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Modelling of Rail Guided Vehicles serving an automated parts-to-picker system

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Abstract: An automated parts-to-picker picking system usually consists of an automated warehouse, with Automatic Storage and Retrieval Systems (AS/RS) that retrieve the Stock Keeping Units (SKUs) of the various needed products from their stocking locations, and of a picking area, with human operators or robots that pick the needed items in order to create a mixed shipping unit. The automated warehouse and the picking area are connected by an automated transportation system, which moves the SKUs from the warehouse to the picking stations and vice versa. The transportation system can be, for example, a ring rail conveyor on which various Rail Guided Vehicles (RGVs) are able to carry one SKU at a time. The present paper proposes a preliminary simulative analysis and, then, a mathematical formulation for this transportation system, useful to properly estimate the number of RGVs that are required to fulfill a certain picking throughput. In fact, it is shown that the picking throughput does not increase linearly with the number of vehicles employed, due to congestion issues.

Keywords: warehouse picking, parts-to-picker, rail guided vehicles, picking throughput

1. INTRODUCTION

In a warehouse, order picking is the activity required to retrieve various items from their storage locations to create a mixed shipping unit required by one or more customers (De Koster et al., 2007). Most of the existing warehouse picking systems are still manual and picker-to-parts, with picking operators walking (or travelling) through the aisles to retrieve the items reported on their picking lists (Napolitano, 2012; Battini et al., 2015). However, in some contexts there could be also the possibility of creating automated solutions, at different levels of automation, with potential benefits of easing picking activities and improve picking performances (Azadeh et al., 2017). Automated picking systems are mainly parts-to-picker, usually with an Automatic Storage and Retrieval System (AS/RS) that retrieves the Stock Keeping Units (SKUs) of the various needed products from their stocking locations, in order to deliver them to human pickers, standing in their picking stations. In such a system, the AS/RS and the picking stations are connected through a proper conveyor, in which all the stock keeping units are moved, from the stocking area to the picking area and, once the picker has taken the number of items he needs, back to the stocking area (Roodbergen and Vis, 2009). The dimensioning of such a system has to take into account the amount of orders, hence, the number of SKUs that have to be moved in a certain time range. This is translated in a certain throughput that the system has to warrant, in terms of SKUs retrieved and stored per hour. Therefore, it emerges the need of understanding the factors that can foster or limit the reaching of the required performances. In particular, it has already been demonstrated in literature, but also faced by the authors in practical industrial applications, that the handling system (e.g. the conveyor) between the automated warehouse and the picking stations can represent a bottleneck (Lee et al., 1996; Schmidt and Jackman, 2000).

The present paper aims at studying a specific kind of material handling system which is usually employed for the transportation of SKUs from the automated warehouse and the picking area and vice versa, which uses Rail Guided Vehicles (RGVs) moving on a fixed path. In this case, RGVs are considered to be an alternative of roll conveyors. Starting from the analysis of the possible factors that can influence the design and the performances of these parts-to-picker systems, it is proposed a preliminary simulative analysis, in order to derive a proper mathematical formulation that can be useful to estimate the right number of RGVs that are required to fulfil a certain picking throughput. In particular, it is shown that, due to RGVs congestion, the picking throughput does not increase linearly with the number of installed vehicles. Hence, it derives that, to ensure a proper system design, it is important to determine the correct trade-off between the size of the RGVs fleet and the picking performance.

The remainder of the paper is structured as follows. In the next section, a brief literature review concerning material handling systems, conveyors and some existing mathematical models for the dimensioning of such devices is presented. Section 3 presents the setting of the system under study and the general results that have been obtained through the 3D simulation with Applied AutoMod® software. Subsequently, Section 4 reports the mathematical model introduced for the calculation of the cycle time, of the system throughput and, hence, for the right dimensioning of a rail guided vehicles conveyor system. Then, in Section 5, the model is applied to the simulation dataset, to compare the analytical formulations to the output of the simulation and to derive some general insights about the observed trends. Finally, in the last section, the conclusions and some suggestions for further researches are proposed.

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2. LITERATURE REVIEW

A material-transport equipment is a material handling system which has the primary function of transporting material within a factory. Examples of material-transport systems are: conveyors, industrial vehicles, monorails, hoists, cranes (Tompkins et al., 2010). A typical classification of such systems considers their degree of automation (walking, riding, automated), the flow pattern (continuous, intermittent or synchronous, asynchronous), the flow path (fixed, variable) the location (underground, in-floor, floor level, overhead) and the throughput capacity (Le-Anh and De Koster, 2006; Roodbergen and Vis, 2009). In case there are many items that have to be moved frequently between specific points, always in the same direction and over a fixed path, usually the conveyor (e.g. roller, belt, chain) represents the best solution. An alternative to a traditional continuous conveyor is a Rail Guided Vehicles system, in which various vehicles move on a closed-loop rail path to retrieve and deliver the required items, which is often used for connecting an automated warehouse to a picking area (Lee et al., 1996; Dotoli and Fanti, 2002).

The existing literature concerning RGVs system is not as wide as the one proposed for conveyor systems (Roy et al., 2016). For these latter systems, there are several contributions focused on understanding and modelling their actual operation, considering the proper design to warrant a certain throughput and to avoid possible congestions and queues of the material (Andriansyah, 2011; Claeys et al., 2015). However, it is important to underline that an RGVs system significantly differs from a conveyor system. In a RGVs system, in fact, the throughput mainly depends on the number of vehicles that are installed, which becomes a fundamental design driver. The so-called *fleet sizing problem* has been addressed several times for Automatic or Laser Guided Vehicles, considering that they work on a limited area, riding always on the same path (Arifin and Egbelu, 2000; Choobineh et al., 2012; Ferrara et al., 2014). However, these models are not easily applicable to a RGVs system serving a picking area, since for RGVs the operating context is usually different, the distances travelled are shorter and they are not allowed to overtake each other (Roodbergen and Vis, 2009). Moreover, due to the interaction of several operation aspects, the modelling of such a system presents a complexity that has often been addressed through simulative analyses. In this direction, one of the researches concerning the design and the operation of an RGVs system has been developed by Lee et al. (1996), through the proposal of a simulation model. In this case, the aim of the study is exactly the determination of the optimal number of RGVs able to warrant the maximum throughput of the system. It is demonstrated that the increase of the number of RGVs leads to an increase of the throughput but only for a certain number of vehicles. Besides this number, in fact, adding one more vehicle could cause congestions and additional costs. However, these outcomes are only based on the simulation results and they are not generalized by an analytical model. Dotoli and Fanti (2002; 2005) analyse a system similar to the one faced in the present paper, though focussing on the interaction between the RGVs conveyor system and the AS/RS of the automated warehouse, which is not the scope of the present paper. There, they propose a modelling based on Colored Time Petri Nets. Another interesting study which uses a simulative approach is by Lin et al. (2004). They investigate the behaviour of a double-loop of an interbay material handling system (for wafer fabrication) considering its throughput and transportation time.

3. SIMULATION SET UP

In order to understand the behaviour of a RGV conveyor serving an automated parts-to-picker system, a 3D software simulation with Applied AutoMod® has been set up. The simulation environment consisted in a rail ring conveyor positioned between an automated pallet warehouse with AS/RS and a picking area (Figure 1). The conveyor length was L=100 m, while the points of pallet- loading and unloading were situated symmetrically on both the longer sides of the ring, equally distributed. Two different configurations of the loading/unloading bays have been considered: one with three points both on the automated warehouse side and on the picking area, and one with five points on each side. The number of travelling RGVs have been varied in a range from 1 RGV to 20 RGVs: 1, 2, 4, 6, 10, 12, 14, 16, 18, 20. It has then been considered two values of RGV speed, v=1.0 m/s and v=1.5 m/s, and two values of stop time, needed for loading (or unloading) a pallet on (from) the RGV: $t_{L/U}$=5 seconds and $t_{L/U}$=10 seconds. The combination of all these parameters has led to 88 different simulation runs. Each simulation run referred to an operation timing of the system of 10 hours, in which the RGVs were continuously involved in retrieving and depositing pallets in the various points (i.e. there were always SKUs ready to be moved from and to the automated warehouse). In each loop, one RGV stopped one time at one of the points on the automated warehouse side and one time at one of the points on the picking area side. The points at which the RGVs had to stop were always different and chosen randomly.

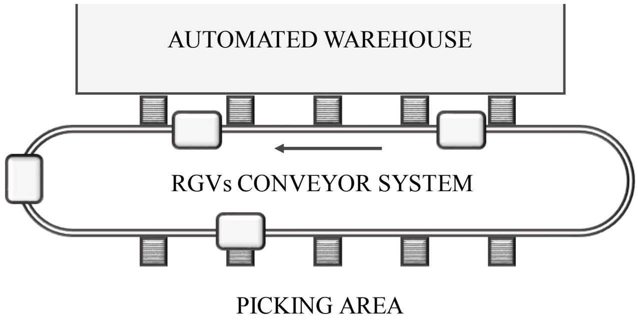

Fig. 1. Rail Guided Vehicles conveyor system under study.

For each simulation run, it has been counted the total number of loops done by the first RGV during the 10 hours. From this data it has been possible to derive the average time per loop t_s:

$$t_s = \frac{total\ simulation\ time}{total\ number\ of\ loops} \tag{1}$$

as well as the single throughput per RGV Q_s, expressed in cycles per hour:

$$Q_s = \frac{3600}{t_s} \tag{2}$$

Then, defining N as the number of RGVs working on the rail conveyor, the total throughput of the rail conveyor system is:

$$Q_{tot_s} = N \cdot \frac{3600}{t_s} \tag{3}$$

As expected, the results of the simulation runs have shown that the total throughput does not increase linearly with the increasing of the number of RGVs. In fact, from a certain number of RGVs onwards, congestion issues emerge, slowing down the whole system. This is shown, for example, through the trends of the graphs in Figure 2 for the average cycle time t_s and Figure 4 for the total throughput of the RGVs system Q_{tot_s}, varying the number of RGVs.

4. MODEL FOR RGV FLEET DIMENSIONING

In this section the mathematical modelling for the evaluation of the performance of an RGVs conveyor system is showed.

First of all, considering the length of the conveyor L, the RGV maximum speed v and acceleration a and the pallet loading (unloading) time $t_{L/U}$, a theoretical cycle time is defined as

$$t' = \frac{L}{v} + 2 \cdot \frac{v}{a} + 2 \cdot t_{L/U} \tag{4}$$

and, similarly to (2), the theoretical throughput of one RGV is

$$Q' = \frac{3600}{t'} \tag{5}$$

Then, considering that a certain total throughput is required to the system Q_r, in terms of cycles that have to be performed per hour according to the pallets that have to be moved from one side to the other, the number of needed RGVs turns out to be:

$$N' = \left\lceil \frac{Q_r}{Q'} \right\rceil \tag{6}$$

From the same data it can be calculated the average speed of a RGV:

$$\bar{v} = \frac{L}{t'} \tag{7}$$

and, then, the average interference space between two consequent RGVs:

$$s = 2 \cdot t_{L/U} \cdot \bar{v} \tag{8}$$

On the other side, the maximum available space per RGV depends on the number of RGVs that are employed and is calculated with:

$$s_a = \frac{L}{N'} \tag{9}$$

Moreover, the parameter introduced in (8) allows to calculate the threshold number of RGVs as:

$$N_k = \left\lfloor \frac{L}{s} \right\rfloor \tag{10}$$

which represents the maximum number of RGVs that can work together on the rail conveyor without causing congestion issues.

It derives that the formulations of both the cycle time t and of the total system throughput Q_{tot} have to take into account this threshold number, as follows:

$$t = \begin{cases} t' & if \;\; N' \leq N_k \\ t' + \Delta t & if \;\; N' > N_k \end{cases} \tag{11}$$

where Δt considers the positive slope of the straight line m, which can well approximate the trend of the cycle time shown in Figures 2 and 3:

$$\Delta t = m \cdot (N' - (N_k + 1)) \tag{12}$$

$$Q_{tot} = \begin{cases} N' \cdot \frac{3600}{t'} & if \;\; N' \leq N_k \\ N' \cdot \frac{3600}{t' + \Delta t} & if \;\; N' > N_k \end{cases} \tag{13}$$

In the next Section, the model here presented is applied and compared to the results of the simulation runs, and some remarks are derived.

5. MODEL APPLICATION AND RESULTS COMPARISON

The proposed model has been applied to the simulation dataset. The results shown in this section concern the cycle time of one RGV, expressed in seconds, and the system total throughput, measured in number of cycles (retrieval and storage of one SKU) performed per hour. In each one of the following figures, four graphs are shown, according to the as many combinations that come out from the two values of the RGV speed, v= 1.0 m/s and 1.5 m/s, and the two stop times, $t_{L/U}$=5 s and 10 s. Each graph displays the threshold number of RGVs N_k, the theoretical values of the cycle time t' or of the total throughput Q'_{tot}, calculated considering that there are no congestions and interferences among the RGVs, the values obtained from the simulation runs (t_s or Q_{tot_s}) and the ones calculated through the introduced formulation, t or Q_{tot}. For the calculation of t, the values of the various m have been derived from the linear approximation of the curve related to the simulation results. In all cases, it can be noticed that the mathematical formulation represents a good approximation of the simulation results.

Figures 2 and 3 show the trend of the cycle time (t', t_s, t) varying the number of RGVs working simultaneously on the rail conveyor system. In Figure 2, the number of stop points for pallet loading/unloading is three, both on the automated warehouse and on the picking area side (3+3), while in Figure 3 the stop points are 5 on both sides (5+5). Looking at the graphs, the threshold number of RGVs N_k varies in all of them but it is the same regardless of the number of stop points. In fact, as it can be seen also from (8) and (10), the threshold number of RGVs depends on $t_{L/U}$ and $\bar{v}$ but it does not depend on the number of stop points. Hence, the increasing of the cycle times, and then, the arising of congestion issues, start from the same number of RGVs. On the other side, the difference in the number of stop points influence the slope of the cycle time curves, that is higher for a lower number of points (3+3): if there are fewer points at which the RGVs can stop, it is more probable to have queues at them. As far as RGV speed maximum v is concerned, it can be pointed out that, of course, a higher speed v lowers N_k and increases the average cycle times, keeping the same $t_{L/U}$. A similar effect, but with a higher impact, can be observed by increasing $t_{L/U}$.

Figures 4 and 5 report the trend of the total throughput of the system (Q'_{tot}, Q_{tot_s}, Q_{tot}), for 3+3 L/U points and 5+5 L/U points, respectively. Here, the graphs show how the performance of the system increases linearly until reaching N_k; after it, the curve has a lower slope. Also in this case it can be seen the greater influence of $t_{L/U}$ with respect to v.

Generally, these graphs clearly show that the increase of the number of RGVs not necessarily leads to an increase of the system throughput, due to congestion phenomenon. In fact, a positive linear correlation exists only until the reaching of the threshold number N_k. Hence, if a throughput higher than $Q_{tot}(N_k)$ is needed, it could be useful to investigate other ways to improve such throughput, besides increasing the number of RGVs. For example, this exploratory study shows that an action on the reduction of $t_{L/U}$ gives higher benefits compared to having faster vehicles. Furthermore, given a certain configuration of the system in terms of length of the rail and number of stop points, these graphs allow to understand the best choices that can allow the reaching of the desired throughput Q_r. For example, looking at Figure 5 and considering Q_r=300 cycles/h, it can be seen that this is achievable with 10 RGVs with no congestion issues for v= 1.0 m/s and $t_{L/U}$=5 s, and with 8 RGVs for v= 1.5 m/s and $t_{L/U}$=5 s. On the other side, if $t_{L/U}$=10 s, 12 RGVs are needed if v= 1.0 m/s while 10 RGVs are necessary if v= 1.0 m/s. Therefore, in this particular case, the first and the fourth settings warrant the same performance of number of cycles per hour with the same number of RGVs, even if in the latter case $N' > N_k$ and there are congestion problems.

6. CONCLUSIONS AND FUTURE RESEARCHES

In this paper, an explorative study concerning Rail Guided Vehicles serving an automated parts-to-picker system has been presented. Starting from a simulation setting developed in Applied AutoMod®, a mathematical formulation for the estimation of the system throughput and of the right number of RGVs to employ has been proposed. In particular, it has been shown that the system throughput Q_{tot} does not increase linearly with the number of RGVs N, due to congestion phenomena. Therefore, it derives that the increase of the system throughput does not necessarily imply the increase of the number of RGVs: in some cases, other actions, like the improvement of the operation of the vehicles, should be investigated. Moreover, the graphs that have been derived have shown that the same throughput can be obtained with different system configurations, leading to the need of a trade-offs analysis.

Due to the narrowness of the simulation dataset, this study represents only a first step for a research that should be widened. Future researches in this sense should consider further simulation runs, by changing more parameters and by assigning them more values. For example, further congestion issues could emerge with the increase of the number of stop points, although in the presented cases the effect was the opposite (i.e. more stop points led to higher throughput). Therefore, it could be interesting to define a 'stop points threshold', similar to the one that has been proposed here for the number of RGVs.

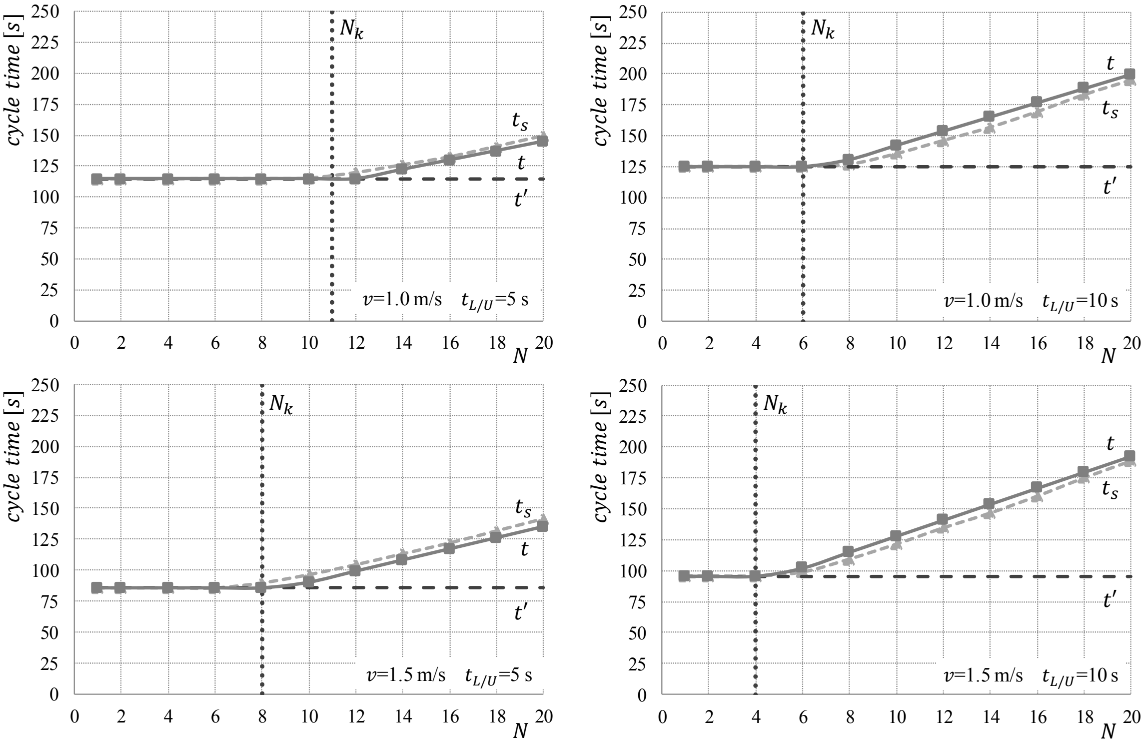

Fig. 2. Average cycle time (t' theoretical, t_s simulation, t formulation) varying the number of RGVs, 3+3 L/U points.

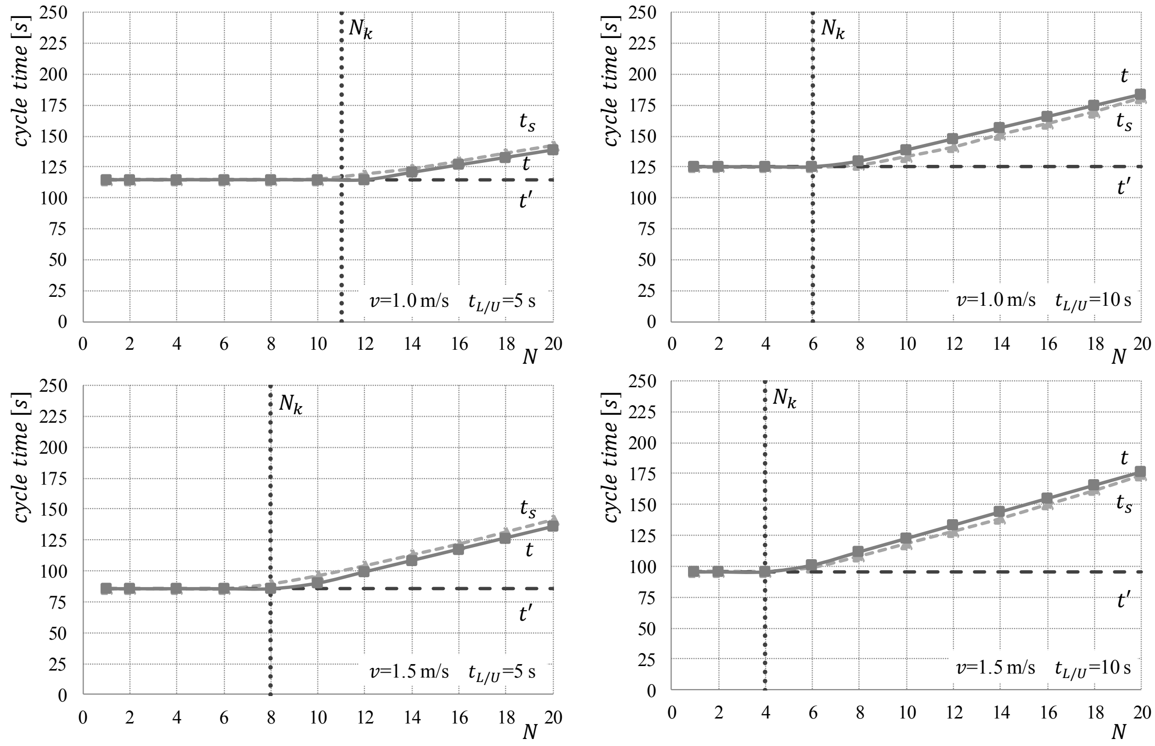

Fig. 3 Average cycle time (t' theoretical, t_s simulation, t formulation) varying the number of RGVs, 5+5 L/U points

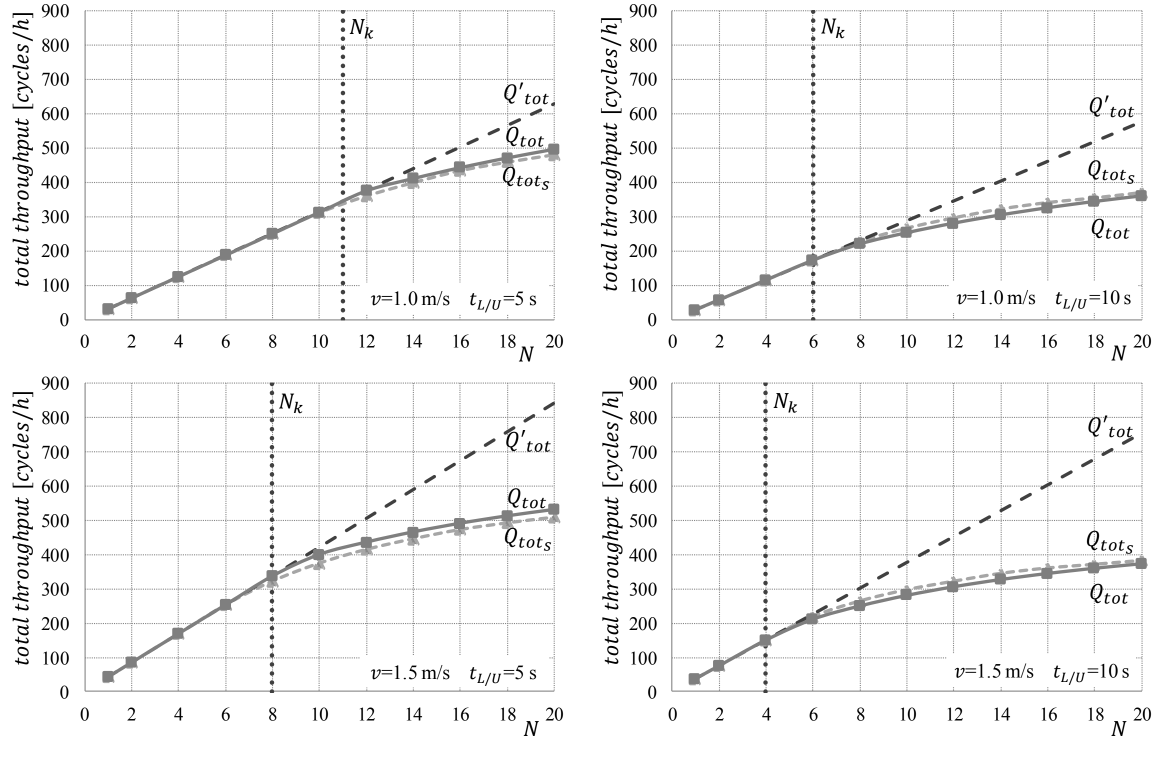

Fig. 4. Total throughput of the RGVs system (Q'_{tot} theoretical, Q_{tot_s} simulation, Q_{tot} formulation) varying the number of RGVs, 3+3 L/U points.

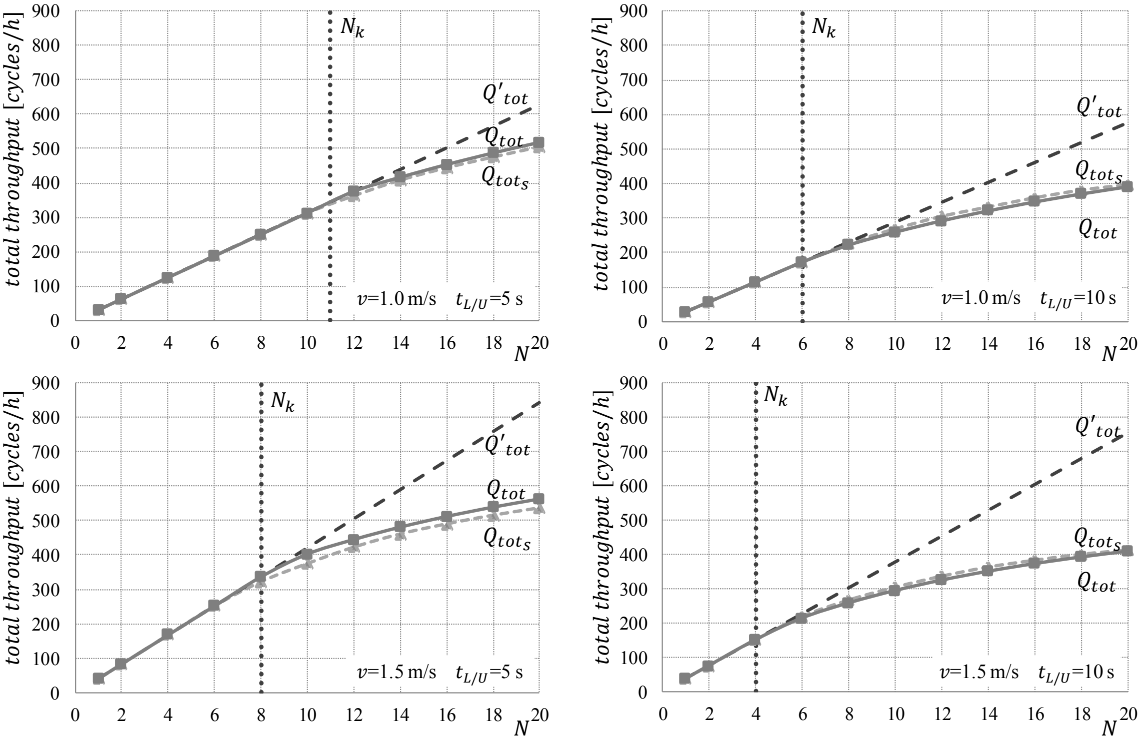

Fig. 5. Total throughput of the RGVs system (Q'_{tot} theoretical, Q_{tot_S} simulation, Q_{tot} formulation) varying the number of RGVs, 5+5 L/U points.

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