Energy efficient dual command cycles in Automated Storage and Retrieval Systems

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Abstract: Sustainable manufacturing claims for more energy efficient operations in warehouse management. In AS/RSs they can be pursued by optimizing storage and retrieval cycles so that the least energy is required to move the crane. While picking operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers, a sustainable approach leads to change this perspective by optimizing storage and retrieval cycles to lower energy requirements. In this paper we propose an energy-based heuristic to re-sequence retrievals in order to perform dual command cycles with the least energy requirements. Impact on both energy savings and round trip times is assessed when moving from single command to dual command cycles, if storage and retrieval operations are combined by the common first-come first-served policy. Further improvements on energy and time performances achievable by adopting different re-sequencing heuristics are then investigated. Factors affecting energy consumption and round trip times such as the storage allocation strategy, the re-sequencing time-based or energy-based policies, the demand distribution, and the shape of the rack, are analyzed by a 2^4 factorial design of experiments.

Keywords: *energy efficiency, Automated Storage and Retrieval Systems, dual command cycles.*

1. Introduction

An automated storage and retrieval system (AS/RS) is a fully automated facility, where cranes running on rails between fixed storage racks pick up and drop off unit loads without the need of human operators.

AS/RSs have been recognized as sustainable facilities [1]. Since they allow to store inventory more densely and vertically than traditional warehouses, they reduce, in facts, energy consumptions to heat, cool, light and ventilate excess square footage. Furthermore, allowing storage of the same number of units in a smaller footprint, AS/RSs require less concrete, reducing carbon dioxide emissions.

From an operations management point of view, energy efficiency can be pursued in AS/RSs by optimizing also their storage and retrieval cycles, so that the least motion energy consumption can be achieved [2]. While picking operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers [3], a sustainable approach leads to change this perspective by matching time performances with energy efficiency ones.

Dual command cycles couple a storage operation to a retrieval one into the same trip, in order to avoid idle travels of the AS/RS machine to/from the I/O station as in single command cycles, where only one operation (storage or retrieval) is performed at a time. In a dual command cycle, therefore, the AS/RS machine departs from the I/O station with a load on board and reaches the desired storage location, then it moves directly towards the selected retrieval location where the load is picked up, and then it comes back to the I/O station. The possibility of performing dual command cycles depends on the simultaneous availability of both storage and retrieval requests. When this occurs, dual command cycles have been recognized by literature to lead to significant time savings if compared to traditional single command ones in the order of 30% [4]. Adopting a sustainable perspective, the first question

to be addressed is therefore how much energy consumption can be reduced by adopting dual command cycles with respect single command ones.
Time savings are strictly related to the storage assignment policy adopted. Graves et al. [4] demonstrated by both analytical and enumeration analysis that maximum time savings are achieved by mandatory interleaving, that means performing dual command cycles whenever possible, with a full turnover strategy rather then the common random allocation. The full turnover strategy is a dedicated assignment policy, which exclusively assigns a given number of locations to a product, on the basis of its demand rate sorted by decreasing order. In this way the most frequently moved items are located to the most convenient positions with respect to the I/O station and maximum improvement on the selected performance is achieved. From the traditional time-based perspective convenience has been read in terms of minimum picking time, which has been the performance to be enhanced. Since it was found that interleaving time accounts for 30% of the total round trip time (equal to the sum of the travel time from the I/O station to the storage location + interleaving time from storage to the retrieval location + time to travel from the retrieval location to the I/O station), the time-based full turnover strategy allows to minimize the one-way travel component from/to the I/O station of a dual command cycle, thus is able to affect the 70% of total time.

In our opinion, when a sustainable perspective is adopted convenience should be read in terms of energy efficiency. Therefore, in order to assess the maximum energy savings achievable by dual command cycles, we introduce a full turnover strategy based on the least motion energy, that means assigning high turnover items to locations requiring the least energy to be served. Energy performance achievable by the energy-based full turnover policy can therefore be considered as upper bounds of energy savings achievable with other less performing but more easy to apply storage policies, such as the random allocation (i.e. each open location can be occupied by every item) or the class-based storage allocation. It was already shown in our previous work [2] how energy-based dedicated zones differs from time-based ones; from the traditional rectangular or L shapes of time-based approach, in fact, step-wise zones are identified by the energy-based one, with a general shift towards upper levels of the rack, due to exploitation of gravity.

Performance improvement gained by dual command cycles depends also on the capability of optimally combining storage and retrieval requests in order to optimize the interleaving phase. A common practice is to adopt a First-Come First-Served (FCFS) policy, which means processing storage requests in the exact sequence they arrive and combining each storage with the first available retrieval request respecting the order it has been inserted into the information system. While processing storage in FCFS order reflects the fact that in general input unit loads are moved by a conveyor to the I/O station of the AS/RS and therefore their sequence is fixed, retrieval requests can be considered as electronic messages, which can be rearranged in any desired sequence.

When a random allocation is performed, and only one open location is available at a time, Bozer et al. [5] explained that the dual command scheduling of AS/RSs can be formulated as a Chebyshev travelling salesman problem, which is known to be NP complete. When multiple open locations are available for storage, the problem involves finding the best storage locations other than coupling storage and retrieval requests and it is in general NP-hard [6]. This is the reason why several heuristics were developed to overcome such complexity. By analytical analysis, Han et al. argued that in order to gain an improvement in throughput greater than 10%, travel-between (i.e. interleaving time from storage locations to the retrieval ones under the hypothesis of rectilinear constant speed motion) must be reduced by over 50%

with respect to FCFS retrievals as it is achievable by the Nearest-Neighbor Heuristic [6]. The overall performance of this heuristic can be enhanced by adopting a class-based storage policy rather than a random one [7]. Near-optimal solutions can be achieved under random storage by the ε-optimum algorithm proposed by Lee and Schaefer [8]. An $O(n^3)$ heuristic for dedicated storage with one open location at a time (meaning that storage locations have been previously identified and no storage choice has to be performed) was also proposed by authors [9] with very good performance with respect to the optimal solution.

In this paper, a heuristic approach to couple storage and retrieval requests within a given time period aiming at minimizing motion energy requirements rather than picking time is proposed for the energy-based full turnover strategy. Time and energy are related by power, but it should be considered that due to simultaneity of movements along vertical and horizontal axes the Chebyshev metric applies to travel time (i.e. machine travel time is the maximum between x-time and y-time), while energy is the sum of the requirements of both the x motor and the y motor installed in the crane. This is the reason why energy savings potential could be different from time savings potential gained by dual command cycles and should be analyzed. Furthermore one can wonder to what extent energy-based dual command cycles overcome time-based ones as regards energy saving if compared to single command cycles and FCFS dual command ones.

Therefore, picking time and energy performances of dual command cycles identified by the proposed heuristic are compared to the commonly use First Come First Served combination approach and Lee Schafer time-based heuristic's one by simulation. Energy saving potential related to dual command cycle optimization is assessed as well as the impact of a sustainable approach on client service levels. Factors such as the shape of the rack affecting motion energy, the ABC demand curves affecting the turnover frequency or the type of full turnover strategy (time-based versus energy-based heuristics) are considered in other to analyze the amount of energy savings obtainable by optimizing both location assignment and picking cycles.

The paper is organized as following. In par. 2.1 the energy model developed in order to compute energy required for crane movements is described. In par. 2.2 an energy-based heuristic for combining storage and retrieval requests is proposed, while in par. 2.3 the design of simulation experiments is described. In par. 3 results are analyzed and conclusions on energy saving potential are collected in par. 4.

2. Methodology

To adopt the new perspective aiming at energy efficient manufacturing, new models and performance measures should be introduced in order to assess energy saving potential of different operation policies.

The first step is the development of an energy model so that motion energy required by the crane to reach each storage location of the AS/RS rack can be estimated. The second step is therefore an energy-based heuristic to combine storage and retrieval requests into dual command cycles. Finally, factors which are expected to affect energy efficiency performance of dual command cycles should be identified and a factorial design of simulation experiments provided. In the following subsections previously described steps are discussed.

2.1. The energy model

The crane movements along the horizontal axis (namely x) and the vertical one (namely y) are described as a rectilinear motion with constant acceleration. A trapezium speed profile is adopted, where three phases can be recognized: acceleration until the maximum speed is reached, constant speed motion, and deceleration in order to stop at the desired location in the rack. When the shift to be performed by the AS/RS machine isn't great enough to reach the maximum speed, a triangular speed profile with only symmetric acceleration and deceleration phases is adopted. The AS/RS machine movements are characterized by their simultaneity along the two axes, and therefore the Chebyshev metric has been applied in literature to calculate travel time. As regards energy, the crane in equipped with 3 independent motors per axis. Since fork cycle to insert and/or drop off unit loads from the rack is independent from their location and can be considered a fixed component of energy requirements, energy for the z axis is neglected in our model. New generation crane are controlled so that their movements along x and y axes not only start simultaneously, but also end at the same time. This allows to avoid the additional torque needed to maintain the load in position while completing the slowest movement as in traditional cranes. To adhere to market behavior, we slow down the fastest motion by decreasing the acceleration/deceleration times so that the maximum speed value achievable is lower than the nominal one, while keeping acceleration at nominal value, as described in [2].

Energy is then computed per axis on the basis of the torque provided at the motor shaft, supposed constant during acceleration due to A.C. 3-phase inverter duty motors. Torque has to counterbalance inertia of load and masses (motor + crane), friction and gravity (for the y-axis). It was so possible to assign to each location in the rack the value of energy required to store into or retrieve from by departing/arriving from/to the I/O station supposed at the lower left corner of the rack. Furthermore, the model allows to dynamically compute energy for interleaving between any pairs of locations in a dual command cycle.

2.2. The energy-based dual command cycle heuristic

We imagine to process storage requests in the same order they arrive, since unit loads are supposed to be moved to the I/O station of the AS/RS by a loop conveyor. Retrieval requests, instead, are re-sequenced in order to save motion energy. In order to limit computational time but also to adhere to a dynamic environment, the list of available retrievals requests is commonly split into blocks which are sequenced one at time [3]. We adopt blocks of 15 storages and 15 retrievals to be combined into N = 15 dual command cycles at time. In our computation we considered unchanged each block until all the pairs have been identified, thus adopting a static approach. In a very turbulent environment, however, it is possible to adopt a dynamic approach by updating the block with new retrievals requests at each iteration before selecting the successive pair of operations.

Let be L_S the list of N storage requests and L_R the list of N retrievals requests in the analyzed block. The energy-based heuristic consists of the following steps.

1. Assign to each element in L_S the open location with the lowest energy required to store the load moving from the I/O station. Let S the set of such locations.
2. Assign to each element in L_R the retrieval location among the available with the lowest energy required to pick the load to the I/O station. Let R the set of such locations.
3. For each pair (s, r) with $s \in S$, $r \in R$, compute energy requirements for moving from storage location s to retrieval location r;

4. Select the pair (s^*, r^*) $s^* \in S$, $r^* \in R$ with the minimum energy requirement and perform the related dual command cycle;
5. Set $S = S - \{s^*\}$, $R = R - \{r^*\}$;
6. Go to step 4 until $S = \emptyset$ and $R = \emptyset$.

The rationale of steps 1 and 2 is attempting to positively affect the one way travels from and to the I/O of a dual command cycle, so that the minimum energy is consumed for them. Steps 3-5 try to minimize energy required by interleaving, which is the only energy component that can be changed with a different combination of storage and retrievals requests. As it has been already assessed [4], in fact, given a block of N storage locations to be served and N retrieval ones, one-way travels from/to the I/O station are fixed both in terms of time and energy, since all the selected locations must be served anyway. The variable component remains the travel between a storage position and the coupled retrieval one in a dual command cycle, that strictly depends on how retrievals are re-sequenced. The above heuristic has a $O(N^2\log_2 N)$ complexity, as shown in Appendix.

2.3. Simulation

By simulation experiments we compare energy consumption and round trip times of dual command cycles with single command cycles under different re-sequencing policies, namely FCFS, time-based, and energy-based ones. We consider only one side rack and one crane per aisle, since results can be modularly extended to all the fronts of an AS/RS. A reorder point replenishment policy is adopted and the size of each dedicated zone corresponds to the Economic Order Quantity (EOQ) of a given items. According to Graves et al. [4] EOQ is calculated assuming an equal ratio of inventory to order costs, so that the introduction of disturbing factors such as the supply policy can be avoided. In this way, zone size and frequency of access to a given location are affected only by demand distribution, as required by the full turnover strategy. Since the storage location policy has been showed in literature to significantly affect picking performances, we apply both the time-based full turnover strategy and the energy-based one. In this way we analyze whether adopting a sustainable perspective even when establishing dedicated zones could lead to significant energy savings with respect to the traditional time-based allocation.

In order to apply Lee-Schaefer heuristic to identify time-based dual command cycles, we need to first select storage and retrieval locations, since this heuristic applies only to re-sequencing of retrievals when locations involved in the decision process have been already established. We introduce a rule similar to step 1 of our energy-based heuristic, that is sorting all open locations dedicated to a given item by their one-way travel time from the I/O station and selecting at each iteration the position with the lowest time to be reached. Similarly to step 2 of the energy heuristic, all occupied locations of a given item are sorted by their one-way travel time to the I/O station and the position with minimum required time is selected for retrieval.

Since the adopted storage policy is strictly related to the ABC demand distribution curve of items stored in the analyzed AS/RS, we consider the ABC shape as a main factor in our analysis and select two levels: a 20-50 curve, meaning that the 20% of items account for the 50% of picking operations, and a more skewed one such as the 20-80 curve.

Nominal speed and acceleration of the crane, angular speed and inertia of motors etc. and shifts to be performed in order to serve locations are related to the shape of the AS/RS rack. Since all these quantities represent an input of the energy model as described in par. 2.1 and in previous research [2], we select also the shape of the rack as a factor of analysis. In particular we compare a horizontally laid AS/RS with 99 columns and 10 levels to a more vertically developed one, characterized by 45 columns and 22 levels for a total amount of 990 available locations in both cases. We used actual data provided by System Logistics SpA, an international manufacturer of AS/RSs, to properly select a crane for each rack.

We first compare single command performances to First-Come First-Served dual command ones by a 2^4 factorial design, including the storage policy, the movement strategy, the ABC distribution and the rack shape as main factors to be analyzed, each at the two levels previously described. The rationale is to assess if dual command cycles can contribute to energy efficiency so significantly as they were proven to do for time reduction. This is the reason why the most actually used policy for re-sequencing retrievals, the FCFS one, is initially adopted. As regards the movement strategy, we mean how storage and retrieval locations to be served are selected before the coupling process based on the FCFS policy is performed. Empty locations for storages as well as available location for retrievals basically depend on the position of dedicated zones established by the storage strategy, but among these the selection of the order by which they will be served depends if movements are optimized by the time-based perspective or by the energy-based perspective. By the former, the location with the minimum one-way time from/to the I/O station is selected among the available, by the latter, instead, the location with the minimum motion energy requirement for the one-way travel from/to the I/O station is identified.

Once established if and how much FCFS dual command cycles overcome single command ones, an analysis on further improvements achievable by dual command cycles when replacing FCFS re-sequencing policy with time-based and energy-based heuristics is performed. A 2^4 factorial design of experiments with 4 factors (storage policy, re-sequencing policy, demand curve, and rack shape) at two levels is selected again. Main factors and related levels are summarized in Table 1.

Table 1.Factors and levels of the 2^4 design of experiments

Factors	Low Level	High Level
Re-sequencing policy	Time-based heuristic	Energy-based heuristic
Storage strategy	Time-based full turnover	Energy-based full turnover
Demand distribution	20-50 ABC curve	20-80 ABC curve
Rack shape	99×10	45×22

Simulation of 450 storage operations plus 450 retrievals is therefore performed. It is supposed that storage and retrievals operations can be always coupled, meaning that requests for both operations are available when planning the AS/RS machine cycles. Heuristics for re-sequencing retrievals are applied to block of 15 storage operations and 15 picking operations at time, for a total amount of 30 blocks to be analyzed. The size of the block is selected as a reasonable trade-off between opposite patterns. On one hand, in fact, computational effort increases as the block size is increased. Furthermore, if a dynamic approach should be adopted, meaning that the list of retrieval requests is updated as much frequently as possible to be aligned with client requirements, then the size of the block should be kept small in order to reduce the frozen window in the planning process. On the other hand, the capacity of really optimizing cycles in the whole planning horizon increases as the block size increases, since more operations are involved in the optimization process.

3. Results

Results from simulation runs show how dual command cycles gain significant performance improvements in comparison to single command cycles.
The average round trip time decreases of 29.7% when moving from single command to First-Come First-Served dual command cycles, in line with well-known results reported in literature.

Energy consumption to move the crane towards the desired storage and retrieval locations is lowered by a 26.6% on average, when storage and retrieval operations are combined into dual command cycles. Thus, dual command cycles are showed to be an effective operative mean to foster energy efficiency in warehouse management other than improve the service level perceived by client, for which they have been traditionally conceived. Main effects of the identified factors on lowering energy requirements are positive, but of limited importance. It comes that deleting one-way idle travels to/from the I/O station and replacing them with interleaving from a storage location to the coupled retrieval one leads itself to a significant improvement, which can be weakly affected by other characteristics of the system.

When replacing FCFS policy with heuristics to combine storage and retrieval requests into dual command cycles, a little improvement on the desire performance can be further achieved. Simulations analysis highlights how a 32.4% of improvement on round trip times is gained on average, and a 30.11% of energy savings can be obtained on average. As concern factorial analysis, the major effect on round trip time reduction if compared to FCFS policy is played by the time-based heuristic, whose implementation gains a 2.4% improvement with respect to the energy-based one. Concerning factorial analysis on motion energy savings when applying heuristics, instead, the major effect is achieved by applying the energy-based full turnover storage policy rather than the traditional time-based one, with a 1.7% increase. This confirms how the storage policy affects results obtainable successively by a proper management of AS/RS machine operations.

It is worthwhile to notice how adopting a full energy-based management of the AS/RS, meaning that both storage and re-sequencing are based on the least motion energy, leads to an energy saving increase of 30.77% with respect to single command cycles, but a time decrease of 30.78%. When a full time-based management is selected, instead, we obtain a 33.2% improvement of round trip times in comparison to single command cycles, and 29.61% improvement of energy requirements. It comes that if the most critical performance for a company is energy consumption, then an energy-based approach leads to the maximum benefit in terms of energy consumption, but renouncing to a 2.4% of improvement in times and the associated service level perceived by customers.

4. Conclusions

Sustainable manufacturing claims for more energy efficient operations in warehouse management. While AS/RS operations have been traditionally optimized in order to minimize picking times directly linked to the service level perceived by customers, a sustainable approach leads to change this perspective by optimizing storage and retrieval cycles so that the least motion energy is required to perform them.

Adopting dual command cycles instead of the more common single ones leads not only to reduce picking time, as traditionally expected, but also to strongly increase energy saving. Comparing single command cycles to dual command ones obtained by coupling storage and retrieval requests by the easy-to-use and largely applied First-Come First-Served policy, a

26.6% of energy saving was found on average. Further improvement of about 3.5% on energy saving can be achieved by implementing heuristics to optimize dual command cycles. In this case, current results show how the major benefit can be gained by a full energy-based approach, thus adopting both an energy-based full turnover storage strategy and an energy-based re-sequencing heuristic.

Appendix

For implementing step 3 of the energy-based heuristic described in par. 2.2, one can compute the N^2 energy values related to all the N^2 possible couples (s, r) and then choose the minimum. However, if an ordering of this N^2 length list is made, the following steps can be implemented faster.

Therefore, let E the ordered list of N^2 tuples (s, r, En(s, r)), where En is the interleaving energy requirement associated to (s, r). It can be computed in time $O(N^2\log_2 N^2) = O(N^2\log_2 N)$.

For each $s \in S$ we build a list L(s) pointing to those elements concerning s and a list L(r) pointing to $r \in R$. Then step 4 can be executed in constant time (the first cell of the list stores the minimum). We use the lists L(s) and L(r) for accessing E and remove the cells of the kind (s,..,...) or (..,r,…). This can be done in time $O(N)$. The loop is repeated N times, therefore the overall complexity is $O(N^2\log_2 N + 2N^2) = O(N^2\log_2 N)$.

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