How Energy Recovery Can Reshape Storage Assignment in Automated Warehouses

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Abstract. In automated storage and retrieval systems energy in descending and deceleration phases of cranes can be recovered into the power supply system instead of being dissipated as waste heat. Such technological opportunity should be exploited by properly modifying control policies in order to improve energy efficiency of warehousing operations. In this paper the impact of energy recovery on the storage assignment process is analysed. A model of energy consumption with recovery is proposed so that each location within a rack can be associated with energy required to be served in a storage or a retrieval cycle. Shape and distribution of zone for energy-based dedicated strategies are analysed. Energy and picking time performances of different storage policies when AS/RSs machines are equipped for energy recovery are analysed and compared.

Keywords: energy efficiency, energy recovery, automated storage and retrieval systems, storage location assignment, picking time.

1 Introduction

While in the process industry energy efficiency has been pursued for several decades due to its energy-intensive nature, in the discrete one the current level of control in energy use is very poor or absent [1]. However, the growing of green consciousness from one hand and energy resource scarcity from the other are inducing all manufacturing firms to pay attention to energy efficiency as a way to pursue sustainability in all its components. This trend is confirmed by results of the 2011 Material Handling Association of America survey on sustainability in warehousing, distribution and manufacturing [2], which have highlighted how for more than 60% of respondents the greatest accomplishment is becoming energy efficient. As asserted by Elkington [3] in his triple bottom line model, in facts, at the intersection of social, environmental, and economic performance, there are activities that organizations can engage which not only positively affect the natural environment and society, but which also result in long-term economic benefits and competitive advantage for the firm. Reducing energy consumption is one of such activities, since it allows to mitigate greenhouse gas emissions related to energy generation, to reduce natural resource exploitation, and to reduce energy supply costs. Moreover it can be associated with a green imagine of enterprise that can attract and consolidate client fidelity.

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Automated warehouses have been seen as intrinsically energy efficient solutions for warehousing. The ability of automated storage systems to store inventory more densely eliminates, in fact, the need for energy to heat, cool, light and ventilate excess square footage [4]. However, automated storage and retrieval systems (AS/RSs) require energy for movements of their cranes to serve locations within racks. Therefore, new attention is claimed to be paid to control policies of AS/RSs in order to minimize energy requirements also for their storage and retrieval operations, so that the sustainable perspective can be fully embraced.

Storage assignment is the control policy that can more strongly affect picking time, which has been the primary performance traditionally pursued in warehouse management for decades, since it is directly linked to service level perceived by customers (see [5], [6], and [7] for comprehensive literature reviews on warehousing). Recent studies have highlighted how it can affect also energy consumption for crane movements and therefore belongs to such activities that can foster sustainability. In particular, when adopting the energy-based full turnover strategy [8], thus allocating more frequently moved items to convenient locations in order to optimize energy requirements for storage and retrieval operations, the shape of dedicated zones changes from the well known time-based rectangular or L shape [9] to a step-wise one, with vertical positions becoming more attractive to exploit gravity in descending phases. These results are based on the assumption of fully dissipating energy when torque becomes negative during descending or deceleration phases and energy flows from the AS/RS machine to motors and is converted into waste heat.

Manufacturers are offering the option of equipping cranes with energy-recovery modules so that energy otherwise dissipated can be re-generated into the power supply system. This technological opportunity should be fully exploited by properly modifying AS/RSs control policies in order to minimize net energy requirements. The challenge becomes to adequate operations management to technological development so that they can enforce each other towards higher and higher sustainability levels. As regards storage assignment, energy recovery can change the relative convenience of each location within a rack, in particular higher locations can become even more attractive, since their gravitational energy can lead to higher electrical energy flows to be supplied to the grid.

Thus, the first question to be answered is if and how energy recovery can change the shape of dedicated zones in comparison to both the traditional time-based zones and the energy-based ones with full dissipation. The second question is how much energy saving can be achieved with the energy-based full turnover strategy associated with energy recovery in comparison to the same storage policy with full dissipation. Furthermore, comparisons with the time-based full turnover policy, where the most frequently moved items are assigned to locations requiring the least picking time, and with other common storage assignment strategies as the random one, can give insight on how much energy can be saved by properly changing the assignment process.

The paper is organized as follows: in sect. 2 the energy model adopted to associate energy consumption to each location in a rack is described, while the shared storage policy is analysed in sect. 3. Zone distributions are analysed in sect. 4, and simulation experiments among different dedicated storage policies are reported in sect. 5.

2 The Energy Model with Recovery

To adopt an energy based storage assignment, energy related to crane movements along vertical and horizontal axes must be evaluated. Movements along z axis to pick up and drop off loads are independent from locations in the racks and therefore they can be ignored.

AS/RS machines are equipped by a different A.C. 3-phase inverter duty motor per axis; the energy required to reach a given location is the sum of energy provided for the x-axis and the energy provided for the y-axis (time, instead, is calculated as the maximum of the values along the two axes due to simultaneity of movements).

Assuming that crane movements can be described as a rectilinear motion with constant acceleration, speed profile for both horizontal and vertical axes can be either triangular, if maximum allowed speed isn't reached due to limited shifts, or a trapezium one if an acceleration phase, a constant speed phase, and a deceleration phase must be considered in sequence [10].

Being torque C constant during the acceleration phase of the crane due to the inverter duty motor type, mechanical energy provided by motors can be calculated by integrating the product of the torque and the angular speed at the shaft over time. The torque provided by each motor has to counterbalance inertia of motor and masses to be moved (crane and unit load), friction and gravity (vertical motion). These forces strictly depend on design specifications, maximum speed and acceleration of the AS/RS machine, so we used actual data provided by System Logistics S.p.A., to compute energy values for a given AS/RS configuration.

New generation cranes are controlled so that horizontal and vertical movements end simultaneously, differing from traditional cranes where an additional torque must be applied to keep in position the load while completing the slowest movement. This means that speed profile of the fastest motion should be modified in order to complete the required shift along the rack in a time as long as the other axis one. We suppose to travel with nominal acceleration until a speed lower than the maximum one is reached and extend the constant phase in order to complete the shift in the same time of the slowest motion. By recalculating for each location the new acceleration/deceleration time and the constant speed time of the fastest motion, it is possible to evaluate the actual energy required to perform a storage or a retrieval cycle in a given position within the rack (energy differs since load is on board during different shifts).

The I/O point is co-located at the lower left corner of the rack, which represents also the optimal dwell point location (i.e. the optimal location where the crane should wait when idle) from the energy perspective, as shown in [8].

We suppose that the y-motor is equipped for energy recovery in order to exploit gravitational energy. An energy recovery factor is introduced whenever the torque becomes negative, generating negative energy flows that partially balance the positive ones related to the other shifts of each single command cycle. Based on actual data from manufacturers, we assume a prudential overall recovery factor of 26% on the energy otherwise dissipated.

3 Energy Savings with Shared Storage Policies

We can evaluate energy savings associated with shared storage policies when energy recovery is performed by analysing the rack energy potentials.

The rack energy potential (REP) can be defined as the sum of the energy values required to complete a single storage plus a single retrieval cycle for all the locations in the rack, i.e. 2 idle travels and 2 travels with load on board per location [8].

Multiplying REP by the overall turnover (total demand divided by rack storage capacity), we obtain a measure of the energy requirement for a given time horizon, when the random storage policy is adopted and every location has equal probability of being visited. Therefore, given a rack storage capacity, energy requirements are proportional to REPs, so we can compare REPs among different rack shapes and different unit load weights to get insight on potential energy savings with shared allocation.

In Table 1 rack energy potentials for a rack storage capacity of 990 unit load locations are reported. We considered two alternative configurations: a 22 levels and 45 columns rack (22×45) and a 10 levels and 99 columns rack (10×99). Since energy recovery depends mainly on gravitational energy, which is related to location height from floor, the rationale is to evaluate the impact that vertical development of the rack can have on energy recovery with respect to horizontal development.

Energy values were evaluated by associating the proper crane specifications with each configuration as suggested by manufacturers.

Unit load weights of 1000 kg, 600 kg and 200 kg were considered in order to evaluate energy savings associated with different classes of product weight.

Table 1. Rack Energy Potentials

Rack	Unit load [kg]	REP [MJ]	Recov. REP [MJ]	Δrel %
22×45	1000	1,262	1,089	13.76
10×99	1000	1,265	1,189	6.03
22×45	600	1,189	1,033	13.15
10×99	600	1,219	1,150	5.65
22×45	200	1,115	976	12.46
10×99	200	1,173	1,112	5.23

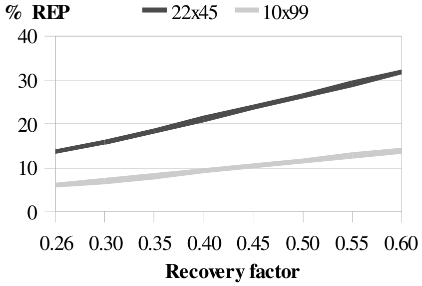

Fig. 1. Relative % decrease of Rack Energy Potentials for different energy recovery factor

Energy saving for a 1000 kg unit load is 13.76% when energy recovery is performed in the 22×45 rack, while it is 6.03% for the 10×99 one. In the more horizontally laid rack, in fact, less energy can be generated during descending phases and recovered into the power supply system. This is enforced when the energy recovery factor grows as shown in Fig. 1, where the curves diverge. As also expected, for a given rack configuration, energy saving grows with increasing unit load weight.

From the design perspective, it comes that the benefit of AS/RSs of allowing better use of vertical space can be further exploited for energy recovery during operations, thus leading to more energy efficient facilities.

4 Dedicated Zones Shape and Distribution

When a dedicated storage policy is adopted, each item is associated with a given number of fixed locations within the rack. The full turnover policy consists in assigning the most convenient locations to items sorted by their turnover frequency (number of visits per unit load location in the planning horizon) in decreasing order.

If the traditional time-based turnover policy is adopted, the most frequently moved unit loads are assigned to locations requiring the least picking time to be served, so that response time to clients can be minimized. In this case, it is a well-known analytical result [9] that dedicated zones have a rectangular or L shape (see Fig. 2).

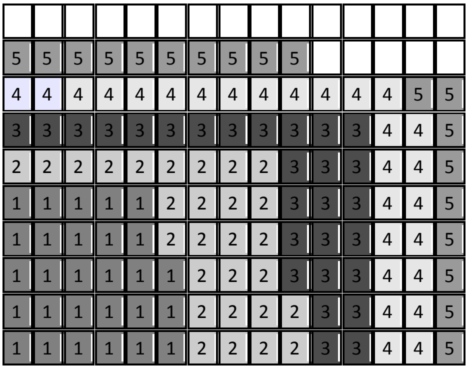

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Fig. 2. Dedicated zones for the time-based full turnover policy for the first part of the 22×45 rack.

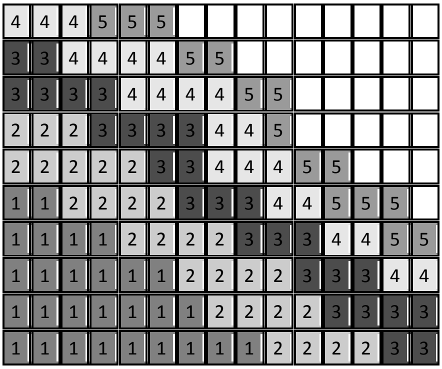

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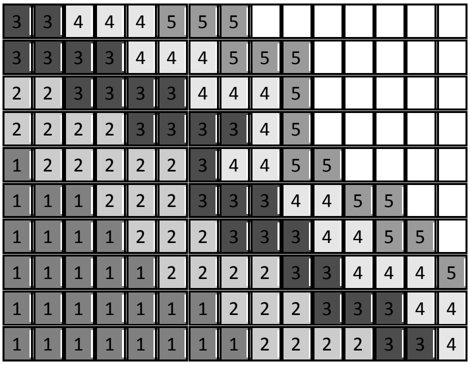
Fig. 3. Dedicated zones for the energy-based full turnover policy with 1000 kg unit loads and full dissipation (22×45 rack, first part)



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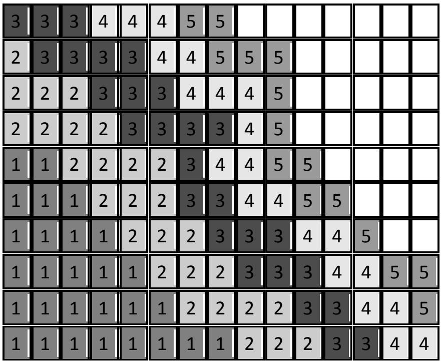
1	1	1	1	1	1	1	1	2	2	2	2	3	3	4

Fig. 4. Dedicated zones for the energy-based full turnover policy with 1000 kg unit loads and energy recovery (22×45 rack, first part)



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1	1	1	1	1	1	2	2	2	2	3	3	4	4	5
1	1	1	1	1	1	1	1	2	2	2	3	3	4	4

Fig. 5. Dedicated zones for the energy-based full turnover policy with 600 kg unit loads and energy recovery (22×45 rack, first part)

When the energy-based turnover policy is adopted, instead, the most frequently moved items are associated with locations requiring the least energy to be served for a complete storage plus retrieval single command cycle. For full dissipation, dedicated zone shape is step-wise, as shown in Fig. 3.

Thus, we wonder about the impact of energy recovery on both shape and positions of dedicated zones. Energy recovered during descending phases is subtracted to the total amount of energy required to complete a storage plus a retrieval single command cycle, and the net value for each location is used for storage assignment.

Results for the first part of the 22×45 rack are shown in Fig. 4. The step-wise shape is confirmed to be a peculiarity of energy-based assignment. The shift towards higher positions from the time-based to the energy-based allocation is even more marked when energy recovery is performed (compare Fig. 2-4). The most convenient positions occupy, in facts, higher and higher levels which assure a favourable net balance of energy requirements and energy recovery.

If dedicated zone distribution for the 1000 kg unit load (Fig. 4) is compared to the 600 kg one (Fig. 5), it can be noticed how lighter items tend to compensate their lower mass by occupying higher positions in order to enhance energy recovery.

5 Performance of Dedicated Storage Assignment Policies

In order to analyse the effect of different dedicated energy policies on energy consumption, simulations over 5 time windows for a total amount of 53090 retrievals per period and related reorder point based storage operations were performed.

We considered 100 different items with strictly decreasing demand. As in the fundamental study by Hausman et al. [9] we adopted a reorder point policy based on EOQ. An equal ratio of inventory to order costs was selected for all products, to avoid considering different supply policies other then demand rates when establishing the number of locations to be dedicated to each item. Since REPs have highlighted how the shape of the rack significantly affects energy performance we considered both the vertically laid 22×45 rack and the horizontally laid 99×10 one in our simulations. Moreover, to study how a different distribution of items among aisles affects energy saving, we considered also the ABC demand distribution within a single aisle comparing 20-50 and 20-80 distributions of the 100 stored items.

We took as reference the traditional time-based full turnover policy which assure the best time performance as demonstrated by Hausman et al. [9] and has been adopted for decades. Then, we adopted the sustainable perspective, which leads to pursue energy efficiency in automated warehouses and therefore to take energy saving rather than time as the primary performance when dedicating zones within a rack. The energy-based full turnover strategy was therefore adopted. We computed performances of the analysed configurations in two cases: when the crane is not provided with energy recovery and when it is, so that benefits of upgrading AS/RS machines with energy recovery can be assessed.

We are interested on creating energy efficient facilities and processes, but we cannot neglect the importance of time performance in warehousing for its direct link with the service level perceived by clients. This is the reason why we computed picking time other than energy requirements for each simulation run, in order to get insight into potential trade-off between time and energy performances.

Results in Table 2 and Table 3 show how relative variations in time and energy performance when moving from the time-based allocation to the energy-based one are of the same magnitude, since energy is the integral of power over time. Therefore a trade-off between picking time and energy consumption arises and a firm should choose what performance leads to major competitive advantage in order to apply the proper allocation policy. However, it should be noticed how in the presence of energy recovery, even the time-based allocation gains energy saving with respect to both time-based and energy-based turnover policies with full dissipation (12.7% for the 22×45 rack and 20-50 demand curve). This means that the energy recovery option can trigger hybrid approaches as a good compromise between time and energy performances, such that of allocating by a time-based policy in order to optimize service level, while still pursuing energy efficiency due to re-generation into the power supply system.

Table 4 allows to analyse, instead, the effect of a radical change of perspective, from the traditional time-based approach associated to time-based assignment with full dissipation to the sustainable perspective of energy-based assignment enforced by energy recovery. In this case improvements on energy efficiency is significantly higher than worsening on time-performance, reaching 16% of energy saving for the 22×45 rack and the 20-50 curve with picking time worsening of 3.5%.

Table 2. Time and energy performances of the time-based full turnover strategy (TB) and the energy-based one (EB) with full dissipation

Rack	**Demand curve**	**Time TB [h]**	**Time EB [h]**	**Energy TB [MJ]**	**Energy EB [MJ]**	**Δ rel Time**	**Δ rel Energy**
10×99	**20-50**	1019.7	1033.9	59036.8	58340.8	-1.39%	1.18%
	20-80	949.7	970.7	55801.9	54878.5	-2.21%	1.65%
22×45	**20-50**	1136.8	1164.4	59779.6	58194.4	-2.42%	2.65%
	20-80	1084.1	1123.5	57057.6	54779.4	-3.63%	3.95%

Table 3. Time and energy performances of the time-based full turnover strategy (TB) and the energy-based one (EB) with energy recovery

Rack	**Demand curve**	**Time TB [h]**	**Time EB [h]**	**Energy TB [MJ]**	**Energy EB [MJ]**	**Δ rel Time**	**Δ rel Energy**
10×99	**20-50**	1019.7	1028.6	54982.9	54552.1	-0.87%	0.78%
	20-80	949.7	962.5	51744.2	51202.1	-1.35%	1.05%
22×45	**20-50**	1136.8	1176.2	52196.5	50220.2	-3.47%	3.79%
	20-80	1084.1	1143.6	50121.7	47289.6	-5.48%	5.65%

More insight on energy recovery can be gained by performing a 2^3 factorial design of experiments, which is obtained by considering the rack shape (99×10 as low level, 22×45 as high level), the ABC demand curve (20-50 as the low level, 20-80 as the high one), and the full turnover policy (the time-based one as the low level, the energy-based one as the high level). Main and interaction effects are reported in Fig. 6 as relative percentage with respect to the basic solution with lower levels. It can be noticed how the rack shape becomes the major factor in the presence of energy recovery, overcoming the demand distribution which was highlighted as gaining the major effect for cranes with full dissipation [8]. Rack shape effect is even enforced by the adoption of the energy-based storage policy, as the significant related interaction effect underlines.

From a design point of view, results suggest that exploiting vertical space when building automated warehouses together with energy recovery option for cranes should become the preferred practice to enhance sustainability. Attention should be paid also to distribute items among racks so that skewed demand curve can be obtained and therefore advantages related to dedicated policies can be maximized.

Finally, from the control point of view, we underline the energy saving achievable by dedicated policies with respect to the common random policy. If energy recovery is performed, for the 22×45 rack and 20-50 curve 22% of relative decrease in energy consumption is gained by the energy-based full turnover policy, reaching 26% for the 20-80 demand curve.

Table 4. Time and energy variation (relative %) from no-recovery time-based allocation to energy recovery based one.

Rack	Demand curve	Δ % Time	Δ % Energy
10×99	20-50	-0.87	7.60
	20-80	-1.35	8.24
22×45	20-50	-3.47	15.99
	20-80	-5.48	17.12

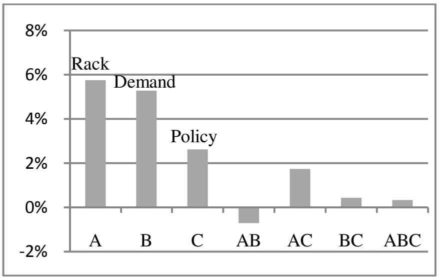

Fig. 6. Main and interaction effects on energy requirements of the rack shape (A), demand curve (B), and the full turnover policy (C)

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