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Multiple Straddle Carrier Routing Problem.

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ABSTRACT

This paper discusses how to route straddle carriers during the loading operation of export containers in port container terminals. The objective of the routing is to minimize the total travel distance of straddle carriers in the quay side. A Genetic Algorithm heuristic is developed for the routing problem, and a numerical experimentation is carried out in order to evaluate the performance of the algorithm.

1. Introduction

Within container terminal different types of material handling equipment are used to transship containers from ships to storage yard, trucks and trains and vice versa. Over the past decades, ships have strongly increased in size, up to 8000 TEU (Twenty feet equivalent unit container). In order to use these big ships efficiently, the docking time at the port must be as small as possible. This means that large amounts of containers have to be loaded, unloaded and transshipped in a short time span, with a minimum use of expensive equipment.

A handling system for the retrieval and transport of containers are straddle carriers (SCs). SCs are used for the retrieval of containers from the stack and for the transport to the quay cranes. This paper gives a planning to efficiently route the SCs inside a container terminal for loading operations.

1.1. Contribution of the Paper

One of the success factors of a terminal is related to the time in port for container vessels and the transshipment rates the ship operators have to pay. We focus on the process of container transport by straddle carriers between the container ship and the storage yard. The primary objective is the reduction of the time in port for the vessels by maximizing the productivity of the Quay cranes, or in other words, minimizing the delay times of container transports that causes the Quay cranes to stop. We investigate dispatching strategy for straddle carriers to containers and show the potential of genetic algorithm to develop the solution.

1.2. Organization of the Paper

The remainder of the paper is organized as follows: section 2 is devoted to preliminaries. In section 3, we present the related works that solve the MSCRP. Next sections will be reserved to detail our methodology; our contribution, the problem formulation. The following section will be reserved to present the Genetic Algorithm, its process and its operators. Section 10 will represent our solution procedure to solve the MSCRP using GA. Finally our paper will be finished by a numerical example in order to prove the efficiency of our method. Some concluding remarks and perspectives to extend this work are finally discussed.

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2. Preliminaries

Container terminals are very specific from a material handling point of view, because of the special characteristics of both the containers and the handling equipment.

Terminals have become increasingly important and more and more scientific literature is devoted to them. This is even truer for the automated terminals which are being established to manage with the increase in costs. The additional increase in ship sizes makes productivity perfection in container handling more important and therefore more research is to be expected. In this paper, we have discussed the related routing problems within container handling.

Operations Research has made important contributions for container terminals. The techniques employed vary from Mixed Integer Programming formulations, queuing models and simulation approaches.

In this paper we analyzed the routing problem of SCs to support tasks between quay cranes and yard areas. Since inbound containers are usually unloaded into a designated open space, the Straddle Carriers do not have to travel much during the unloading operation. However, the time for loading depends on the loading sequence of containers as well as the number of loaded containers. In this paper we focus on minimizing the travel time of the Straddle Carriers for loading outbound (export) containers.

We formulated a nonlinear integer programming model for multiple SCs working with one quay crane. Based on certain operational concepts, a heuristic genetic algorithm is designed to solve this problem. We exploited the algorithm to analyze some real cases. Our study can provide companies not only the routing plan of SCs and the estimated period of tasks finished but also the required number of deployed SCs.

3. Related Works

Little research has been done on this topic although the practical importance of this problem. **In 1993, Dirk Steenken et al.** adopted two models to solve the MSCRP. In the first model they reduce the problem to a simple TSP with assumptions that one SC is engaged. They use the balance and connect heuristic applied to solve the sequencing insertions in printed circuit board assemblies, referencing to Ball and Magazine (1988), various heuristics were investigated to solve this problem like the nearest neighbour heuristic (NN), the successive or cheapest insertion (SUC) and a 2-optimal exchange method (2OP), best results was found using the SUC method.

The expansion of this problem to multiple one is achieved by introducing fictitious vehicle depots and by using an assumption that two jobs should not succeed each other within the same tour if there is a great difference in their due dates. They also reported that they have added another procedure to their initial solution and a new term not explained.

The second model is developed using an analogy to machine scheduling (MAS) mentioned by Maas and Vob (1991). This model is based on some dispatching rules to select insertion positions.

In 2003, V. Franqueira presents a discussion about the multiple straddle carrier routing problem. Two constraints of this routing problem are discussed; the conflicts between SCs must be resolved; and container stock in the storage yard must be shared between all SCs.

The first constraint is divided into two types; a travel conflict exists when SC tries to cross another SC and a space conflict when a SC tries to move the same location where another SC is already placed.

The resolution of these types of conflict between SCs is presented by **Ki Young Kim in 1998** for the travel conflict of two SCs. He proposes two strategies; the waiting strategy and the exchanging roles between SC's strategy. For the space conflict he uses a waiting strategy and a substitutive one.

The routing problem of multiple SCs (more than two) was also presented by K. Y. Kim with considering that containers are located in one or multiple blocks according to the assumptions that a pseudo work schedule would be constructed by appending the work schedules of all SCs, and there is no interference between equipments. Therefore the multiple routing is reduced to a single routing one. By solving the single SC problem for the pseudo work schedule would theoretically solve the overall problem.

However V. Franqueira suggest that these assumptions turn the problem completely artificial, since each SC route will have to be selected manually from the output and each SC routing will have to occur in sequence and never in parallel.

V. Franqueira present a solution to some multiple routing problem, using the single SC routing procedure, by providing (through manual work) the container distribution table for each SC separately. However, this procedure seems inappropriate since the potential parallelism of multiple SCs is ignored.

The paper presents by **L.N. Spasovic et al. in 1999** results of a research designed to evaluate the potential for improving productivity and the quality of service for a straddle carrier operation. A methodology was developed to quantify possible savings from redesigning the straddle operation. The main effort was to develop and evaluate a series of algorithms for straddle assignment and control. The algorithms differ in a manner in which the straddles are given assignments to move containers. Their research focused only on trucks. The productivity of the whole group of straddles is not analyzed. This should include the straddles servicing on-dock rail, the cranes during ship loading and unloading as well as re-warehousing of containers in the yard.

E. Nishimura et al. in 2005 presents in their paper a Genetic Algorithm heuristic to solve the trailer routing problem using a dynamic routing assignment method. They focus on the tours related to one cycle operation of the quay cranes. Experimental results demonstrate that the dynamic assignment is better than static one. The drawback to their solution procedure is the complexity of the trailer routing, which may increase the possibility of human error. Trailer drives may find difficult to follow the complicated itineraries assigned to them, resulting in mistakes in driving.

4. Problem Formulation

The following notations are used in our model to formulate the SC routing problem:
ts_i: The time spent by the SC inside the yard-bay j
$y^t_{ij} = 1$ if a SC moves from yard-bay i to yard-bay j in subtour t, 0 otherwise
$z^t_{ij} = 1$, if a SC moves from yard-bay i to yard-bay j during partial-tour t,0, otherwise
n: the number of yard-bays,
l: the number of container groups,
B: the set of indexes of yard-bays, 1, 2 ... n
$B(h)$: The set of the yard-bay numbers which contain containers of group h,
r_t: the number of containers which should be picked up in subtour t.
$c_h j$: The initial number of containers of group h stacked at yard-bay j,
d_{ij} : The travel distance between yard-bay i and j.
x^t_j = the number of containers picked up at yard-bay j in subtour t (a decision variable)

The problem can be formulated as

$$\min \sum_{t=0}^{m} \sum_{(i,j)\in B(h)} (Td_{ij} + ts_j)y^t_{ij} + \sum_{t=1}^{m} \sum_{(i,j)\in B(h)} (Td_{ij} + ts_j)z^t_{ij} \quad (1)$$

subject to

$$\sum_{j,k\in B(h)} \left(y^{t-1}_{ji} + z^t_{ki}\right) - \sum_{j,k\in B(h)} \left(y^t_{ij} + z^t_{ik}\right) = 0 \; i \in B(h), t = 1, 2, ..., m \quad (2)$$

$$x^t_j \le M\left(\sum_{k\in B(h)} z^t_{kj} + \sum_{i\in B(h)} y^{t-1}_{ij}\right) \quad j \in B(h), t = 1, 2, ..., m \quad (3)$$

$$\sum_{j\in B(h)} x^t_j = r_t \quad (4)$$

$$x^t_j - c_{hj} = 0 \quad j \in B(h), h = 1, ..., l \quad (5)$$

$$y^t_{ij} \in \{0, 1\} \quad i, j \in B(h) \quad (6)$$

$$z^t_{ij} \in \{0, 1\} \quad i, j \in B(h), t = 1, 2, ..., m \quad (7)$$

$$x^t_j \ge 0 \quad j \in B(h), t = 1, 2, ..., m \quad (8)$$

(1) Minimize the total travel time of a SC inter/intra yard-bays

(2) Flow conservation

(3) These constraints imply that only when a SC visits a yard-bay can it pick up containers at the yard-bay.

(4) The number of containers picked up should be equal to the number requested by the work schedule

(5) No containers will be left behind, i.e. containers stocked at yard bays will all be picked up.

5. Problem Complexity

Similar problem to the SCRP is Traveling Salesman Problem (TSP). We know that TSP is a NP-complete problem. If we consider the yard-bays (SCRP) as cities (TSP) and the distances between blocks or yard-bays (SCRP) as the distances between the cities (TSP), we can visualize a TSP to SCRP conversion. Therefore a solution for the SCRP is also a solution for TSP what means that, if a polynomial solution could be found for SCRP, a polynomial solution for TSP could be found as well. As no polynomial solution has ever been found for TSP, the same is true for SCRP. Since no polynomial-time solution for SCPR can found, heuristics are a good alternative.

6. Mathematical Formulation of MSCRP

We focus in the quay side operations where:

LQ: transport a container to the quay crane to be loaded in the ship (*QC loading a vessel*)

ULQ: picking up an unloaded container from the quay zone and deliver it to the storage yard. (*QC unloading a vessel*)

The MSCRP may be formulated as follows:

$$\min \sum_{(i,j)\in P} C_{ij} y^t_{ijk} \quad (9)$$

Subject to

$$\sum_{i\in P} \sum_{k\in H} y^t_{ijk} = 1 \; j \in B(h), t = 1, 2, ..., m \quad (10)$$

$$\sum_{j\in P} \sum_{k\in H} y^t_{ijk} = 1 \quad \forall i \in P \quad (11)$$

$$Z^t_{ik} = \sum_{j\in P} y^t_{ijk} \quad \forall i \in P, k \in H \quad (12)$$

$$\sum_{k\in H} kz^t_{ik} = \sum_{k\in H} kz^t_{ijk} \quad \forall i \in Q, j \in S^i \quad (13)$$

$$y^t_{ijk} \in \{0, 1\} \quad \forall i \in Q, j \in P, k \in H \quad (14)$$

$$z^t_{ik} \in \{0, 1\} \quad \forall i \in P, k \in H \quad (15)$$

P: set of points that straddle carriers visit
H: set of straddle carriers
Q: set of quay cranes
C_{ij}: cost of move from points i to j
S^i: set of container stack points relevant to quay crane i
y^t_{ijk}: = 1 if SC k travels from points i to j in subtour t, 0 otherwise
z^t_{ik}: = 1 if point i is served by SC k in subtour t, 0 otherwise.

(8) minimize the total travel distance of a SC

(9),(10) ensure that every point must be visited exactly once and involved in a tour.

(11),(12) assure that a SC that has picked up containers at an ULQ must deliver them to its relevant stack points and that a SC must deliver containers that have been picked up at its dedicated stack points. In other words, origin points and the relevant destination points are involved in a particular tour.

7. Genetic Algorithm

We need an approach to search the feasible route. The most of the model's constraints are as equality form and, therefore, obtaining of the feasible solutions is a hard task. In this case, the probability of reaching infeasible solutions is more than feasible solutions and therefore we need a population-based approach such as GA to better exploration of the solution routing. GA is a well-known meta-heuristic that its efficiency is verified for many problems in the literature.

7.1. Our Representation

In our GA application, a candidate solution to an instance of the SCRP specify the number of required containers, the possible visited yard bays, the partition of the demands and also the delivery order for each route. Each chromosome represents a feasible solution. For our problem a chromosome is a set of containers that can be visited by a SC to perform a QC work schedule. For example a QC demands rt containers type A to load them into a containership, SC has to move toward the yard bays that include this type of containers, and transports them to the QC. Each container has a transportation cost depends on its position inside the storage yard and especially in its chromosome's cost.

Each container is characterized by its position and its type. The position is defined by the number of yard bay, stack and level. The type or group is determined by the function *IsRequired()*. It is similar to a decision variable which will be equal to 1 (true) if the group of the current container is the same as the required type and 0 (false) otherwise. So we will take under consideration only the containers that have value = 1, by applying *isRequired( )* on them. Therefore we begin our procedure by this set of required containers from which we construct the initial generation of n chromosomes. Each chromosome is created by rt nodes. Each node represents a container from the set of the required ones.

Let $C^{i}_{s,l}$ design the container inside yard bay i in stack s at level l

7.2. Genetic Operators

7.2.1. Fitness Function

For our solution procedure we will take under consideration the sigmoid function as defined in E. Nishimura et al. 2001; where z(y) denotes the objective function value.

$$f(y) = \frac{1}{1 + e^{z(y)/10000}} \qquad 0 \leq f(y) \leq 0.5$$

For the feasible solutions, our GA calculates the cost of each route that satisfies the objective function of the SSCRP. Then it compares between these costs and selects the smallest amount one.

7.2.2. Reproduction

It is a process in which chromosomes are copied according to their scaled fitness function values, i.e., chromosomes with a higher fitness value would have more of their copies at the next generation. This can be done by randomly selecting and copying chromosomes with probabilities that are proportional to the fitness values (costs of routes presented in each chromosome).

Initial Situation

We have n nodes which represent the number of the available required containers.

GA will randomly choose r_t nodes from this table and constructs the first generation of chromosomes.

7.2.3. Crossover

After reproduced chromosomes constitute a new population, crossover is performed to introduce new chromosomes (or children) by recombining current genes.

In our algorithm, we use the 2-point crossover. In this crossover, two cut points are randomly chosen on the parent chromosomes. In order to create an offspring, the string between these two cut points in the first parent is first copied to the offspring, then the remaining position are filled by considering the sequence of activities in the second parent (starting after the second cut point). When the end of the chromosome is reached, the sequence continues at position 1.

A crossover may generate infeasible children in terms of constraint, i.e., a child chromosome may have container to be picked up twice. In order to keep the feasibility the crossover operation is performed in the following manner.

7.2.4. Mutation

This genetic operator introduces random changes to the chromosomes by altering the value to a gene with a user-specified probability called mutation rate.

Two genetic operators are applied to all the individuals with preset probabilities along the evolution. These two operators are recombination operator and mutation operator. The first one is used to build an offspring (children) by preserving edges (borders) from both parents. The second one is used to apply (insertion, swap, or inversion) operators to each gene with equal probabilities.

The insertion operator selects a node and inserts it in another randomly selected place.

The swap operator consists in randomly selecting two nodes and exchanging them. Inversion operator reverses the visiting order of the nodes between two randomly selected cut points.

8. Solution Procedure

We have n available required containers, and rt containers among them will be picked up. And V SCs. We have $(V \times n)$ possibilities as follow:

Each gene represent this required container placed at yard bay i, stack s, level l which we maintain them fixed and we change at each time the identification of the SC that will pick it up.

$C^{i,v}_{s,l}$(i, s, l are fixed and v varies between 1...V);

For example $C^{5,2}_{4,1}$ is a required container placed in yard bay 5, stack 4, level 1 and picked up by SC number 2.

We generate a set of chromosomes having (r_t) genes which are selected from the set of $(n \times V)$ containers. We apply genetic operators; we calculate the cost of the resulting chromosome which is explained in the algorithm developed below whose principle is:

Divide the correspondent chromosome into ($S\,V$) sub-chromosomes, each one represent the list of containers belonging to the initial chromosome and that will be picked up by a particular SC. Calculate the cost of each sub-chromosome which will be the sum of the costs of containers picked up by the SC correspondent to this sub chromosome by recourse to the objective function of the problem.

We remark here that many SCs can work at the same yard map simultaneously. So in subtour t we can found V straddles working, each one is picking up a different container. Therefore in each sub-chromosome the cost of any container is dependant of the list of all containers of the initial chromosome (of all sub-chromosomes) this is done by updating the yard map after each loading/unloading container and empty positions are usually changed.

The cost of the initial chromosome is the maximum value of costs of its divided sub chromosomes.

The selected solution will be the chromosome from the resulting ones having minimum cost.

The multiple straddle genetic procedure is presented as follow:

1 we have n available required containers and V available SCs

2 we generate $n \times V$ genes, each one represent a container characterized by its position (yard bay, Stack and level) and the identification of the SC that pick it up.

3 Repeat until termination:

- a Reproduce set of chromosomes

  Each one is composed of r_t genes chosen arbitrary from the $n \times V$ ones.

  In each generated chromosome we have a number of straddles carriers that we use to pick up the containers presented in it. This number is ($S\,V$) where $S\,V \leq V$ and $S\,V \leq r_t$ and $S\,V > 0$.

- b Verify if this chromosome represent feasible solution or not (we must not have in a chromosome more than one gene having the same i, s and l with different value of v). If this condition is ignored we delete this chromosome else go to b, c, d, e, f.

- c Calculate fitness value of each chromosome and select best-ranking individuals having higher value for the next generation

- d Breed new generation through crossover, recombination and mutation (genetic operations inversion, swap, and insertion) and optimization methods applied on selected chromosomes to give birth to offspring.

- e For each resulting child, reorganize the set of genes order by the identification of SC. We mean that each parent chromosome will be divided into ($S\,V$) sub-chromosomes where ($S\,V$) is equal to the number of SCs used in the parent.

- f For each sub-chromosome (f) where (f) varies from 1 to ($S\,V$), evaluate it by adding the costs of each container presented in this sub-chromosome. Those costs are calculated using the expression of the objective function (chapter 4) of each container minimizing its cost.

- g To determine the cost of the whole chromosome, we select the maximum of costs of all sub-chromosomes forming it.

4 From all resulting chromosomes generated in step 3, we select the one that has minimum cost. it represents the best route

9. Numerical Example

A MATLAB program was used to solve the above mixed-integer programming for an example problem. The MATLAB is a programming environment for algorithm development, data analysis, visualization, and numerical computation. All experiments were performed on a 4GHz Pentium dual core computer. In the following tables the presented solutions of the GA procedure are the best ones between 12 generations for every iteration.

An illustrative example is presented as follow, we suppose a 5 yard-bays, 4 SCs, 10 stacks of 3 lines (levels) in each yard bay, and 9 containers (type A) exist in the storage yard where 7 should be transported to the QC.

$n = 9$ available required containers

$V = 4$ SCs.

$C^1_{1,1}$ $C^1_{6,1}$ $C^1_{10,1}$ $C^2_{3,1}$ $C^2_{4,2}$ $C^4_{4,3}$ $C^4_{10,3}$ $C^5_{4,1}$ $C^5_{5,2}$

For each container from this list we generate three genes. For example for the first container $C^1_{1,1}$

we generate these three genes $C^{1,1}_{1,1}$, $C^{1,2}_{1,1}$, $C^{1,3}_{1,1}$

$C^{1,1}_{1,1}$ is the container $C^1_{1,1}$ which will be picked up by SC_1

$C^{1,2}_{1,1}$ is the container $C^1_{1,1}$ which will be picked up by SC_2

$C^{1,3}_{1,1}$ is the container $C^1_{1,1}$ which will be picked up by SC_3

So, we will reproduce $n \times V$ genes $(9 \times 4$ genes) among them we will select 7 genes. We generate a set of chromosomes.

Each one is composed of 7 from the 36 available genes. We apply to each generated chromosome genetic operators (crossover, recombination, mutation and optimization).

We calculate the cost of each resulting chromosome and we select the best solution having minimum cost.

Let it be the following chromosome Ch_1. Each gene represents a required container. So it is characterized by its cost which is calculated referring to the objective function.

$C_{1,1}^{1,1}$	$C_{6,1}^{1,2}$	$C_{10,1}^{1,3}$	$C_{4,1}^{5,2}$	$C_{5,2}^{5,2}$	$C_{4,3}^{4,1}$	$C_{10,3}^{4,3}$
↓	↓	↓	↓	↓	↓	↓
Cost1	Cost2	Cost3	Cost4	Cost5	Cost6	Cost7

In this example, there are containers that can be picked up by SC_1, SC_2 or SC_3. So we obtain Three Sub-chromosomes ($SV = 3$).

Sub-Chromosome1 (containers belonging to this chromosome and picked up by SC_1)

$C_{1,1}^{1,1}$	$C_{4,3}^{4,1}$

Sub-Chromosome2 (containers belonging to this chromosome and picked up by SC_2)

$C_{6,1}^{1,2}$	$C_{4,1}^{5,2}$	$C_{5,2}^{5,2}$

Sub-Chromosome3 (containers belonging to this chromosome and picked up by SC_3)

$C_{10,1}^{1,3}$	$C_{10,3}^{4,3}$

We evaluate the cost of each gene representing a particular required container by recourse to the objective function of the SCRP and to the scheduling tasks:

$C_{1,1}^{1,1}$	$C_{6,1}^{1,2}$	$C_{10,1}^{1,3}$	$C_{4,1}^{5,2}$	$C_{5,2}^{5,2}$	$C_{4,3}^{4,1}$	$C_{10,3}^{4,3}$

SC_1 $v=1$	SC_2 $v=2$	SC_3 $v=3$
$C_{s,l}^{i,1}$	$C_{s,l}^{i,2}$	$C_{s,l}^{i,3}$

We calculate the cost of schedule work of each SC

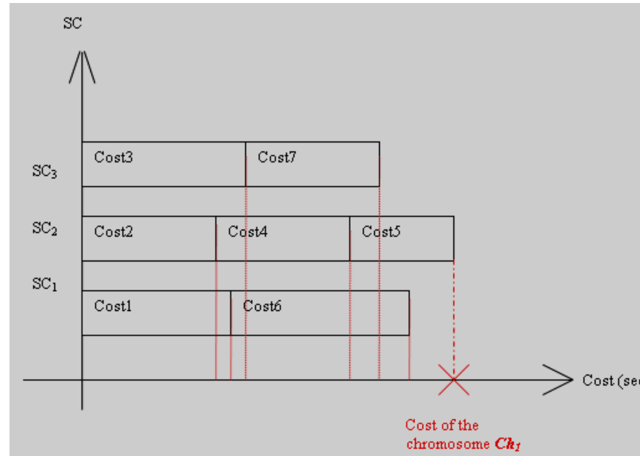
Cost (SC_1)	$cost3 + cost7$
Cost (SC_2)	$cost2 + cost4 + cost5$
Cost (SC_3)	$cost1 + cost6$

So the cost of the whole chromosome is the highest value of costs of all its sub-chromosomes.

$$\text{Cost}(Ch_1) = \max(\text{cost}(SC_1), \text{cost}(SC_2), \text{cost}(SC_3))$$

So on for all generated and resulting chromosomes until the population converges and finally we select the chromosome having minimum cost which represents the best route.

Figure 1: Cost of a selected chromosome.



Source: Authors

10. Conclusion and Future Work

In this study, we addressed the routing problem of Straddle carriers at a container terminal. We aim to increase the productivity of the terminal. The problem can be defined by two formulations: one for a single Straddle carrier, the other for more Straddle carriers. Although the former is a particular case of the latter, it can be treated separately.

The GA procedure that is employed for solving the problem of more than one SC is a heuristic and does not necessarily provide an optimal solution. The routing scheme developed in this paper reduces capital and operating terminal costs. As shown from the examination of the experiments' results, the cost reduction turns out to be possible through the reduced SC fleet size deployed, which results from the shorter total travel distance (more precisely shorter empty travel distance) of SCs employed.

This paper's contribution to the literature is the development of new, efficient routing principle of SC at a maritime container terminal which saves yard operation time and costs.

As this SC routing has practical applications, port operators may look into ways of implementing it. The routing plan principle is useful to the container terminal management for both tactical and operational decisions. For example, terminal operators can simulate the SC routing or movement while they are engaged in ship handling, in order to determine the SC fleet size to be deployed when planning new terminals. In the operational stage we can simulate the SC movement in order to make up a daily or weekly SC work schedule given a prospective cargo handling profile.

The only disadvantage to the use of the scheme is its complexity, which may increase the possibility of human error. SC drivers may find difficult to follow the complicated itineraries assigned to them, resulting in mistakes in driving. However, such types of errors could be minimized through the use of proper communication and tracking systems.

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