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Efficacy and Space Optimization in Industrial Warehouses: An Evaluation of Paternoster Continuous Vertical Conveyors

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Abstract: In the field of industrial buildings, notably within warehouse settings, the optimization of floor space emerges as a paramount concern. The deployment of equipment facilitating continuous transport is mandated to not only augment throughput but also to economize on spatial allocation. Within this spectrum, continuous vertical conveyors, particularly of the paternoster variety, have been adopted as a quintessential solution. This study delineates the design intricacies of a paternoster continuous vertical conveyor, elucidating the methodology employed in calculating its maximal throughput, movement resistance, and the requisite power for its electric motor. Through a rigorous analytical approach, the performance of the paternoster conveyor is meticulously evaluated and juxtaposed against alternative continuous vertical conveyor systems. The findings underscore the paternoster conveyor's efficacy in achieving high throughput efficiency while conserving space, thus reaffirming its utility in industrial warehousing. The evaluation employs comparative metrics to highlight the paternoster system's superiority in specific operational parameters. This analysis contributes to the corpus of knowledge by providing a comprehensive examination of paternoster conveyors, thereby aiding in the selection of efficient transport solutions within the constraints of warehouse space optimization.

Keywords: Continuous vertical conveyors; Paternoster system; Throughput efficiency; Space optimization; Industrial warehousing; Electric motor power; Movement resistance

1 Introduction

Transport machines are various devices for transferring and manipulating transport units in the production and storage of materials and goods. The basic task of transport machines is the possibility of spatially and cinematically connecting two points: the beginning (source) of transport and the end (sink, place of material use).

The general division of transport machines can be carried out into non-continual transport machines (cranes: bridge, portal, construction, floating, truck cranes, and lifting platforms) [1–3], continuous transport machines (mechanical conveyors: belt, roller, elevators, chain, screw, vibrating, pneumatic, and hydraulic conveyors) [4–7], and floor transport means (which move freely or with control on the surface or are on the route (rails)) [4].

Conveyors, as representatives of continuous transport machines, are used in mass production, assembly, and process industries, especially in the automotive industry. Also, they are characterized by a long transport line that can change the direction of movement according to the technological needs of the manufacturing process. Formed are around a path from profiled supports along which articles with rolls move, connected in a closed circle by some type of chain (lamella chain or chain with calibrated links). A chain conveyor can safely transport materials from one level to another, which, when done by human labor, would be laborious and expensive.

The paper [8] presents results that augment theoretical principles governing the determination of elevator capacity and transport comfort. By delving into the mathematical modeling of elevator drive load, analyzing traffic flow dynamics, and proposing methodologies for assessing transport comfort, the study contributes valuable insights to enhance the understanding and optimization of elevator operations.

The use of continuous vertical conveyors in industry, especially in warehouses, is very common, primarily because they save floor space and have a greater throughput than elevators or cranes, which do not transport loads continuously [7, 9, 10].

Paternoster, or paternoster lift, is well known from the past as a passenger elevator consisting of a series of linked doorless compartments that move slowly in a loop up and down inside a building without stopping [7]. Passengers can carefully step on or off any floor they like. The continuous vertical chain conveyor (Paternoster type) is similar, but it is used for cargo transport [11]. Paternoster continuous conveyor runs in automatic mode, provided no input or output conveyor is blocking the transport process.

2 Continuous Vertical Conveyor – Paternoster Type

2.1 Conveyors Description

The continuous vertical chain conveyor, paternoster type (Figure 1), consists of a box containing a chain inside, a drive sprocket with an electromotor, and a tension sprocket. The product carriers are attached to the chain and move in a circular motion together with the chain, keeping the loads horizontal during transport. The paternoster conveyor uses fork carriers and can reach various height positions, both for infeed and outfeed (Figure 2).

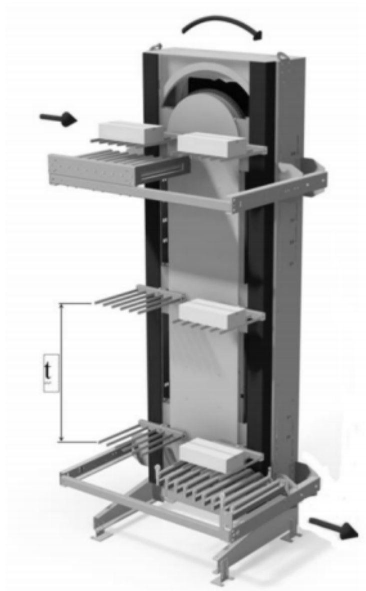

Figure 1. Paternoster chain conveyor with two heights

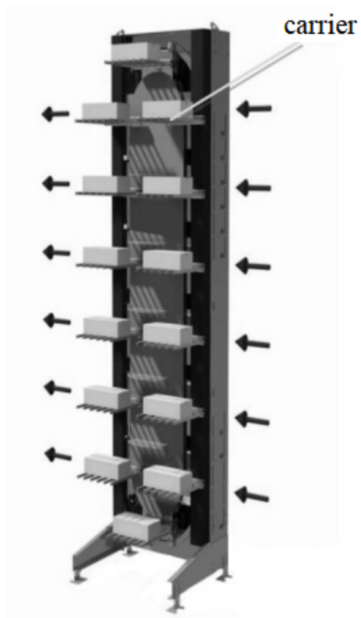

Figure 2. Paternoster conveyor with six heights

As soon as a carrier enters the area of an infeed conveyor and the next carrier is empty, the feeding in of a load can start. The paternoster control device informs the infeed conveyor how much time is still available to start and complete the infeed process. If the available time is greater than the time required, the infeed process may start. If the infeed cycle takes too long or if there is some irregularity, the paternoster conveyor will stop transporting.

A similar procedure applies for unloading. As soon as a fork carrier enters the area of an outfeed level and the load on the carrier is also destined for this level, the available time will be calculated and the unloading cycle will start if the available time is greater than the required unloading time. Unloading must be completed before the next loaded carrier enters the hazardous area; otherwise, the conveyor will stop rotating.

The conveyor control software is made up of the main module and at least two sub-modules, of which there is one infeed module and one outfeed module.

The main software module can operate with multiple infeed and outfeed sub-modules. The function of the main software module covers: moving the fork carriers, keeping track of the current position of carriers by means of an encoder, handling communication with the sub-modules (infeed and outfeed conveyors), and protecting the conveyor carriers against damage.

Furthermore, the function of the sub-modules (infeed and outfeed conveyors) covers: transporting loads to the desired height, handling communication with the main module, securing and monitoring conveyor runs, handling communication with the upstream and downstream control systems, etc. Infeed modules are always on one side of the conveyor, and outfeed modules are on the other side.

The paternoster conveyor enables two infeed and two outfeed directions at every height level. Possible infeed and outfeed directions are shown in Figure 3, both for elevating and descending the products. Not feasible combinations of loading and unloading for elevating are: B1, B2, C3, and C4, and not possible infeed/outfeed directions for descending are: 5F, 6F, 7G, and 8G.

Also, the paternoster conveyors enable continuous product transport on two or more levels (Figure 4), depending on the conveying requirements. In this manner, the conveyor design can easily suit the product flow demands.

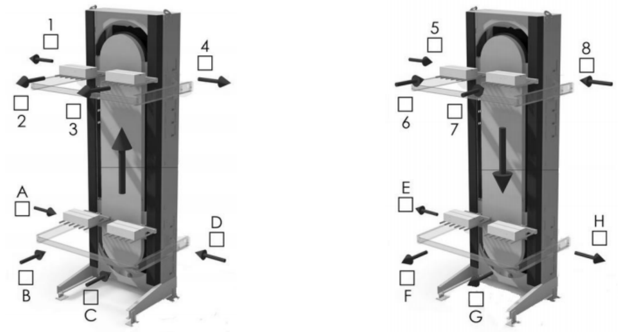

Figure 3. Paternoster infeed and outfeed directions combinations for lifting (left) and lowering (right)

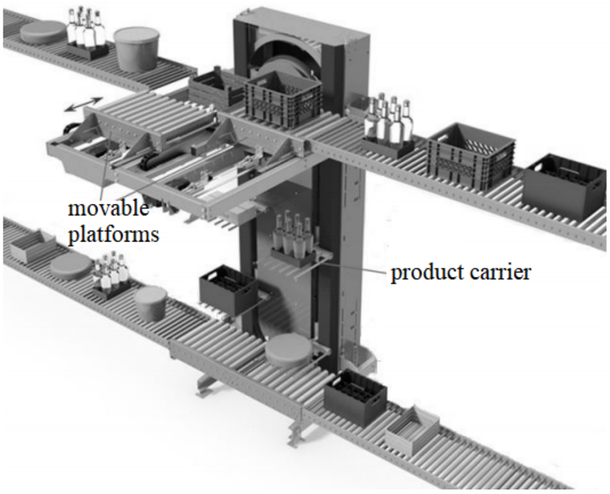

Figure 4. Paternoster conveyor with a product flow on two levels

2.2 Conveyors Versatile Applications

Besides vertical transport, paternoster conveyors have a wide and versatile application in production, industry, and warehousing. Because vertical conveyors occupy minimal floor space, paternoster conveyors can be implemented in almost every factory or warehousing layout.

The paternoster conveyors enable the continuous movement of some products upwards and the transport of other products downwards. This type of conveyor can be easily combined with other horizontal or inclined conveyors ('combi solution'). The paternoster conveyors can also sort products vertically or serve as a buffer for products. If a passage for AGVs or forklifts is needed in the working area, the paternoster conveyor can build a conveyor bridge by using two vertical conveyors.

If there is a need to transport objects from one height level to another, with minimum requirements for floor space, it is also feasible to implement a paternoster vertical conveyor hanging on the first level (height) and transport goods upwards to the second or third level. This could save money, and the ground floor level will remain completely free for other activities.

2.3 The Basic Design of Paternoster Conveyors

The minimal distance between the paternoster fork carriers is the sum of parcel height (h_{P}), the required necessary height for loading, i.e., unloading of products (h_{N}), and the security height (h_{SEC}) for emergency stopping of the conveyor in case of malfunctions or other irregularities.

The distance between the product carriers (carrier pitch or step) must be sufficient to secure the unloading of parcels. Figure 5 depicts a paternoster conveyer scheme, which includes an explanation of the carrier pitch calculation for the parcel descend. The same calculation applies to the ascent of the parcels. The fork carrier pitch, or step (*t*), must be greater than:

$$t = t_{fork} \geq h_p + h_N + h_{SEC} \tag{1}$$

Here, h_{P} is the parcel height, or the maximal parcel height if different parcels are used; h_{N} is the necessary height corresponding to the loading (unloading) time at infeed (outfeed) positions ($h_{\mathrm{in/out}}$) or moving time of the bridge platform if there are several loading (infeed) or unloading (outfeed) points at different heights $(h_{\text{mov.plat}})$; and, finally, h_{SEC} is security height for emergency stopping of conveyors in case of malfunctions or other irregularities. Let us assume the size of the parcels as: $a_{\mathrm{P}} \times b_{\mathrm{P}\times} h_{\mathrm{P}} = 0.5 \times 0.4 \times 0.35[\,\mathrm{m}]$.

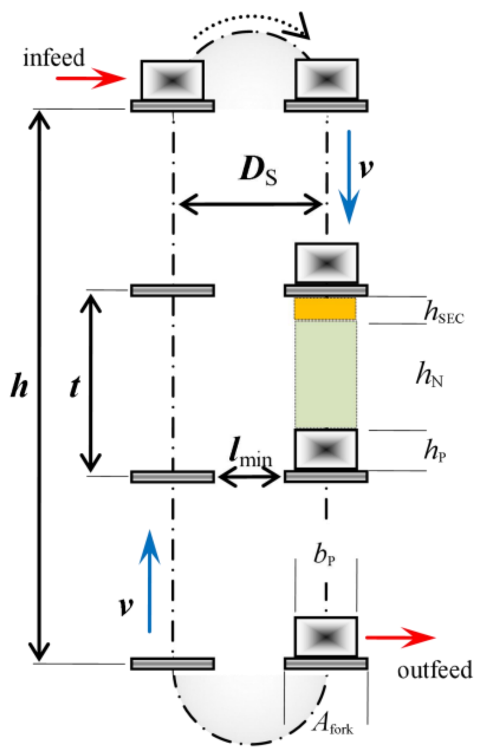

Figure 5. Paternoster conveyor scheme

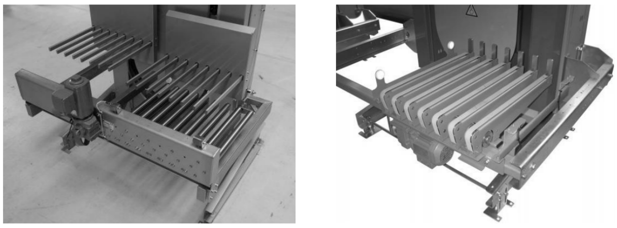

Figure 6. Rectangular conveyor scheme

The infeed or outfeed height depends on loading, i.e., unloading solutions. One solution has a moving bridge platform (see Figure 4), which moves and frees the passage when the fork carrier with the load needs to pass, i.e., it does not move if the load needs to be unloaded there. This is achieved because the bars of the fork carriers pass through the rollers of the moving bridge platform, and the load is retained on the platform and directed by platform rollers to the next horizontal conveyor for further transport.

First, we consider the case involving movable bridge platforms (see Figure 4) and several infeed and outfeed height levels. Assuming a typical conveyor velocity of $v = 0.5[\mathrm{~m/s}]$, the height that the bridge platform travels during the time of $t_{\text{mov.plat}} = 1[\mathrm{s}]$ is given as:

$$h_{\mathrm{N}}(\mathrm{a}) = h_{\text{mov.plat}} = v \cdot t_{\text{mov.plat}} = 0.5 \cdot 1 = 0.5[\mathrm{~m}] \tag{2}$$

and with the security height of $h_{\mathrm{SEC}} = 0.1[\mathrm{m}]$ and the parcel height of $h_{\mathrm{P}} = 0.35[\mathrm{m}]$, the fork carrier pitch (step) is:

$$t_{\mathrm{a}} = t_{\text{fork}}(\mathrm{a}) \geq h_p + h_{\text{mov.plat}} + h_{SEC} = 0.35 + 0.5 + 0.1 = 0.95[\mathrm{m}] \tag{3}$$

If the design assumes that neither of the two bridge platforms (on the infeed and on the outfeed height) moves, a fixed roller (Figure 6 left) or a belt conveyor (Figure 6 right) can be used in that case, and the required fork carrier pitch (step) is smaller. If there is one infeed point height level with a synchronized loading conveyor and one outfeed height level with a fixed roller or belt conveyor for unloading, the necessary height is given as:

$$h_{\mathrm{N}}(\mathrm{b}) = h_{\text{in /out}} = v \cdot t_{\text{in / out}} \tag{4}$$

Here $h_{\text{in/out}}$ is the distance traveled by the fork carrier during the loading or unloading of the parcels, i.e., the required height for infeeding or outfeeding, and $t_{\text{in/out}}$ is the loading or unloading time. The infeed or outfeed conveyor speed should be greater than the chain paternoster conveyor speed ($v_{\text{in/out}} \geq v$). For the roller conveyors shown in Figure 6 left, the typical speed is about $v_{\text{in/out}}(\text{roll}) = 1[\mathrm{m/s}]$, and for the belt conveyors depicted in Figure 6 right, the speed is greater, at least $v_{\text{in/out}}(\text{belt}) = 2[\mathrm{m/s}]$. Counting with an infeed or outfeed load traveling distance $\left(l_{\text{in/out}}\right)$ slightly greater than the dimension of the parcel $\left(l_{\text{in/out}} > a_{\mathrm{P}}\right)$, this implies that the required necessary height in the second case is $h_{\text{in/out}}(\text{roll}) = 0.3[\mathrm{m}]$ for the roller conveyors and $h_{\text{in/out}}(\text{belt}) = 0.15[\mathrm{m}]$ for the belt conveyors. With a security height of $h_{\mathrm{SEC}} = 0.1[\mathrm{m}]$, the fork carriers' pitch for the second solution reads:

$$\begin{aligned} t_b(roll) &= t_{fork}(roll) \geq h_p + h_{in/out}(roll) + h_{SEC} = 0.35 + 0.3 + 0.1 = 0.75\ [m] \\ t_b(belt) &= t_{fork}(belt) \geq h_p + h_{in/out}(belt) + h_{SEC} = 0.35 + 0.15 + 0.1 = 0.6\ [m] \end{aligned} \tag{5}$$

2.4 Paternoster Conveyor Case Study

Let us assume that the load lifting height is set to be $h = 3[\mathrm{~m}]$, with a defined conveyor speed of $v = 0.5[\mathrm{~m/s}]$, i.e., the transportation speed of the chain and carriers with loads.

The parcel size is very important. The conveyor manufacturer Qimarox [12] limits the parcel basis dimensions to 0.6×0.6 [m], with variable parcel height, and with a maximal parcel weight of 50 [kg]. The calculation given here assumes the load weight of $m_{\mathrm{P}} = 30[\mathrm{kg}]$, and the defined parcel size: $a_{\mathrm{P}} \times b_{\mathrm{P}} \times h_{\mathrm{P}} = 0.5 \times 0.4 \times 0.35[\mathrm{m}]$.

The parcel carriers have a fork shape with a single weight of $m_{\text{fork}} = 2.5[\mathrm{kg}]$, and dimensions of $A_{\text{fork}} = 450[\mathrm{mm}]$, $B_{\text{fork}} = 573[\mathrm{mm}]$, according to the standard versions of the conveyer producer [12]. This implies that the parcels are placed transversally onto the carriers (see Figure 5). If the minimal safety distance between carriers is set to $l_{\min} = 75[\mathrm{mm}]$, then the minimal sprocket diameter $D_{\mathrm{S}}(\min)$ is: $D_{\mathrm{S}}(\min) \geq A_{\text{fork}} + l_{\min} = 450 + 75 = 525[\mathrm{mm}]$.

As defined by the producer [12], the minimal sprocket diameter is $D_{\mathrm{S}}\,(\min^*) = 550[\mathrm{mm}]$. The conveyer chain 16B-01 is implemented in this case with a pitch of $p_{\text{ch}} = 25.4[\mathrm{mm}]$, a weight of $m_{\text{ch}} = 2.8[\mathrm{kg/m}]$ and a chain tensile strength of $F_{\text{ten}} = 60[\mathrm{kN}]$. Both the chain sprockets, the driving sprocket at the top and the tension sprocket at the bottom, have $z_{\mathrm{s}} = 76$ teeth, with the median diameter of $D_{\mathrm{S}} = 614.64[\mathrm{mm}] > D_{\mathrm{S}}\,(\min^*) = 550$ [mm]. For the required lifting height of $h = 3[\mathrm{m}]$, the required chain length L_{ch} is given as:

$$L_{\text{ch}} = D_{\mathrm{S}} \cdot \pi + 2 \cdot h = 614.64 \cdot \pi + 2 \cdot 2997 = 7924.95[\mathrm{mm}] \approx 7925[\mathrm{mm}] \tag{6}$$

For the applied chain 16B-01, the fork carrier pitch is $t_{\text{fork}} = 39 \cdot p_{\text{ch}} = 990.6[\text{mm}]$, with $N_{\text{fork}} = 8$, the number of fork carriers for parcels on the entire length of the paternoster conveyor chain.

A very similar conveyor performance can be reached with larger sprockets (with $z_{\text{s}} = 84$ teeth), the median diameter of which is $D_{\text{S}} = 679.3$ [mm], with $N_{\text{fork}} = 8$ fork carriers, and with the minimally longer carrier pitch (step) of $t_{\text{fork}} = 40 \cdot p_{\text{chain}} = 1016[\text{mm}]$ and chain length of $L_{\text{ch}} \approx 8128[\text{mm}]$.

The transportation tactic is:

$$Tact = t_{\text{fork}} / v \approx 1/0.5 = 2[\text{s}] \tag{7}$$

The throughput of the so-designed vertical paternoster conveyor is:

$$Q_i = 3600 \cdot v / t_{\text{fork}} \approx 3600 \cdot 0.5/1 = 1800[\text{ items } /h] \tag{8}$$

where the conveyor capacity is given as:

$$Q_m = Q_i \cdot m_p \approx 1800 \cdot 30 = 54000[\text{ kg/h}] = 54[\text{t/h}] \tag{9}$$

The movement resistance of the paternoster vertical conveyor [4] is computed as:

$$F_w = f_{pnc} \cdot [(q_m + 2 \cdot q_{ad}) \cdot L + F_z] + q_m \cdot h \tag{10}$$

where, F_{z} = 1250 [N] is chain tensile force, h = 3 [m] is the transport height between two consecutive levels, closely $L \approx L_{\text{ch}}/2 \approx 4[\text{m}]$ is the carrying chain length equal to the retrieving chain length, q_m, q_{ch}, q_{fork}, and q_{ad} are the movement resistance of transported material (parcels), of the chain, of the fork carriers, and an additional movement resistance of all moving parts (chain and 8 fork carriers), respectively. They are given below:

$$\begin{gathered} q_m = \frac{Q_m \cdot g}{3.6 \cdot v} = \frac{54 \cdot 9.81}{3.6 \cdot 0.5} = 294.3[\text{ N/m}] \\ q_{ch} = m_{ch} \cdot g = 2.8 \cdot 9.81 = 27.5[\text{ N/m}] \\ q_{\text{fork}} = m_{\text{fork}} \cdot g / t_{\text{fork}} = 2.5 \cdot 9.81/1 = 24.5[\text{ N/m}] \\ q_{ad} = q_{\text{fork}} + q_{ch} = 24.5 + 27.5 = 52[\text{ N/m}] \end{gathered} \tag{11}$$

Finally, f_{pnc} = 0.04 is the movement resistance coefficient of the paternoster vertical conveyor.
Hence, for the considered conveyor, the movement resistance force is:

$$F_w = 0.04 \cdot [(294.3 + 2 \cdot 52) \cdot 4 + 1250] + 294.3 \cdot 3 = 996.63[N] \approx 1[kN] \tag{12}$$

And the required power of the electric motor is:

$$P_m = \frac{F_w \cdot v}{\eta} = \frac{1 \cdot 0.5}{0.9} = 0.556\ [kW] \tag{13}$$

where, $\eta = 0.9$ is the utilization of the conveyor's driving mechanism.

If we need higher conveyor performance, other solutions may be derived. For the same conveyor chain type 16B-01, sprockets with $z_{\text{s}}(2) = 84$ teeth and the median diameter of $D_{\text{S}}(2) = 679.3[\text{mm}] > D_{\text{S}}(\min^*) = 550[\text{mm}]$ can be applied. In that case, there are $N_{\text{fork}}(2) = 10$ fork carriers installed over the chain length. All the necessary data for this solution is given in the 2nd row of Table 1.

Furthermore, even higher conveyor performance can be achieved if sprockets with $z_{\text{s}}(3) = 72$ teeth and the median diameter of $D_{\text{S}}(3) = 582.3[\text{mm}] > D_{\text{S}}(\min^*) = 550[\text{mm}]$ (same chain 16B-01) are used. This enables $N_{\text{fork}}(3) = 11$ fork carriers to be installed over the chain length. All the data for the third solution is also provided in the 3rd row of Table 1. In the 3rd case, the carrier pitch requirements, Eq. (1), must be accounted for.

Table 1. Key calculated parameters for three variants of paternoster vertical conveyor

	N_{fork}	L_{ch} [m]	$t_{\text{fork}}(\text{r})/p_{\text{ch}}$	$t_{\text{fork}}(\text{r})$ [mm]	$Tact$ [s]	Q_i [items /h]	P_{m} [kW]
$1'$	8	7.925	39	≈ 1000	≈ 2	≈ 1800	≈ 0.56
$1''$	8	8.128	40				
2	10	8.128	32	812.8	1.62	2214	0.67
3	11	7.823	28	711.2	1.42	2530	0.74

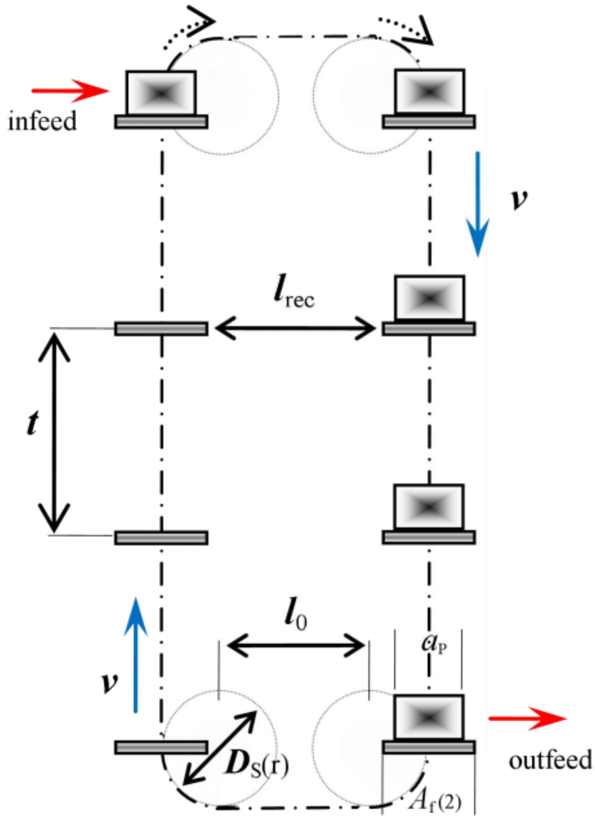

Figure 7. Paternoster conveyor outfeed solutions (roller and belt conveyor)

2.5 A Rectangular Conveyor

A rectangular conveyor (Figure 7) can be an alternative solution for vertical transport in cases of larger parcel dimensions. This would be the case if the above-considered parcels had to be placed longitudinally on the fork carriers. This section provides a conceptual solution and a way of computing the necessary parameters of a rectangular conveyor that should meet the requirements of larger product sizes, weighing up to 50 kg. The rectangular conveyor has four sprockets, two up and two down, placed at a horizontal distance of l_0. and a required vertical height of h. The minimal horizontal distance between the fork carriers (Figure 7) for the rectangular vertical conveyors is given as:

$$l_0 \geq A_{\text{fork}} + l_{\text{rec}} - D_{\text{S}}(\text{r}) \tag{14}$$

Smaller sprockets are used for the rectangular conveyor, and for the same initial data as for the previous paternoster conveyor, a relatively large number of solutions can be realized. For example, for all four sprockets with $z_{\text{S}}(\text{r})$ = 33 teeth with the same chain (16B-01) as above, the calculated parameters for the rectangular vertical conveyor are given in Table 2.

Table 2. Key calculated parameters for two variants of the rectangular vertical conveyor, with $z_{\text{s}}(\text{r}) = 33$ sprockets teeth and the median sprocket diameters of $D_{\text{S}}(\text{r}) = 267.2[\text{mm}]$

	l_0 [mm]	l_{rec} [mm]	N_{fork}	L_{ch} [m]	$t_{\text{fork}}(\text{r})$ [mm]	$t_{\text{fork}}(\text{r})/p_{\text{ch}}$	Q_i [items/h]	P_{m} [kW]
$\mathbf{1(r)}$	390.3	82.4	10	7.620	762	30	2362	0.71
$\mathbf{2(r)}$	632.0	320.0	11	8.1034	736.6	29	2443	0.74

The conveyor manufacturer [12] limits the carrier distance (pitch) to $t_{\text{fork}}(\text{min}) = 750[\text{mm}]$, i.e., the pitch of the product carrier is $75[\text{mm}]$. This means that the links for the fork carrier at the chain are given at every $75[\text{mm}]$ distance. Hence, the links are not positioned exactly at the chain pitch.

The product size is limited to 600 × 600 [mm] x height, and 900 × 610 [mm] × height for the XL paternoster version. In both versions, the maximum load weight is 50 [kg].

The throughput of the paternoster conveyors is maximized by the producer at 2000 [items/h], i.e., 200 loads per hour per carrier, which results in a maximum capacity of about 10 [t/h]. The conveyor variants enable maximal lifting heights from 2 [m] up to 20 [m], which covers nearly all production halls and warehouses. They have a minimal footprint of 1.1 $[\mathrm{m}^2]$ to 1.5 $[\mathrm{m}^2]$ for the XL version of the paternoster conveyor.

The power consumption of the conveyors' electromotors is in the range of 0.37 to 4 [kW], depending on the required lifting height and load weight. The price of the Paternoster conveyor, depending on the height, versions, and equipment, starts at $25,000.

3 Evaluation of Paternoster Vertical Conveyors

The evaluation of the paternoster vertical conveyors needs to account for some important aspects, such as the use of floor space, transportation height, infeed and outfeed directions and heights, ascending and descending, throughput and capacity, price of the conveyor, integration cost, energy consumption, and maintenance cost.

Based on the above-listed aspects, paternoster continuous vertical conveyors have many advantages:

-a relatively simple construction,

-continuous vertical transport enabled,

-goods kept in the horizontal position while moving up or down,

-lifting and lowering multiple products simultaneously,

-a very small footprint-minimal occupation of the floor space,

-high throughput and solid capacity (because of the load weight limitation),

-high transportation heights,

-possibility of many infeed and outfeed height levels,

-at least two infeed directions and two outfeed directions are allowed at each level,

-low energy consumption and maintenance cost,

-apart from transport, they can also be used for sorting, buffering, bridging, combi-transport, or other similar activities in production and warehousing, etc.

Disadvantages of the paternoster vertical conveyors are:

-small dimensions of parcels (what can be improved by rectangular conveyors),

-limited weight of the products,

-relatively low speed,

-limited capacity for higher lifting heights,

-needed integration costs,

-necessary synchronization between the infeed/outfeed conveyor and the paternoster conveyor,

-solid price, etc.

In comparison with the inclined belt conveyors, the paternoster conveyors have a similar throughput for loads up to 50 kg and smaller lifting heights. Still, inclined belt conveyors can realize much greater capacity because of their greater transportation speed and heavier loads. However, the paternoster conveyors have a much smaller footprint.

In comparison with the spiral modular belt conveyors, the paternoster conveyors have a smaller capacity but also a smaller energy consumption, maintenance costs, and footprint, which is in their favor.

In comparison with the continuous vertical conveyors – vertiveyors, the paternoster conveyors have lower integration costs, much lower synchronization needs, offer greater infeed and outfeed heights and directions, and a slightly higher throughput.

In comparison with the cargo lifts, the paternoster conveyors have a greater throughput but cannot transport larger loads with a significant weight, like pallets, etc.

4 Conclusions

Paternoster vertical conveyors have a simple construction and are very useful for vertical transport. The basic conveyor design presented in this paper matches the performance given by the paternoster conveyor manufacturer [12].

Paternoster vertical conveyors have greater throughput than many other continuous vertical conveyors, and their smaller height makes them as efficient as inclined belt conveyors. It has a very small footprint compared with other vertical conveyors and enables lifting and lowering multiple products simultaneously. Those are the three most important conveyor characteristics. Paternoster conveyor's applications are in industry or in warehousing with frequent transport of smaller products, for vertical sorting, or as a buffer.

Future research should be related to increasing conveyors' capacity, especially for higher lifting heights, increasing chain speed, and improving synchronization with infeeding and outfeeding conveyors. Also, paternoster conveyors could be used widely in combination with other transport systems or directly to generate predictions for vertical smart AS/RS (Automated Storage and Retrieval Systems).

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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