Modelling and strategic design of automatic intermodal freight terminals

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***Abstract*—This work concerns the strategic planning of a freight railway terminal where the transfer of cargo units between road and rail is supposed to be automatic and realized horizontally. More specifically, the considered terminal is an innovative platform where containers or swap bodies are loaded/unloaded on/from the train horizontally by means of shuttles which move on a track parallel to the train one. The main objective of the paper is the optimal definition of the terminal layout, in terms of physical structural elements and number of handling resources, in order to minimize the overall costs of cargo handling systems and taking into account a maximum stopping time limit for trains at the terminal.**

I. Introduction

Intermodal freight transportation has been strongly improving for some decades and it will likely continue to improve in the next years. New technologies are needed in order to increase the efficiency of intermodal terminals, by speeding up loading/unloading operations and transfer movements among different transportation modes. Thanks to its characteristics, intermodal transportation is the most appropriate way of moving goods taking into account economical issues together with environmental and congestion ones, being these latter more and more important and binding. Different research works have been devised aiming at planning intermodal freight transportation systems at different decision levels (i.e. strategic, tactical, operational), as can be found in [1], [2].

Intermodal transportation presents a multitude of opportunities for developing competitive alternatives to road transport and therefore rebalancing the modal split, which is one of the priority of the European Commission policies. In fact, apart from being more "environmental friendly" compared for instance to the "all road" solution, intermodal transportation is able to offer a complete door-to-door service without using trucks for medium-long distance transport. Besides, the high flexibility of containers and swap bodies makes it suitable for different types of cargo. Finally, if a minimum threshold of volumes and distance is reached, costs demonstrate to be very competitive in respect to other transportation modes. However, intermodal transport is characterized by a much higher degree of complexity than unimodal transportation solutions in terms of its organization, administration and technologies in use. Those complexities have an impact in economic and efficiency terms and, consequently, in the limitation to the growth of intermodal transportation. So, in order to reduce the total costs related to intermodal freight transportation, highly automated and innovative technologies are needed.

This paper is an extended version of [11] and deals with the strategic planning of a railway terminal devoted to container transportation. Some review works refer to optimization and planning methods for intermodal container terminals, including also port terminals [3], [4]. With regard to strategic planning methods for the design of container terminals, some works can be found in the literature aiming at defining the number of handling resources, the storage space dimensions, and so on. Among the others, in [5] a decision support system is defined for capacity planning of container terminals, both for designing a new terminal and for tuning an existing one. In [6] a network model for the overall terminal is presented, that can be used as a decision tool for investment appraisal of container terminals. In [7] a planning method is proposed in order to define the optimal storage space dimensions and the optimal number of cranes in the terminal. In [8] a queue-based discrete-time model is defined for representing the dynamics of a seaport terminal and for optimizing it in terms of number of handling resources and yard size. The goal of this paper is to formulate a strategic planning problem in relation to an innovative intermodal system, named Metrocargo. Being a brand new system, not already in force, few authors have approached this topic so far, such as in [9] or [10]. For the same reason, the proposed approach is different from those found in the literature, because it is specifically devised in order to take into account some specific aspects of the considered terminal.

Metrocargo system, patented by an Italian transportation company, allows to quickly and safely move cargo on/from trains, significantly reducing the total handling time and, consequently, the related costs. The central idea at the basis of this innovation system is to apply the same concept utilized for passengers transport to freight one. So the rail transportation, that actually works as a point-to-point transport, can be considered as a transportation in a network; in this network cargo units are progressively loaded on different trains up to their final destinations. Thanks to an innovative device, cargo units are loaded on train cars in an horizontal way and directly under the electric feeding line, so allowing to dramatically reduce the total logistic cost in comparison with traditional systems, with a consequent improvement of the overall system competitiveness.

In the last few years, other innovative techonologies for the horizontal loading/unloading have been developed and they are currently utilized in intermodal transportation, such us Modalohr, Cargo Domino and CargoBeamer. The first one is an innovative intermodal and highly automated system for the transportation of trucks and semitrailers between Aiton, in France and Torino Orbassano, in Italy. With this system vehicles are loaded directly on trains with the direct benefit of allowing them to overcome particularly hostile road routes, mountain passes or congested areas. Cargo Domino is a truck-train intermodal system formed of a horizontal mechanical transfer system placed on specific trucks. The transfer is realized in this way: the truck stops side by side to the train; then an appropriate system provided with suitable forks takes the cargo from the truck and put it on the train wagon. However, with Cargo Domino system, common cargo units cannot be utilized, unless specific modifications are made. Finally, Cargo Beamer is an innovative solution for intermodal transport of semi-trailers. It is the first case in which a traditional semi-trailer has been introduced; it is also compatible with swap bodies and containers.

The paper is organized as follows. Section II provides a framework for the problem formulation; in Section III the proposed iterative procedure is shown. Finally, in Section IV some final conclusions are presented together with some remarks on current and future research.

II. Description of the Problem

The objective of the present paper is the strategic planning of an automated railway terminal, provided with Metrocargo system, which strives for becoming a point of reference in the intermodal transportation in the Italian context. In the following, Metrocargo system is described, then the problem formulation is treated.

A. Metrocargo system

The main objectives of Metrocargo system are shifting big traffic volumes from road to rail, simplifying rail transport using shuttle trains with prefixed schedules and itineraries, reducing environmental pollution and congestion. Moreover, the goal is to minimize the total handling time and the total logistic cost related to freight intermodal transportation, so improving the overall competitiveness of Italian transportation and logistic system.

In traditional intermodal solutions (both referring to ports, freight villages or inland ports), terminals are off line and trains must be shunted away from the electrified track using diesel locomotives, pulled to a loading yard, loaded, and brought back to the regular track by diesel traction. The total time required to perform all these operations ranges from 10 to 12 hours per train (Fig. 1).

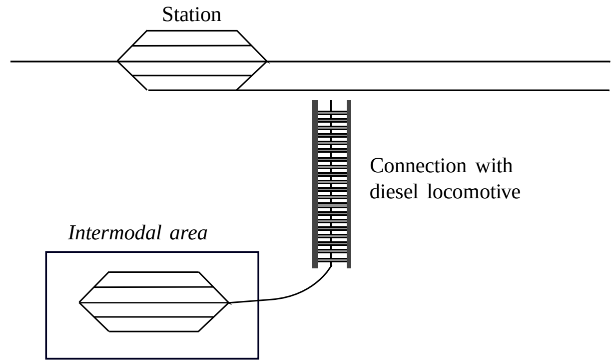

Fig. 1. Traditional railway system

With Metrocargo system, instead, as Fig. 2 shows, trains remain directly under the electrical track in a sort of "button-hole" parallel to the main rail truck, where they are automatically and safely loaded and unloaded. This new approach, thanks to the elimination of the onerous traction break and to the automation of all the operations, allows a tremendous decrease in total handling time from 10-12 hours to only about 30-40 minutes per train.

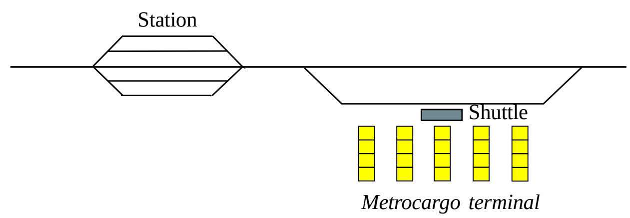

Fig. 2. Metrocargo railway system

More specifically, traditional terminals are connected to the network through a non elictrified siding track, which branches out from the tracks bunch linked to the reference railway station. In this situation, once arrived in the destination station, the train must be towed, through an operation of terminalization with a diesel locomotive inside the terminal itself. This operation is often managed, in the first tract, by a shunting team of the railway company and, for the final tract, by the terminal personnel, with consequent additional costs and times. Besides, the movement of cargo units, based on the lifting technique, obliges to operate with expensive infrastructures, such as gantry cranes or reach stackers, and it requires large spaces for storage and for shunting of handling means. On the other hand, Metrocargo solution is based on an innovative horizontal handling system that utilizes terminals equipped with automated storage areas, which are placed contiguous to railway tracks. The whole of operations is performed without leaving the electrical feeding line (it is operated under electrical cables) and without bringing the train out of the station, but simply making it deviate on a parallel track.

The Metrocargo terminal stocking area is completely automatic, composed of some bays (perpendicular to rail tracks); each bay is divided in various slots where containers are stored (Fig. 3).

The activities connected to the Metrocargo plant can be described through the following phases:

- entrance of cargo units in the system;

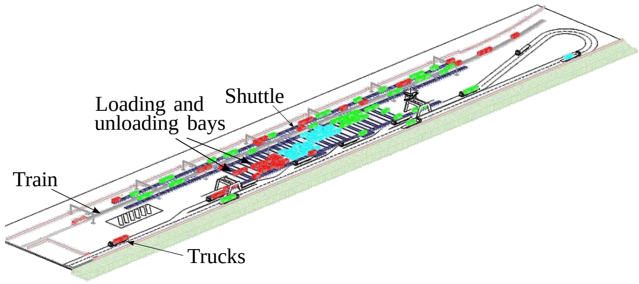

Fig. 3. Framework of a Metrocargo terminal.

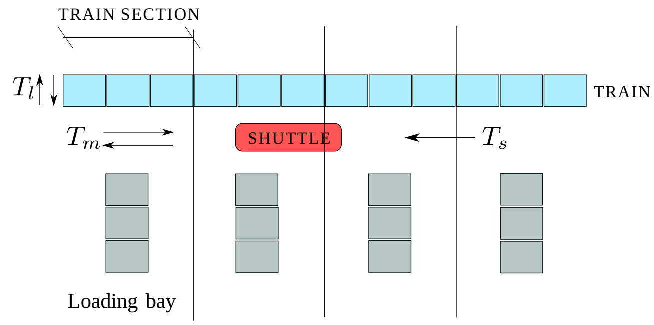

Fig. 4. A schematic representation of a Metrocargo terminal.

- loading of cargo units on the train;
- unloading of cargo units from the train;
- exit if cargo units from the system.

As far as regards the first phase, cargo units arrive in the terminal through road or maritime means; they are placed on the receiving area of the plant linked to the moving area inside the terminal. The arrival of each unit is signalled by a centralized management software. According to the software indications, which plans the sequences of loading and transfer, containers are disposed in a specific bay in the stocking area. In the second phase, each cargo unit placed in the loading area is grabbed by a shuttle through forklifts. Then, thanks to optical means, the shuttle detects the cargo units outlines and aligns itself to the fixing devices placed on the wagon in the predefined position. The loading can be made in parallel by all the shuttles that are present in the system. Then, the unloading of cargo units from train wagons is operated analogously to the loading phase; the shuttles, after lifting up the containers from wagons, utilizes the forklifts for making the unloading operations and deposit them in the automatic storage area. After a break, that can be of few minutes or some hours, the cargo units are loaded through cranes or forklifts on trucks which provide for their delivery.

The rapidity of loading/unloading operations, connected with Metrocargo methodology, allows to reduce the number of operative tracks to one. Building them close to each other and in a parallel position to the railway line, an electrified "buttonhole" is obtained. The use of the horizontal transfer allows the entrance and the following direct exit of the train on the primary railway line without the necessity of railway shunting operations.

B. Problem formulation

A general scheme of the terminal layout is depicted in Fig. 4. Trains arriving at the terminal are unloaded/loaded by means of one or more *shuttles* which run parallel to the train itself. Containers are stored in the terminal in rows (perpendicular with respect to the train) which are called *bays*, composed by a given number of slots. Note that loading bays (storing containers to be loaded on the train) and unloading bays (with containers to be unloaded from the train) are separated. Moreover, we define as *train section* the section of the train relevant to one bay.

The main objective of the problem is to define the optimal layout of this innovative terminal, in terms of number of resources, that means number of shuttles and loading/unloading bays, with the final goal of minimizing the related costs. The decision variables in the considered framework refer to the number of shuttles and the number of bays. Two cost terms can be in general considered: the storage cost and the cost of shuttles. Nevertheless, the cost of the stocking area does not depend on the number of bays, nor on the number of shuttles. Thus, the shuttle cost is the only cost term to be considered; such a cost is a simple linear expression of the number of shuttles. Moreover, the only constraint to be taken into account is the total handling time which must be lower than a given threshold. In order to state such a constraint, it is necessary to determine the handling time as a function of the decision variables. The total handling time is composed of three terms (as depicted in Fig. 4): the moving time T_m, which is the time spent by the shuttle for moving along the shuttle track within each train section; the shifting time T_s that represents the time spent by the shuttle for moving from one bay to the next one; the lifting time T_l which is the time needed for lifting up and down all the required containers. As it will be better clarified in the following, T_m and T_s are function of the number of bays, while T_l is not depending on it.

We propose an iterative procedure starting from the case in which one shuttle is adopted: if in this case it is possible to find a number of bays such that the stopping time limit is not exceeded, the procedure stops. This means that the optimal solution is given by one shuttle and the obtained number of bays. Otherwise, the case of two shuttles is analysed and so on.

For the problem formulation, the following input data are necessary:

- C represents the train capacity, in terms of number of cargo units in a train (they can be either containers or swap bodies of different length);
- λ is the average length of one container;
- v is the average speed of the shuttle;
- C^L and C^U are, respectively, the number of containers to be loaded and unloaded for a given train.

The decision variables are:

- B^L, i.e. the number of loading bays;

- B^U, i.e. the number of unloading bays;
- N, i.e. the number of shuttles (as already specified, this value is obtained by means of an iterative procedure, thus it is implicitly considered).

Being the number of sections equal to the number of bays, and being these latter decision variables, the number of sections is found only once it is known the number of bays through the procedure here proposed.

With reference to the possible implementation of Metrocargo system, two different scenarios have been considered:

- scenario 1, in which loading and unloading operations are performed on the same side of the train (Fig. 5);
- scenario 2, in which loading and unloading operations are performed on the two different sides of the train, so not interfering one with each other (Fig. 6).

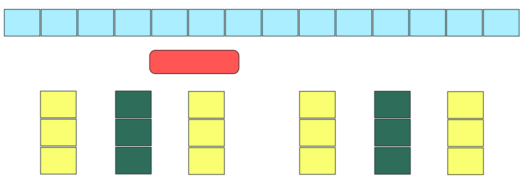

Fig. 5. Example of scenario 1 ($B^L = 4$ and $B^U = 2$).

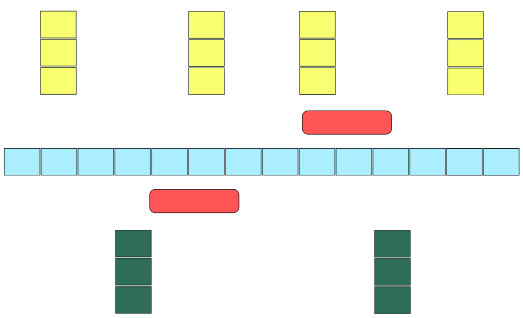

Fig. 6. Example of scenario 2 ($B^L = 4$ and $B^U = 2$).

In fact, according to the available area at the terminal, loading and unloading operations can be assigned to both sides of the train with the purpose of reducing interferences and accelerating operations, so decreasing the total handling time.

In both scenarios, some assumptions are made. As already introduced, it is assumed that the whole train length is ideally divided in exactly as many sections (of equal length) as the number of bays. It can be demonstrated (some details will be provided in Subsection III-C) that in each section the position of the bay which minimizes the total handling time is in the centre of the section; so each bay is placed in a barycentre position within its section.

It is worth underlying that the number of containers placed on a train results to be exactly equal to the sum of containers in the bays. In this way, it is assumed that the frequency of trains passing in the terminal is low enough to allow the reorganization and preparation of containers for the next train. Besides, the possibility of using the terminal as a buffer area is not taken into account.

Moreover, in our analysis we assume that the time required by the automatic devices for making the cargo units translating along the bays is always lower than the time spent by the shuttle for handling one cargo unit. This means that when the shuttle comes back in front of the bay to manage the next container, this latter is ready to be managed in the upper extreme of the bay.

Another basic hypothesis concerns the way in which containers to be loaded or unloaded are assumed to be placed on trains. More specifically, in our analysis we assume that all the containers to be handled are placed in the less favourable position compared to the bay one ("worst case"). This means that they are placed in the extremes of their section. To clarify this point, Fig. 7 shows the "worst case" logic in opposition to the "best case" one (Fig. 8), in the case of 3 containers to be handled in a section of 9 containers.

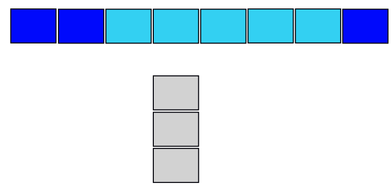

Fig. 7. Handling 3 containers in a section of 8 containers -"worst case"

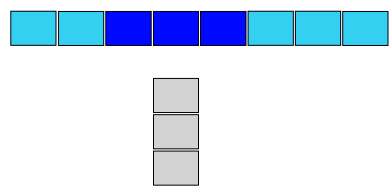

Fig. 8. Handling 3 containers in a section of 8 containers -"best case"

III. Planning Procedure

In this section we present an iterative planning procedure that allows to find out the optimal number of terminal resources that minimize the total handling time and, consequently, the related costs. The goal is to define the correct number of bays for loading (B^L) and unloading (B^U) operations. As already introduced, the way in which we determine these values is associated with the verification that the total time, i.e. T^{tot}, spent by the shuttle to unload and load a train is lower than the maximum acceptable stop time of the train in the terminal, defined as T^*_{max}. This latter constant can assume different values according to the particular flow volume that characterizes a specific Metrocargo terminal.

In the following, the case of one shuttle and the case of two shuttles are treated in detail.

A. Case with one shuttle

As stated above, the total handling time is composed of three different terms. Let us now focus on the first component T_m. If we consider a generic single section, we can determine the time necessary to handle a given number of containers. This handling time is the same both in the loading case and in the unloading one. If we define Γ as the number of containers in a section, the section length is given by $\lambda\Gamma$ (remember that λ is the average container length). Given a section of $\lambda\Gamma$ length in which γ containers have to be loaded (or unloaded), it can be proved that the distance covered by the shuttle $S_m(\gamma)$ is given by the following expression:

$$S_m(\gamma) = \gamma\lambda\Gamma - \lambda \sum_{i=3}^{\gamma} 2 \cdot \lceil \frac{i-2}{2} \rceil \tag{1}$$

The way in which (1) is obtained follows. We analyse how $S_m(\gamma)$ changes while γ is increased by one unit at a time. In the case with $\gamma = 1$ (Fig. 9), the space $S_m(\gamma)$ that the shuttle has to cover is given by:

$$S_m(1) = \lambda\Gamma \tag{2}$$

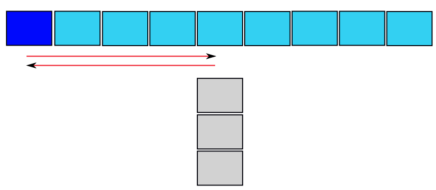

Fig. 9. Loading of $\gamma = 1$ containers in a section of $\lambda\Gamma$ length

In the case with $\gamma = 2$ (Fig. 10), the distance that the shuttle has to cover is given by:

$$S_m(2) = \frac{1}{2}\lambda\Gamma + \frac{1}{2}\lambda\Gamma + \frac{1}{2}\lambda\Gamma + \frac{1}{2}\lambda\Gamma = 2\lambda\Gamma \tag{3}$$

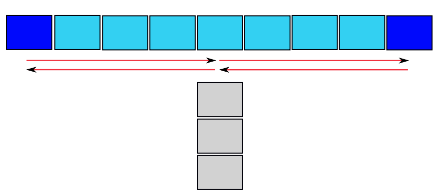

Fig. 10. Loading of $\gamma = 2$ containers in a section of $\lambda\Gamma$ length

In the case with $\gamma = 3$ (Fig. 11), the space that the shuttle has to cover is obtained as:

$$S_m(3) = 2\lambda\Gamma + 2\left(\frac{1}{2}\lambda\Gamma - \lambda\right) = 3\lambda\Gamma - 2\lambda \tag{4}$$

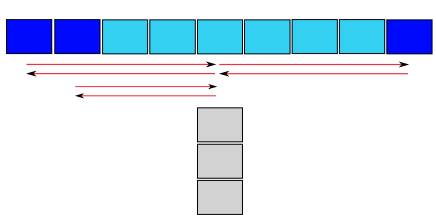

Fig. 11. Loading of $\gamma = 3$ containers in a section of $\lambda\Gamma$ length

Analogously, it is possible to write the following:

$$S_m(4) = 2\lambda\Gamma + 4\left(\frac{1}{2}\lambda\Gamma - \lambda\right) = 4\lambda\Gamma - 4\lambda \tag{5}$$

$$S_m(5) = 2\lambda\Gamma + 4\left(\frac{1}{2}\lambda\Gamma - \lambda\right) + 2\left(\frac{1}{2}\lambda\Gamma - 2\lambda\right) = 5\lambda\Gamma - 8\lambda \tag{6}$$

$$S_m(6) = 2\lambda\Gamma + 4\left(\frac{1}{2}\lambda\Gamma - \lambda\right) + 4\left(\frac{1}{2}\lambda\Gamma - 2\lambda\right) = 6\lambda\Gamma - 12\lambda \tag{7}$$

$$S_m(7) = 2\lambda\Gamma + 4\left(\frac{1}{2}\lambda\Gamma - \lambda\right) + 4\left(\frac{1}{2}\lambda\Gamma - 2\lambda\right) + 2\left(\frac{1}{2}\lambda\Gamma - 3\lambda\right) = 7\lambda\Gamma - 18\lambda \tag{8}$$

$$S_m(8) = 2\lambda\Gamma + 4\left(\frac{1}{2}\lambda\Gamma - \lambda\right) + 4\left(\frac{1}{2}\lambda\Gamma - 2\lambda\right) + 4\left(\frac{1}{2}\lambda\Gamma - 3\lambda\right) = 8\lambda\Gamma - 24\lambda \tag{9}$$

Expressions (2)÷(9), if generalized, give rise to (1). Note that, when all containers in the section are handled, it is always:

$$S_m(\Gamma - 1) = S_m(\Gamma) \tag{10}$$

since the shuttle does not have to horizontally move when handling the last container of the section (that is considered to be the one in the centre of the section).

The time for loading C^L/B^L containers in a section can be obtained from (1) by replacing γ with C^L/B^L and Γ with C/B^L, and dividing by the shuttle speed v. Moreover, in order to obtain the total moving time for loading operations T_m^L, it is necessary to multiply by the number of loading bays B^L:

$$T_m^L(B^L) = \frac{1}{v}\left[\lambda\frac{C^L C}{B^L} - B^L\lambda \sum_{i=3}^{\lceil C^L/B^L \rceil} 2 \cdot \lceil \frac{i-2}{2} \rceil\right] \tag{11}$$

Similarly, the total unloading time (for unloading C^U containers) is the following:

$$T_m^U(B^U) = \frac{1}{v}\left[\lambda\frac{C^U C}{B^U} - B^U\lambda \sum_{i=3}^{\lceil C^U/B^U \rceil} 2 \cdot \lceil \frac{i-2}{2} \rceil\right] \tag{12}$$

With regard to the shifting time T_s, that is the time spent by the shuttle to move among bays, for the loading phase it is given by the following expression:

$$T_s^L(B^L) = \frac{1}{v}\left[(B^L - 1)\lambda\frac{C}{B^L}\right] \tag{13}$$

and similarly, for containers to be unloaded, it is given by:

$$T_s^U(B^U) = \frac{1}{v}\left[(B^U - 1)\lambda\frac{C}{B^U}\right] \tag{14}$$

Concerning the third term of the total handling time, that is the lifting time T_l, for containers to be loaded it is expressed by:

$$T_l^L = C^L \cdot \tau^s + a \tag{15}$$

where τ^s represents the time for lifting one single container and a is a constant that corresponds to the time needed by two automatic columns to approach the first container. For containers to be unloaded, the lifting time is given by:

$$T_l^U = C^U \cdot \tau^s + a \tag{16}$$

It is now possible to write the equation related to the total handling time required by one shuttle to perform loading and unloading operations. If we refer to scenario 1, in which loading and unloading tasks are executed on the same side of the train, the total handling time is given by:

$$T^{tot} = T^{tot,L} + T^{tot,U} = (T_m^L + T_m^U) + (T_s^L + T_s^U) + (T_l^L + T_l^U) \tag{17}$$

In order to find the correct number of loading and unloading bays, it is necessary to meet the constraint on the maximum stop time of the train in the terminal, i.e. T^*_{max}, and thus to impose the following inequality:

$$\begin{aligned}\frac{1}{v}\Bigg[\lambda\frac{C^L C}{B^L} - B^L\lambda\sum_{i=3}^{\lceil C^L/B^L\rceil} 2\lceil\frac{i-2}{2}\rceil + \\ +\lambda\frac{C^U C}{B^U} - B^U\lambda\sum_{i=3}^{\lceil C^U/B^U\rceil} 2\cdot\lceil\frac{i-2}{2}\rceil\Bigg] + \\ +\frac{1}{v}\left[(B^U-1)\lambda\frac{C}{B^U} + (B^L-1)\lambda\frac{C}{B^L}\right] + \\ +\left[\tau^s(C^L + C^U) + 2a\right] \le T^*_{max}\end{aligned} \tag{18}$$

In general, there is an upper bound for the number of bays, which depends on physical space constraints in the terminal. Therefore, also the following condition must be met:

$$B^L + B^U \le B_{max} \tag{19}$$

where B_{max} is the maximum number of bays allowed in the considered terminal.

If the conditions defined by (18) and (19) are not verified for any value of B^L and B^U, this means that more shuttles are needed, in order to parallelize operations. Thus, the case of two shuttles must be analysed.

Referring now to scenario 2, in which loading and unloading operations are performed on different sides of the train, we have to distinguish the loading and unloading times, thus considering two separate cases. The total loading time is given by the following:

$$T^{tot,L} = T_m^L + T_s^L + T_l^L \tag{20}$$

thus the inequality to be met is:

$$\begin{aligned}\frac{1}{v}\left[\lambda\frac{C^L C}{B^L} - B^L\lambda\sum_{i=3}^{\lceil C^L/B^L\rceil} 2\lceil\frac{i-2}{2}\rceil\right] + \\ +\frac{1}{v}\left[(B^L-1)\lambda\frac{C}{B^L}\right] + \left[\tau^s C^L + a\right] \le T^*_{max}\end{aligned} \tag{21}$$

Analogously, the total unloading time is given by:

$$T^{tot,U} = T_m^U + T_s^U + T_l^U \tag{22}$$

and the relative inequality is:

$$\begin{aligned}\frac{1}{v}\left[\lambda\frac{C^U C}{B^U} - B^U\lambda\sum_{i=3}^{\lceil C^U/B^U\rceil} 2\lceil\frac{i-2}{2}\rceil\right] + \\ +\frac{1}{v}\left[(B^U-1)\lambda\frac{C}{B^U}\right] + \left[\tau^s C^U + a\right] \le T^*_{max}\end{aligned} \tag{23}$$

Analogously to scenario 1, there is an upper bound on the number of bays due to physical space constraints in the terminal. Thus, the following condition must be taken into consideration:

$$\max(B^L; B^U) \le B_{max} \tag{24}$$

Therefore, for scenario 2, we have to face two separate problems. The former is relevant to the definition of the number of loading bays, by considering (21) and (24); the latter is relevant to the unloading bays, corresponding to (23) and (24). Of course it could happen that (21) and (24) are verified for certain values of B^L (implying that one shuttle is enough in the loading side), but (23) and (24) are not verified (implying that in the unloading side more than one shuttle is needed).

B. Case with two shuttles

In this section we analyse the case in which we can use two shuttles, being one shuttle not enough to perform all the loading/unloading operations required within the imposed time limit. In order to avoid interferences among shuttles, the train length is divided in two equal parts, without overlappings. In this way each shuttle is allowed to move only within its competence area without entering other shuttle areas. The problem to be solved is similar to the one analysed for the case of one shuttle but it concerns a shorter length and a fewer number of containers.

Let us first analyse the problem considering scenario 1. The inequality to be solved is the following:

$$\max(T^{tot}_{s_1}, T^{tot}_{s_2}) \le T^*_{max} \tag{25}$$

where s_1 and s_2 represent shuttle 1 and shuttle 2 respectively.

Considering again the "worst case" context, let us assume that the most underprivileged shuttle (associated with the maximum total handling time) is shuttle 1. This shuttle has to load and unload in a section a number of containers given, respectively, by the following value:

$$K^L = \frac{\min(\lceil \frac{C}{2} \rceil; C^L)}{\lfloor \frac{B^L}{2} \rfloor} \quad (26)$$

$$K^U = \frac{\min(\lceil \frac{C}{2} \rceil; C^U)}{\lfloor \frac{B^U}{2} \rfloor} \quad (27)$$

As a matter of fact, in the worst case, the shuttle has to load a quantity of containers that is the minimum between C^L (that is the case in which all the containers to be loaded are in the competence area of the shuttle) and the superior part of $\frac{C}{2}$. The unloading case is analogous. The total handling time to perform all the terminal operations is therefore given by the following expression:

$$\begin{aligned} T_{s_1}^{tot} = \frac{1}{v} \Bigg[& \lambda \lceil \frac{B^L}{2} \rceil K^L \lceil \frac{C}{B^L} \rceil - \lambda \lceil \frac{B^L}{2} \rceil \sum_{i=3}^{\lceil K^L \rceil} 2 \lceil \frac{i-2}{2} \rceil + \\ & + \lambda \lceil \frac{B^U}{2} \rceil K^U \lceil \frac{C}{B^U} \rceil - \lambda \lceil \frac{B^U}{2} \rceil \sum_{i=3}^{\lceil K^U \rceil} 2 \lceil \frac{i-2}{2} \rceil \Bigg] + \\ & + \frac{1}{v} \left[(\lceil \frac{B^L}{2} \rceil - 1) \lambda \lceil \frac{C}{B^L} \rceil + (\lceil \frac{B^U}{2} \rceil - 1) \lambda \lceil \frac{C}{B^U} \rceil \right] + \\ & + \left[\tau^s (K^L + K^U) + 2a \right] \leq T_{max}^* \quad (28) \end{aligned}$$

Obviously, the constraint given by (19) must also be verified.

Consider now scenario 2 with two shuttles. As underlined previously in the paper, the two sides of the train represent two disjointed cases. For the loading side, the time required by the most underprivileged shuttle (i.e. shuttle 1) for loading all containers, is given by:

$$\begin{aligned} T_{s_1}^{tot,L} = \frac{1}{v} & \left[\lambda \lceil \frac{B^L}{2} \rceil K^L \lceil \frac{C}{B^L} \rceil - \lambda \lceil \frac{B^L}{2} \rceil \sum_{i=3}^{\lceil K^L \rceil} 2 \lceil \frac{i-2}{2} \rceil \right] + \\ & + \frac{1}{v} \left[(\lceil \frac{B^L}{2} \rceil - 1) \lambda \lceil \frac{C}{B^L} \rceil \right] + \\ & + \left[\tau^s K^L + a \right] \leq T_{max}^* \quad (29) \end{aligned}$$

In order to be able to state that two shuttles are enough for the loading case, together with (29), the upper bound on the number of bays due to physical constraints given by (24), must also be met. If (29) and (24) are not simultaneously verified, it means that two shuttles are not enough to perform all the loading operations.

The unloading case for scenario 2 with 2 shuttles is analogous to the loading one and therefore it is not reported here for space limitations.

In order to summarize, we propose an iterative procedure that starts from the case in which only one shuttle is available and verifies the possibility of performing the necessary loading/unloading operations within a predefined time limit (and within the maximum number of bays). If one shuttle is not enough, the number of shuttles is increased by one and the fulfillment of time (and space) constraints is verified again, until finding the necessary number of shuttles. Note that in this way the number of shuttles to be used is of course minimized.

C. Optimal position of bays

We are now going to give a sketch of the proof of the following statement "the optimal position of the bay which minimizes the total handling time is in the centre of its section". This means that the barycentre position is the optimal one.

Let us consider one section composed of 7 containers. Assuming that the default position of the bay is in the centre of the section, we calculate $S_m^i(\Gamma)$, i.e. the distance that the shuttle has to cover when the bay is placed i positions far from the centre of the section. Note that the superscript i represents the number of train slots (cargo units) that the bay is shifted on the left or on the right with reference to the barycentre position. Moreover, it is assumed that all containers in the section must be handled (i.e. $\gamma = \Gamma = 7$). If the bay is placed exactly in the centre of the section (Fig. 12), the space $S_m^0(\Gamma)$ covered by the shuttle is given by the following formula:

$$\begin{aligned} S_m^0(\Gamma) = 2\lambda\Gamma + 4(\frac{1}{2}\lambda\Gamma - \lambda) + 4(\frac{1}{2}\lambda\Gamma - 2\lambda) \\ = 6\lambda\Gamma - 12\lambda \quad (30) \end{aligned}$$

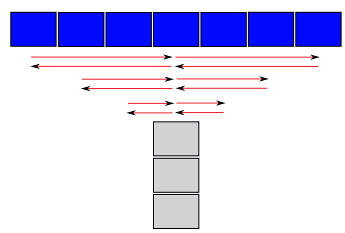

Fig. 12. Bay position in the middle of the section

If the bay is placed one slot shifted on the right or on the left in respect to the middle of the section, the distance that the shuttle has to cover is given by (Fig. 13):

$$\begin{aligned} S_m^1(\Gamma) = 2(\frac{1}{2}\lambda\Gamma + \lambda) + 2(\frac{1}{2}\lambda\Gamma) + 4(\frac{1}{2}\lambda\Gamma - \lambda) + \\ + 4(\frac{1}{2}\lambda\Gamma - 2\lambda) = 6\lambda\Gamma - 10\lambda \quad (31) \end{aligned}$$

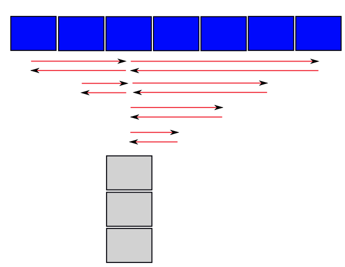

Fig. 13. Bay position one unit shifted from the centre of the section

Analogously $S_m^2(\Gamma)$ is given by:

$$S_m^2(\Gamma) = 2(\frac{1}{2}\lambda\Gamma + 2\lambda) + 2(\frac{1}{2}\lambda\Gamma + \lambda) + 2(\frac{1}{2}\lambda\Gamma) + \\ + 2(\frac{1}{2}\lambda\Gamma - \lambda) + 4(\frac{1}{2}\lambda\Gamma - 2\lambda) = 6\lambda\Gamma - 4\lambda \quad (32)$$

Finally, if the bay position is at the extremes of the section (that is the last allowable bay position), $S_m^3(\Gamma)$ is given by the following expression:

$$S_m^3(\Gamma) = 2(\frac{1}{2}\lambda\Gamma + 3\lambda) + 2(\frac{1}{2}\lambda\Gamma + 2\lambda) + 2(\frac{1}{2}\lambda\Gamma + \lambda) + \\ + 2(\frac{1}{2}\lambda\Gamma) + 2(\frac{1}{2}\lambda\Gamma - \lambda) + 2(\frac{1}{2}\lambda\Gamma - 2\lambda) = 6\lambda\Gamma + 6\lambda \quad (33)$$

In order to understand which bay position minimizes the distance covered by the shuttle (and consequently the time needed to handle all the required containers), all the distances $S_m^i(\Gamma)$, $i = 0, \ldots, 3$, have been converted in times dividing them by the speed v:

$$T_m^i(\Gamma) = \frac{S_m^i(\Gamma)}{v} \quad (34)$$

Then, the following difference is determined:

$$\Delta T_m^i = T_m^0(\Gamma) - T_m^i(\Gamma) \quad (35)$$

thus, leading to $\Delta T_m^1 = \frac{2\lambda}{v}$, $\Delta T_m^2 = \frac{8\lambda}{v}$, $\Delta T_m^3 = \frac{18\lambda}{v}$. Generalizing, for a generic value of i, ΔT_m^i is given by:

$$\Delta T_m^i = \frac{2i^2\lambda}{v} \quad (36)$$

Therefore, we can conclude that moving the bay away from the middle of the section makes the time needed to perform all the operations increase. So, the barycentre position is the optimal one.

IV. Conclusions

A strategic planning procedure has been presented in order to define the optimal layout of a Metrocargo terminal, an innovative intermodal system which allows to quickly move freight on/from trains in an automatic and horizontal way. The developed iterative procedure has demonstrated to be an effective and simple tool to find the optimal layout of the terminal, especially in the case in which few shuttles are needed.

Current and future research will be focused on the formulation of a mathematical programming problem for the case with more than two shuttles. In fact, the iterative procedure works well for the strategic planning of small terminals, with limited number of resources. However, when the problem dimension increases, this kind of approach is no more efficient. So, from three shuttles on, a mathematical programming problem is definitely most appropriate.

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