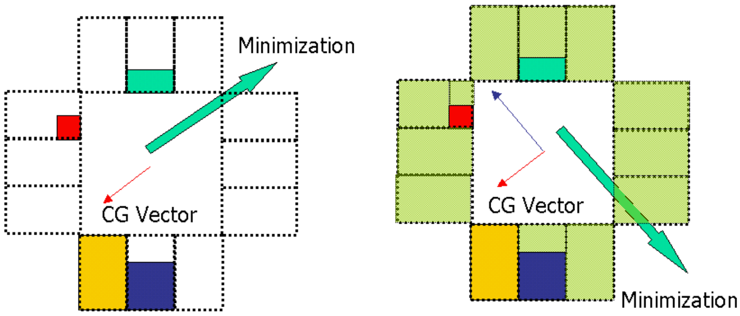
(2) **Cargo placement relaxation:** As shown in Fig. 5, the proposed method relaxes (i) the cargo size by dividing cargos into the minimum size (*i.e.*, the half-size cargo), and then (ii) relaxes the constraint of maintaining the original shape of cargos. Note that the weight of cargos is divided equally and divided cargos are placed from the heavy one to the light one by minimizing the CG gap. This relaxation contributes to avoiding many tests on a huge combination of placements of cargos of many sizes.

(3) **Continuous relaxation:** Just relax discrete constraints to continuous ones.

3.2 Approach to the cargo layout problem

Using the above three types of relaxation, this paper tackles the cargo layout problem by calculating the lower bound for the branch-and-bound method as follows.

- *Relaxation to combinatorial optimization problem I*: The lower bound is calculated by solving the combinatorial optimization problem I, applying both an objective function relaxation (method A, B or C) and cargo placement relaxation. We call this *heuristic relaxation* because two types of relaxation are used.
- *Relaxation to linear programming problem:* The lower bound is calculated by solving the



(i) Method B (ii) Method C

Fig. 4: **Methods B and C**

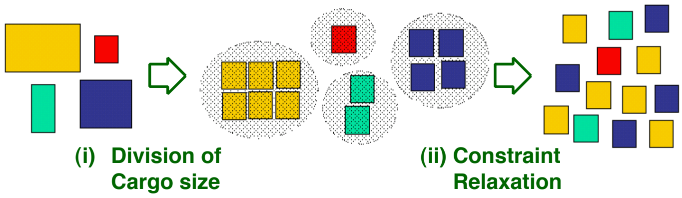


Fig. 5: **Cargo Placement Relaxation**

linear programming problem, applying both an objective function relaxation (method A, B or C) and continuous relaxation. We call this *LP relaxation*.

- *Relaxation to quadratic programming problem:* The lower bound is calculated by solving the quadratic programming problem, applying continuous relaxation. We call this *QP relaxation*.

4 SIMULATION

4.1 Simulation design

The following three simulations were conducted as a comparative study.

- **Simulation 1:** Comparison of the full search method and the branch–and–bound methods employing either of the three types of relaxation described in Section 3.2. Note that method A is used for an objective function relaxation in both heuristic relaxation and LP relaxation.
  - *Full search*
  - *Heuristic Relaxation:* Relaxation-to-combinatorial optimization problem I
  - *LP Relaxation:* Relaxation-to-linear programming problem
  - *QP Relaxation:* Relaxation-to-quadratic programming problem

  As LP and QP relaxation, specifically, their problems in our simulations are solved by using GLPK [8] and BMPDM [9] packages, respectively.

- **Simulation 2:** Comparison of heuristic relaxation employing either of the three types of objective function relaxation, *i.e.*, methods A, B, and C described in Section 3.1.

- **Simulation 3:** Comparison of the same four methods mentioned in simulation 1, *i.e.*, the full-search method and the branch-and-bound methods with the three types of relaxation. Note that method C is used instead of method A in this simulation.

4.2 Simulation setting

To investigate the effectiveness of the proposed heuristic relaxation for the branch-and-bound method, we conduct intensive simulations of a case of closely resembling real missions. Concretely, we

Tab. 2: Simulation Case

Case	Cargo Type				Number of Feasible Solutions
	Single	Half	Double	Triple	
A	3	0	0	0	18
B	3	0	0	2	108
C	0	6	0	1	1,440
D	2	4	1	1	10,368
E	4	0	1	4	103,680
F	4	4	0	2	1,126,656

Tab. 1: Cargo Size and Average Weight

Type	Size (mm)	Average Weight (kg)
Single	425×502×248	18.6
Half	425×248×235	7.14
Double	425×502×502	29.6
Triple	425×749×502	32.1

employ the case shown in Fig. 1 that has one rack-bay consisting of four racks, each of which consists of several types of cargo.

There are four types of cargo, *i.e.*, half-, single-, double-, and triple-size cargo, and each actual size and average weight is set as shown in Tab. 1 which is based on real HTV missions [14]. In accordance with a real HTV mission, the size of each dotted line rectangle shown in Fig. 1 corresponds to one triple-size cargo (*i.e.*, the size of one rack corresponds to three triple-size cargos).

The simulations deal with the six cases, from A to F as shown in Fig. 2. In case A, for example, the quantity of single-, half-, double-, and triple-size of cargos is 3, 0, 0, and 0, respectively, and the number of feasible solutions is 18. The complexity of the cases increases from A to F by setting the number of feasible solutions by moving a figure one place to the left. Note that the weights of all cargos differ but are assumed to be uniform (*i.e.*, the CG of each cargo is at its actual center). The same weight value is used for all six cases.

All simulations in this paper were conducted on a Windows XP computer with a Pentium 4, 2.4 GHz processor and 512 MB of memory.

4.3 Evaluation Criteria

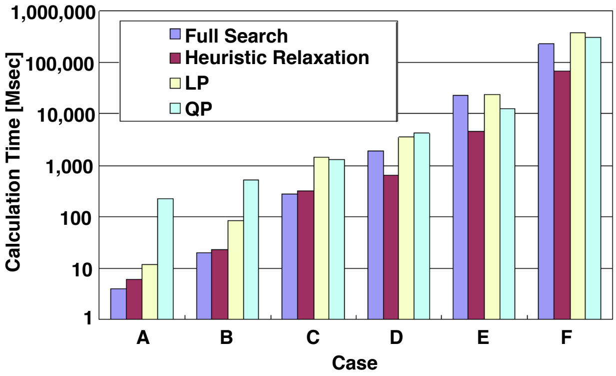
In each simulation, the following two evaluation criteria are investigated. Specifically, the former criterion is calculated in the unit of milliseconds. Note that all simulations are conducted until an optimal solution is found, and their results show average values over ten runs.

- Calculation time
- Number of nodes created in the branch-and-bound method

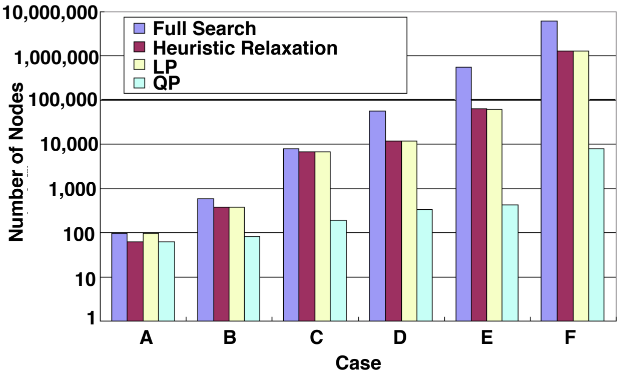
4.4 Simulation results

Figs. 6, 7, and 8 show results of simulations 1, 2, and 3, respectively. The vertical axes on the left and right figures respectively indicate (a) calculation time, and (b) the number of nodes, while the horizontal axis indicates the six cases. In particular, the blue, red, yellow, and skyblue boxes in simulations 1 and 3 respectively represent the results of a full-search, heuristic relaxation, LP relaxation, and QP relaxation. The red, skyblue, and orange boxes in the simulation 2 respectively represent the results of methods A, B, and C. From the simulation results, the following implications have been revealed:

1. From simulation 1, heuristic relaxation using method A finds an optimal solution with the shortest calculation time as the complexity of cases increases, but it creates a lot of nodes, just like LP relaxation.
2. From simulation 2, heuristic relaxation using method C finds an optimal solution in the shortest calculation time and creates the smallest number of nodes in comparison with methods A and B.
3. From simulation 3, heuristic relaxation using method C finds an optimal solution with the shortest calculation time as the complexity of cases increases, and it creates smaller number of nodes than those in the full-search and LP relaxation. Furthermore, method C contributes to not only heuristic relaxation but also LP relaxation in terms of improving both calculation time and number of nodes.

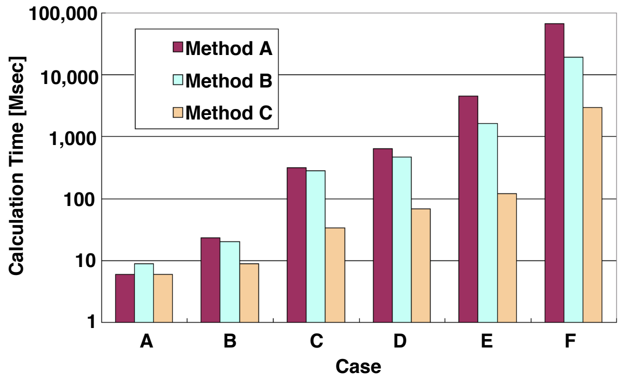


(a) Execution Time [Msec]

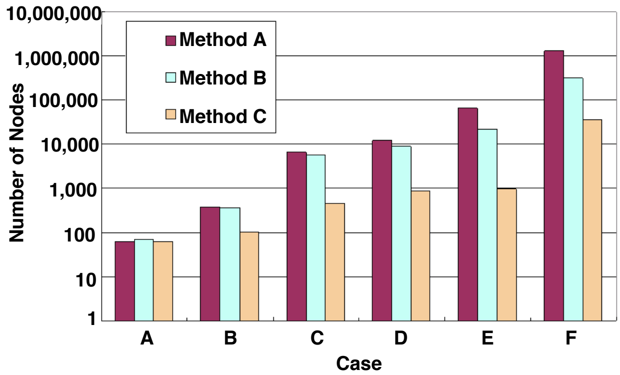


(b) Number of Nodes

Fig. 6: **Simulation Result (Simulation 1)**

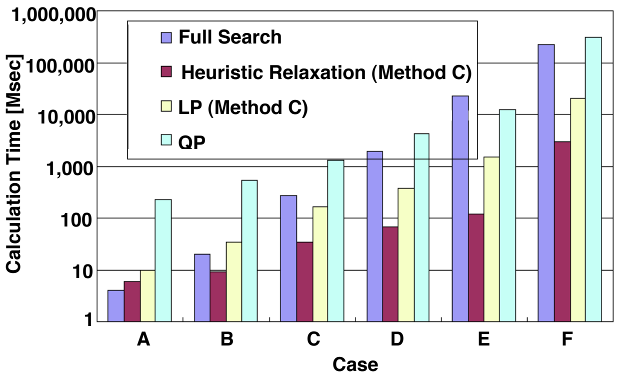


(a) Execution Time [Msec]

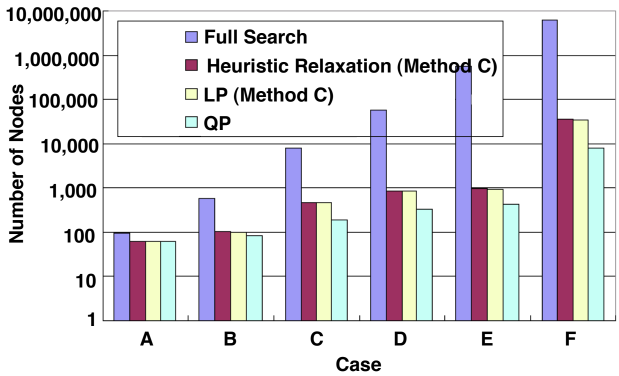


(b) Number of Nodes

Fig. 7: **Simulation Result (Simulation 2)**



(a) Execution Time [Msec]



(b) Number of Nodes

Fig. 8: **Simulation Result (Simulation 3)**

Here, focusing on the result of simulation 3 where the number of nodes in QP is the smallest, a hybrid brand-and-bound method may be useful that calculates the lower bound by heuristic relaxation using method C if the branch can be cut according to the calculated lower band, otherwise calculates the lower bound by QP relaxation.

5 DISCUSSION

5.1 Integration to multiagent approach

Our previous research proposed a cargo layout system for the HTV, which has a novel architecture that employs the concept of a *multiagent systems* [15] to determine appropriate placement of all cargos. This system has the advantage that it can find a good feasible solution (*i.e.*, where the gap between the CG of a spacecraft and its target location is less than 25 *mm*) within one second [13, 14]. The point of this approach is that it does not guarantee an optimal solution, but it is powerful for finding a quasi-optimal solution very quickly. In contrast, a operations research approach like our brand-and-bound method guarantees an optimal solution, but it generally requires a lot of calculation time in comparison with the meta-heuristic approach. This fact indicates that the multiagent approach and operations research approach have different advantages and defects, but both approaches have the potential of being able to compensate for each other's defects by their integration as follows: (1) a quasi-optimal solution can be found by the multiagent approach; and then (2) the quasi-optimal solution is used for an initial date (*i.e.*, the starting search point) for our brand-and-bound method with heuristic relaxation.

5.2 Other optimization approaches

Bussolino, Fasano, and Novelli proposed a cargo layout system for the ATV that employs the *MIP (Mixed Integer Programming)* approach [10] as an operations research approach [1] to maximize the total number of high-priority cargos [2, 4, 5]. The difference between the cargo layout problem addressed in this paper and that in the ATV one is that the former has a non-linear objective function while the latter has a linear one. From another viewpoint, HTV employs a minimization of the gap between the CG of a spacecraft and its actual center as the target of optimization, while AVE employs it as a constraint. The choice between HTV-type optimization and ATV-type optimization depends on how critical the CG of a spacecraft is for its orbit and amount of fuel.

[1] Other research employing operations research in space is found in [3].

6 CONCLUSION

This paper addressed *cargo layout optimization* in a spacecraft such an HTV, ATV, and MPLM, and proposed its optimization method by exploring the branch-and-bound method. Concretely, a heuristic relaxation for the branch–and–bound method was proposed to minimize the gap between the CG of a spacecraft and its actual center. To investigate the effectiveness of the proposed relaxation, intensive simulations were conducted and the following implications were reveled: (1) heuristic relaxation using method C finds an optimal solution with the shortest calculation time as the complexity of cases increases, and it creates the mostly smallest number of nodes in comparison with the full-search method and two other branch–and–bound methods based on linear and quadratic programming problems; (2) method C contributes to not only heuristic relaxation but also to LP relaxation in terms of improving both calculation time and the number of nodes.

However, these results have only been obtained from comparisons using one full-search method and three types of relaxation (*i.e.*, heuristic, LP, and QP relaxation) and from one example (*i.e.*, the simple case of the cargo layout problem for HTV). Therefore, further careful qualifications and justifications, such as experiments using other types of relaxation or more concrete examples are needed to generalize our results. Such important directions must be pursued in the near future in addition to the following future directions: (1) exploration of a hybrid brand-and-bound method that combines our heuristic relaxation with QP relaxation; (2) integration of the brand-and-bound method and the multiagent approach to find an optimal solution quickly; and and (3) investigation of the case where the weight of cargo is not uniform.

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