Coalition-based Approach for Reach Stackers Routing Problem in Container Terminals

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Abstract—The emergence of containerization had revolutionized the freight maritime transport. The number of the daily handled containers is continuously growing, and port authorities are facing new challenges.

Depending on the organization and the level of automation of the container terminal (CT), different vehicles are used to transport the containers, such as Automated Guided Vehicles, Reach Stackers, Straddle Carriers. In our case, we focus on using Reach Stackers.

Throughout this paper, we present, formulate and propose a model to solve the Reach Stackers Routing Problem (RSRP) as a Vehicle Routing Problem with Time Windows and Pickup and Delivery (VRPTWPD). First, we draw an analogy between these two problems. Second, we present a state of the art of methods dealing with the vehicle routing problems in CT. Finally, we propose an approximate Multi-Agent method, using coalition formation approach and implementing heuristics.

We aim to minimize the service time of containers while respecting time windows and RS capacity constraints.

To assess the performance of the proposed model, we exhibit an experimental study based on the Mitrovic-Minic benchmark. The results were very encouraging, showing a high efficiency ratio and a reasonable number of used vehicles.

Keywords
Maritime Container Handling, VRP, Negotiation, Multi-Agent Systems

1. Introduction

Container terminals (CT) are considered as complex systems and include various decision problems. These decisions are often formulated as scheduling problems. In [1], authors classify them into four classes: Arrival of the vessels, Unloading and loading of the vessels, Transport of containers and containers Stacking. Many researchers are interested to these different issues in order to improve terminals performance and optimize resources allocation. The present work focuses on the container transport problem, inside the CT and especially the Reach Stackers Routing Problem (RSRP).

When studying this problem we noticed its strong similarity to a well known problem, the Vehicle Routing Problem (VRP). This problem has been extensively studied and a multitude of resolution techniques have been proposed. In the literature, we distinguish many versions of the VRP, therefore we will try to determine which version is closer to our problem and draw the analogy between them.

The remaining of the paper is organized as follows. In Section 2 we present the RSRP and we detail its mathematical formulation. Section 3 provides a literature review of VRP and containers transport problem in CT. Section 4 describes the proposed approach which is based on coalition formation. Section 5 reports the experimental results and finally some conclusions are drawn in section 6.

2. Problem statement

2.1 Description

Depending on the organization and the level of automation of the CT, various types of vehicles are used to transport containers, such as Automated Guided Vehicles (AGV), Reach Stackers (RS) and Straddle Carriers (SC). In our case, we are interested in Reach Stackers. We consider a homogenous fleet where all the vehicles have the same characteristics (capacity, speed, maximum service time...) and are guided by a driver.
As shown in Fig. 2.1, the RS are scattered on the quay, which is considered as a kind of depot, and they have to transport the containers that are unloaded from vessels from the quay to their locations in the storage area, and collect other containers from the storage area and stack them on the quay, to be loaded later on the corresponding ship.

In addition, the operations of pick up and delivery should take place in well-defined intervals or slots (depending on the time required for a crane to retrieve the container from the vessel or the storage areas). Based on this description we note that the closest version of the VRP, to our problem, is the VRP with time windows and pickup and delivery. In Table 1, we dress the analogy between these two problems.

<table>
<thead>
<tr>
<th>Table 1: Analogy between the VRP and the RSRP</th>
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</thead>
<tbody>
<tr>
<td>VRPTWPD</td>
</tr>
<tr>
<td>Depot</td>
</tr>
<tr>
<td>Vehicles</td>
</tr>
<tr>
<td>Customers</td>
</tr>
<tr>
<td>Delivery</td>
</tr>
<tr>
<td>Pickup</td>
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<tr>
<td>Time Windows</td>
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### 2.2 Mathematical formulation

In this problem we consider several vessels loading or unloading containers in the current planning period, these vessels are going to be served by a Reach Stackers fleet.

#### Table 2: Notations

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>(X_{ijv})</td>
<td>A binary variable indicating whether the vehicle (v) carries a container from the point (i) to (j)</td>
</tr>
<tr>
<td>(V)</td>
<td>A set of vehicles (V = {1, 2, ..., k})</td>
</tr>
<tr>
<td>(P)</td>
<td>A Set of points to visit (location of containers to pick up ((n)) and those to deliver((m)))</td>
</tr>
<tr>
<td>(T_{tij})</td>
<td>The duration of the transport of a container from a point (i) to (j)</td>
</tr>
<tr>
<td>(T_m)</td>
<td>The duration of containers handling (loading by a crane from blocks or to trucks)</td>
</tr>
<tr>
<td>(d_{di})</td>
<td>The date of departure of the vehicle (v) from (i)</td>
</tr>
<tr>
<td>((a_i, b_i))</td>
<td>The time windows of the operations of pickup or delivery of a container in a point (i)</td>
</tr>
<tr>
<td>((x_i, y_i))</td>
<td>The coordinates of the location of a container</td>
</tr>
<tr>
<td>(D_i)</td>
<td>The destination of the container collected at a point (i)</td>
</tr>
<tr>
<td>(DistMax)</td>
<td>The maximum distance a vehicle can daily travel.</td>
</tr>
<tr>
<td>(Distij)</td>
<td>The distance between the point (i) and the point (j).</td>
</tr>
</tbody>
</table>

In what follows, we use the notations described in Table 2 and we consider the following assumptions:

1. A storage area is either dedicated to the export operations or the import operations.
2. We have a fleet of Reach Stackers (vehicles) of the same capacity (One container).
3. The RS are scattered on the quay, this is equivalent to a one single depot.
4. The Origin and destination of each container are known in advance.

The objective is to reduce the overall service time of the entire set of containers and to minimize the maximum number of RS used. Given these descriptions and hypothesis we formally define the RSRP as:

\[
\min \sum_{v \in V} \left[ \sum_{i \in P} \sum_{j \in P, j \neq i} X_{ijv} \times (T_{tij} + T_m) \right]
\]

Subject to:

\[
\sum_{i \in P} X_{ijv} = 1, \forall j \in P \text{ and } \forall v \in V \quad (2.1)
\]

\[
\sum_{j \in P} X_{ijv} = 1, \forall i \in P \text{ and } \forall v \in V \quad (2.2)
\]

\[
X_{iDi} = 1, \forall i \in P \text{ and } \forall v \in V \quad (2.3)
\]

\[
a_i \leq d_{di} \leq b_i, \forall i \in P \quad (2.4)
\]

\[
d_{di} + T_m + T_{tij} \leq d_{dij}, \forall i, j \in P, j \neq i \text{ and } v \in V \quad (2.5)
\]

\[
\sum_{i \in P} \sum_{j \in P, j \neq i} Dist_{ij} X_{ijv} \leq DistMax, \forall v \in V \quad (2.6)
\]

As we have already presented our objective is to reduce the service time of the containers transportation. This objective is subject to the following constraints:

- Constraints (2.1) and (2.2) ensure that each point is visited only once and is only involved in one tour.
- Constraint (2.3) ensures that the RS can visit a destination point only after collecting a container. Besides, a full RS can visit another pickup point only delivering the current carried container.
- Constraint (2.4) states that the operation of pickup/delivery must be made within a defined time window.
- The constraint (2.5) is a precedence constraint between points.
- The constraint (2.6) ensures that the distance traveled by a vehicle during a route must not exceed the maximum distance that it can perform.
3. Literature review

Considering the analogy between our RSRP and VRPTWPD, we firstly present a review of the main works related to the VRP. Then, we especially focus on works dealing with container handling.

Many exact and approximate methods have been proposed to formulate and solve the VRP in the literature. Among the most known exact methods, we mention Branch and Bound algorithm, linear programming and dynamic programming detailed in [12, 20].

Because of the high complexity level of the VRP and its wide applicability to real-life situations, the most successful methods in solving VRP and its extensions are heuristic methods which are described in [5] like Constructive Heuristics, GRASP [7], Tabu Search [6] and Ant Colony System [8].

To our knowledge, distributed methods are also applied to the general VRP we can cite two main systems:

- MAS-Mars System: Proposed by Fischer et al [3], and based on Contract Net Protocol [3]. This system is a generic model representing the transport system in general. It is dedicated to shipping companies. The vehicle routing problem is considered as a particular instance of this system.

- TELETRUCK System: Based on Holonic Multi-Agent Systems and proposed by Burckert et al in [11]. It is an extension of the MAS-MARS system. In this system, physical objects (trucks, containers, trailers ...) are modeled as basic agents. These agents must work together in groups called holons (natural or artificial structure that is stable and consistent which may be made by other holons). A holonic system is characterized by a level of cooperation and/or collaboration more advanced than the standard SMA.

Another known technique in the field of the MAS was introduced to the resolution of the VRP: Coalition formation. In [9], Kefi et al propose a model (Coal-VRP) based on the formation of coalitions for solving the PTV with time windows. They distinguish two classes of agents: interface agent and control agent. The Coal-VRP has been validated against the Solomon’s benchmark. This model has been improved by Boudali et al [10]. They proposed an extension to Coal-VRP, denoted DyCoal-VRP based on dynamic coalition’s generation, to overcome Coal-VRP spatial and temporal complexity.

By studying the literature of the containers transport problem we noted three interesting findings:

1) The majority of papers dealing with transport problem in container terminals, propose agent-based Decision Support Systems (DSS) to optimize the whole container terminal operations [14, 15, 16], besides this few works do not provide any details of how agents are proceeding or any experimental results.

2) Other works focus on simulating the CT’s operations. The implemented simulators are used to evaluate the robustness of operational policies in a CT [18, 19] and to help stakeholders and to enhance the decision making process via visualization tools [17].

3) Despite the similarity between the VRP and the containers transport problem in CT, few researchers have been interested in this issue, and those that have considered the container’s transport problem as a VRP use essentially meta-heuristics and heuristics approaches. These works are recapitulated in Table 3.

To summarize, we notice that the distributed resolution of VRP has not been sufficiently and comprehensively surveyed and compared, especially VRP in container terminal ports. In this paper, we concentrate on the modeling and the resolution of RSRP in container port by analogy to VRP with Time window and pickup and delivery (VRPTWPD). To achieve this goal we propose a Multi-Agent model based on coalition formation.

4. Proposed model

This section is dedicated to the description of our Multi-Agent model denoted CA-RSRP. Though, we will briefly discuss and argue the choice of an agent-based method.

The problem of containers transport is naturally distributed, it also requires the use of multiple entities (trucks, containers, drivers, customers ...). Therefore, Multi-Agent systems are very well adapted and appropriate to apprehend such problem [3]. In addition, Multi-Agent systems inherit, from artificial intelligence domain, the benefit of symbolic processing (at the knowledge level), so the real-world entities are easily modeled and manipulated by agents.
The proposed model is based on a set of Container Agents (CA) which negotiate and collaborate in order to be assigned and satisfied by a vehicle. Container agents model the containers to transport from the quay to the storage area and vice versa. Each one is characterized by its type (“delivery” if the container must be transported from the quay to the storage area, and “pickup” inversely), its origin and destination, the time window in which it has to be carried. Each CA has a state that is updated during the solving process.

The CAs negotiate and proceed in two phases, the Pairs Formation and the Coalition Formation.

In the following subsections we are going to detail the phases of the CA-RSRP.

4.1 Definitions

Throughout the remainder of this document we will use the following terms

- **Container agent (CA):** an agent that models a container. We distinguish two types of containers:
  - Delivery Container (L): A container that should be transported from the quay to the storage area.
  - Pick up Container (C): A container that should be transported from the storage area to the quay.

- **Status of CA:** Throughout the resolution process, each CA goes through the following status:
  - Free: in the beginning of the Pairs Formation phase.
  - Partially assigned (PartA): when it forms a Pair with another CA.
  - Permanently Assigned (PermA): when it is assigned to a coalition.

- **A Pair:** A couple of two CA that will be served successively by the same vehicle. We distinguish two types of Pairs:
  - Heterogeneous Pair: The CAs forming the Pair have different types (Delivery or Pickup).
  - Homogeneous Pair: Both CAs forming the Pair have the same type.

- **Coalition:** A coalition is a group of one or more pairs of container agents, which can be transported by a single vehicle.

4.2 Pair Formation

In this first phase, each agent tries to get paired with the CA with which it is served at lower cost in terms of time. Because the RS are initially on the quay (in the Depot), it is more suitable to transport firstly a delivery CA so that the RS is not empty when it leaves the quay. Therefore the agent that initiates the pairs formation phase is a delivery CA. Thus, each delivery CA sends a request for pairs formation to all the agents.

![Fig. 4.1: Principle of Clarke and Wright saving algorithm](image)

Fig. 4.1: Principle of Clarke and Wright saving algorithm

On receiving such a request, each agent calculates the time required, for a vehicle, to carry him in the same route with the proposal’s transmitter. After receiving proposals, each delivery CA send an acceptance to the best proposal’s sender (the one with which it is carried at the lower cost in terms of time). A refusal is sent to agents whose proposals do not meet the constraints of time windows and capacity. The selection of the best proposal is made by means of a heuristic inspired from the Clarke and Wright savings algorithm [4] (see Fig. 4.1). The agents have to confirm the proposals in the rest of the conversation. Interactions of the CAs in the pairs formation phase are described in Fig. 4.2.

![Fig. 4.2: Interaction between agents in the Pairs Formation phase](image)

Fig. 4.2: Interaction between agents in the Pairs Formation phase

To summarize, the main idea of this phase is to take full advantage from each displacement of a vehicle. In fact, each container tries, through negotiation, to get paired with the container with who he causes the less empty time. It comes to minimize the duration of empty movements (when the vehicle is traveling without any load) to can decrease the overall service time and offer a better fleet utilization.

4.3 Coalition Formation

In the second phase, the pairs formed in the previous phase negotiate together in order to gather in larger coalitions while respecting the time windows and RS’s capacity constraints.

When all CAs pass to the state “PermA” the coalition formation phase is initiated. Each CA is now characterized by its rank in the pair (first or second).

Agents ranking second in each pair are responsible for sending requests for coalition formation to the first ranking CA of the other pairs. These latter will calculate the cost of an eventual assignment with the request’s sender, verify the constraints validity (relating to time windows and RS capacity) and send their proposals to the involved agents. Fig. 4.3 models the interaction of agents throughout the Coalitions Formation phase.
The Coalition Formation phase is inspired from the ECNP proposed in [3] and the agent communication is based on the FIPA ACL standard [13].

After receiving the proposals, each agent checks the capacity and time window constraints and save the coalition proposals’ senders in a sorted list according to the waiting and empty times. When all the proposals are received, the agent chooses the best bidder pair (top of the list) and behaves according to the different scenarios as follows:

1) The best bidder pair is assigned to a coalition and the receiver is not yet assigned: The receiver sends a “Take Me with you” message, it asks the best bidder pair if he can incorporate him in his same coalition.

2) The receiver is assigned to a coalition and the best bidder pair is not yet assigned: The receiver sends a “Come with me” message, it invites the best bidder to enter to his coalition.

3) Both the receiver and the best bidder pair are not assigned to a coalition: The receiver checks if there is a coalition not yet saturated and tries to fit into it, if not it creates sends a “Create new” message to inform the best bidder that he should create a new coalition and add him to it.

When receiving any of these messages (“Take Me with you”, “Come with me” or “Create new”), the agent examines its contents and decide what action to perform. Then it updates its status to “PermA” and sends a CONFIRM message to the issuing agent. When an agent Receives a CONFIRM message it updates its status to “PermA” and check if all other agents are in state “PermA”, in which case it sends them alerts (INFORM message) to inform them of the termination of the coalition formation phase.

To summarize, this phase is based on the negotiation between the pairs formed in the previous phase. The CAs try to gather in coalitions by sending messages and using simple heuristics to choose the best bidders. New coalitions are formed only if a CA receives a “Create new” message and CAs are inserted in different existent coalitions by means of “Take Me with you” and “Come with me” messages. Capacity and time windows constraints must be validated before each one of these operations.

5. Computational results

In this section, we present the tests performed to validate the proposed model. The first subsection (5.1) describes the benchmark used and the second one (5.2) presents the results and some interpretations.

5.1 Test instances

To assess the performance of CA-RSRP so far, we choose a known benchmark developed by Mitrovic-Minic [2]. Nevertheless, we have modified it to fit our problem that considers real world features.

We add a column specifying the type (Delivery/Pick Up) of the container, and we discard the column of arrival time seen that we assume that the containers’ arrival times are all known in advance. The type of each container is determined depending on its departure and destination locations with respect to the depot location. The benchmark defines for each container its starting point and destination coordinates, its time window and its type (Pickup/delivery). The tests are launched 10 times for each instance, and the results shown in the next subsection represent the average of the 10 tests values.

5.2 Results

In order to validate the results we defined two measures:

- **The Activity ratio**: It represents the percentage of time in which the vehicle is not idle. It's formulated as follow:

  \[
  \text{Activity ratio} = 1 - \frac{\text{Vehicle's waiting time}}{\text{Vehicle's service time}}
  \]

- **The Efficiency ratio**: as one of the objectives that we have set is the minimization of the empty movements, it represents the percentage of time in which the vehicle travels while it is loaded. The Efficiency ratio is formulated as follow:

  \[
  \text{Efficiency ratio} = \frac{\text{Vehicle's empty time}}{\text{Vehicle's service time}}
  \]

In Fig. 5.1 we compare the evolution of the number of vehicles required to serve 25 and 50 containers. We note that although the containers number is doubled, the number
of vehicles is increased (5 trucks for 25 containers and 7 trucks for 50 containers). We think that this number can be reduced if we enhance the model through merging the formed coalitions with respect to the capacity and time windows constraints. However, these changes can decrease the efficiency and the Activity ratios if coalition merging generates additional waiting and empty times.

![Fig. 5.1: Number of required vehicles](image1)

As shown in Fig. 5.2, the efficiency ratio is over the 0.6 for all the instances. Moreover, when the number of containers increases, this ratio is slightly improved (≃0.75). A good Efficiency ratio evinces a good fleet exploitation.

![Fig. 5.2: Evolution of the Efficiency ratio](image2)

Although the values of the Activity ratio are declined, when increasing the number of containers, they are still encouraging. In fact, this ratio is always between 0.8 and 0.9 for the 25 containers and between 0.7 and 0.8 for 50 containers, as it is exhibited in fig. 5.3.

![Fig. 5.3: Evolution of the activity ratio](image3)

6. Conclusion

Throughout this article we presented and formulated the RSRP as a VRP with time windows and pickup and delivery. Firstly, we have drawn an analogy between these two problems, then we presented a state of the art of the art of agent-based methods tackling to VRP in a container terminal.

To solve this problem, we proposed an approximate Multi-agent model CA-RSRP, based on the coalitions formation and implementing simple heuristics.

To validate our resolution approach, we provide empirical study using Mitrovic-Minic benchmarks dedicated to the VRPTWPD. The results of this study are very promising. They show a high efficiency ratio and a reasonable number of required vehicles.

References


