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The optimization of a picker to product Order Picking System: a supporting decision tool based on a multi-parametric simulation approach

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Abstract

Modern fulfilment centers need to process a far higher volume of smaller orders with increasing picking costs. These picking costs can be up to 60% of total warehousing costs. Order picking is a process of gathering requested stock keeping units one order at a time, while picking operations involve a lot of large and medium-sized companies which belong to many industrial and service sectors. A significant example is now represented by the recent growth of e-commerce companies, which operate in growing global and extended markets. This study shows and measures the impact of alternative policies and configurations of manual picker to part order picking systems, with the aim of designing and optimizing robust facilities, minimizing global costs and maximizing their performances in terms of efficiency and customer service quality. The impact of the most critical and decisive parameters is quantified by a dynamic multi-parametric modeling of warehousing system and by using an integrated approach. Compared to the studies in the literature this approach is innovative. The analysis is based on modeling of thousands of what-if scenarios, which interactively support the management decision-making process. The effectiveness of simulation as a supporting decision tool is justified by the computational complexity of the whole design problem and by a set of innovative and practical results useful to system designer and controller.

Keywords

Order picking, picker to product, simulation, design and control optimization, class based storage.

1. Introduction

New, global and extended markets have to process and manage increasingly differentiated products with shorter life cycles, low volumes and reducing customer delivery times. To survive in today's global marketplace, companies need to be able to deliver products on time, maintain market credibility and introduce new products and services faster than competitors. Recent growth and strength development of e-commerce has brought a new focus on warehousing facilities and in particular on the design and management of Order Picking Systems (OPS).

The advanced technology can shrink geographical distance and restructure supply chains, enhancing industrial alliances and enabling efficient timely exchange of information between purchasers and suppliers, but needs to be integrated with efficient manufacturing and logistic operating policies. These policies could efficiently support physical and electronic information flows, and drastically reduce global system costs. E-commerce fulfilment centers need to process a far higher volume of smaller orders with increased picking costs. Modern companies attempt to achieve high-volume production and distribution using minimal inventories throughout the logistic chain and according to shorter response time (van den Berg 1999). They are replacing several relatively small distribution centers with a small number of larger ones, covering more extensive networks and involving a large number of system entities as confirmed by the study by Simpson and Eranguc (2001). In warehouse and distribution centres products have to be picked from a set of specific storage locations by an orderpicking (OP) process driven by customer orders. Each orderline represents one product or article code in a certain quantity, which has to be shipped to a specific customer (Gray et al. 1992, Koster et al. 1999).

Existing paradigms concerning logistics facilities are strongly influenced by these reasons, but in the light of recent changes it is now reasonable to study and develop new solutions on the integrated management of physical and electronic information flows (Ferrari et al. 2002). Van den Berg (1999) recognizes that these new market forces and fast technological developments in both material handling and in information systems affect warehouse management and control tremendously.

The aim of this study is to show and measure the impact of alternative policies and configurations of manual OPSs in order to design robust systems, minimizing global costs and maximizing their performances in terms of efficiency and customer service quality. The object of the dynamic approach adopted is to model OPS by considering all the most critical and decisive parameters involved, so that it is possible to represent alternative operating scenarios and optimize system design and control. The research approach is based on the integration of planning and control processes, without neglecting interrelationships between all the system factors and parameters involved. According to a dynamic multi-parametric modeling of the generic picker to part OPS, a data base interactive tool to support management optimizing decision-making process is developed. Thanks to a set of thousands of simulation runs, the best values can be chosen for a set of *free* system factors which respect a pool of physical and managing system constraints (*unfree* parameters). As far as possible the optimizing approach is standard and systematic, in agreement with the great number of parameters involved. As demonstrated by research in the literature, this integrated approach is new. Picking operations involve a lot of large and medium sized companies belonging to many industrial and service sectors, such as the apparel industry, the food sector, wood furniture production and logistic outsourcing providers.

The remainder of the paper is divided into 6 sections. After the introduction, section 2 defines and describes the generic problem of design and control of a manual OPS. After an overview, Section 3 presents the approach to solving the optimization problem and a demonstration of its computational complexity. Then section 4 describes the multi-parametric dynamic model. Section 5 summarizes the principal results of research involved. And finally section 6 discusses conclusions and further research.

2. Picker to part OPS

Van den Berg (1999) defines OP as a process of gathering stock keeping units (SKU) that have been requested an order at a time. He classifies management decisions concerning warehousing systems into two principal families:

1. *planning decisions,* which refer to an intermediate term and to policies that are developed at the tactical level. They principally concern fulfilment activity;
2. *control decisions,* which affect the short term and operational decisions. They refer to routing, sequencing, scheduling and orderbatching problems.

This study is interested in developing an interactive tool, which supports the planning, and control decisions in OPSs.

OPSs can be classified as *picker to part* (or product) systems when the picker is travelling to picking locations, and *part* (or product) *to picker* if materials are brought to the picker. The first *picker to part* situation is generally identified by *manual OP* label: pickers ride in vehicles picking along physical slots. Known examples of part to picker systems are Automated Storage and Retrieval System (AS/RS), miniload and carousel. These are not object of this study.

For many industrial applications automatic solutions, such as AS/RS and Automated Guided Vehicle Systems (AGVS), are inconvenient for several reasons, such as great number of items code, presence of heterogenous shapes of products, building's physical constraints and specific activities required. Of these aspects the present research confines itself to the study of manual OPSs, whose in-depth and integrated-base studies are not, as yet, developed, as is clearly demonstrated in the literature. It is very important to underline that these warehouses are widely found in industrial concerns for stocks of raw materials, components, spare parts and finished goods.

Referring to the retrieval approach, there are two principal macro classes of OPS:

- *unit load systems*. Materials are moved and stored by devices capable of moving and storing only a single-unit handling load;
- *less than unit load* systems with multiple stops per trip. Vehicles are capable of handling multiple unit loads simultaneously: orderpickers, which could be identified with operators-aboard retrieval machines, retrieve sets of items or multiple handling units of the same item on a single OP cycle. They visit different slots of warehouse facility before returning to input/output (I/O) or depot areas. Each picker is responsible for picking a complete customer pool of orders during a mission (Caron et al. 2000).

This study deals with the second class of design problems, and includes OP optimization in unit load system because it is a particular case of less than unit load systems in which each picking cycle is made of only one stop within the warehouse facility.

The adopted and most diffused system layout configuration, which is based on orientation of picking aisle, is *lengthwise* (or longitudinal): stocking parallel aisles run perpendicular to the warehouse front-end with a central depot, as shown in Figure 1.

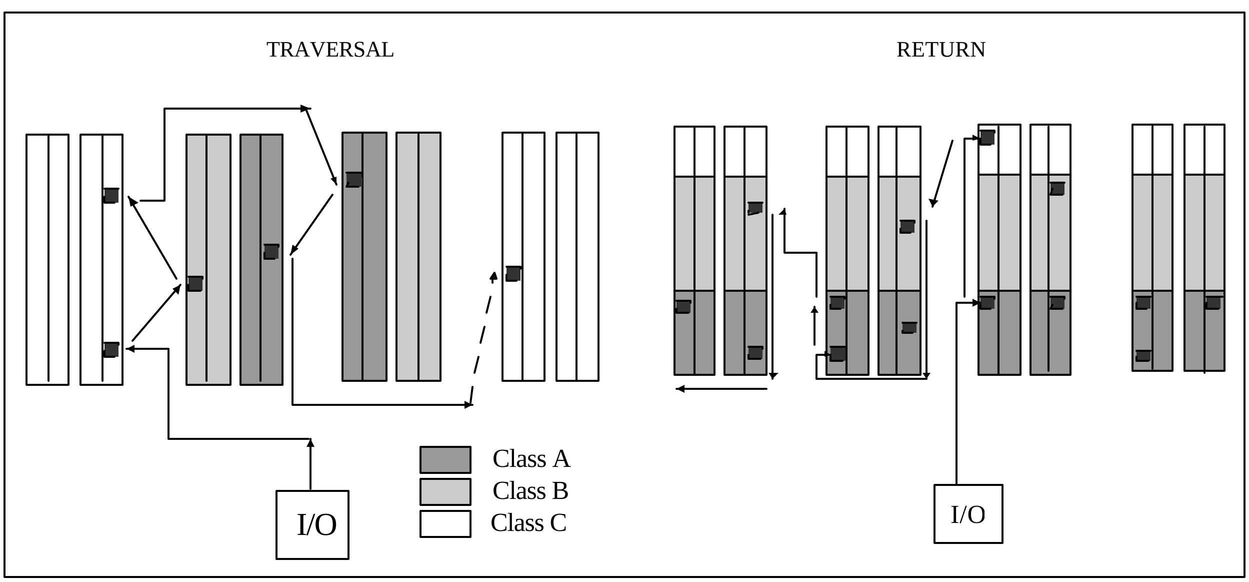

Figure 1. Traversal and return policies.

Roodbergen and de Koster (2001) call this configuration *basic warehouse layout*. Moving pickers are able to change aisles at the front and rear of the warehouse (*two cross aisles*). The storage area system known as *forward-reserve* or *low-level picker to part* (Caron et al. 2000) is adopted: lower levels of storage rack are used for manual OP (*forward area*), while higher levels contain bulk storage (*reserve area*). Therefore the generic facility object of this study is a two-cross, forward-reserve and less than unit load *picker to product OPS.*

Interesting surveys, frameworks and classifications on warehousing problem and OPS are presented by Gray et al. (1992), Larson et al (1997), van den Berg and Zijm (1999), Rouwenhorst (2000) and Kim et al. (2002). It emerges that stock area design process, which is the specific object of this study, has crucial interrelationships with other design steps involving receiving docks, packing area and shipping docks. Simpson and Eranguc (2001) model OP function within a supply chain system in terms of fixed costs, inventory costs and deterministic demand. A numerical case study of an OPS based on a cognitive design procedure is presented by Yoon and Sharp (1995). They show a great deal of interrelationships between all involved decisions. Kim et al (2002) model entities (goods and parts) and resources (order pickers) as agents of a co-operative process.

2.1. Costs of an OPS

Direct labor costs in an OPS can be up to 60% of total warehousing costs (de Koster et al. 1999, Lin and Lu 1999, Simpson and Eranguc 2001). OP accounts for over 65% of total operating costs for a typical warehouse, while travel time accounts for about 50% of all OP activity (Tompkins et al. 1996, van den Berg and Zijm 1999, Vaughan and Petersen 1999).

Caron et al. (2000) list the principal contributions to total picking cycle time:

- administrative time at the I/O point at the start and end of the tour;
- *processing time* (spent time extracting items and documenting the picking activity);

- *travel time* between pick locations. It could reach 60% of global order picker's time (Brynzer and Johansson).

The importance of reducing picking variable travelling cycle time emerges, which is a monotone increasing function of the traveled distance. For this reason the performance of the generic OPS is a measure of the distance traveled in a picking cycle which can be considered to be equal to the OP cycle time when picker moves within each aisle at average velocity.

3. Solving approach to support OPS design and control.

As Yoon and Sharp (1996), Vaughan and Petersen (1999) and Malmborg and Al-Tassan (2000) demonstrate, the decisions on design and control of an OPS involve a great deal of interdependent relationships between a variety of factors. Rouwenhorst et al. (2000) present a hierarchical framework for the design of an OPS. It is based on a set of clusters of relevant problems to be solved simultaneously. An integrated approach is necessary, but current and traditional analysis has oriented research towards isolated subproblems, as the current literature shows. The adopted simulative tool is an effectiveness instrument effective in supporting decisions about dynamic systems (Bechtel and Jayaram 1997, Kosfeld 1998, Helo 2000, Riddals et al. 2000, Ferrari et. al 2002), expecially when taking the computational complexity of the generic optimization problem into consideration. The OPS optimization problem, named Order Picking Problem (OPP), belongs to the NP-hardness class of decision problems as defined by Operations Research (Papadimitriou and Steiglitz 1982, Lawler et al. 1993). It is configurable as a routing instance, which can be traced to the well known Traveling Salesman Problem (Lawler et al. 1985, Dell'Amico et al. 1997). In particular, the generic OPP is configurable as a Vehicle Routing Problem (VRP), which consists of constructing a set of at most *m* vehicle routes of least total duration, according to a portfolio of capacity and time constraints, and in order to simultaneously satisfy a group of retrieval requests. Batching too is an NP-hard problem (Pan and Liu 1995, Dell'Amico et al 1997). A generic NP-hardness problem is not solvable in reasonable (polynomial) time: for this reason the approach based and developed on dynamic simulation modeling is justified. The aim of this study is to provide a computational base tool for OPS planning and management which could be used by decisionmakers to explore a wide range of operating configurations in order to investigate all potential impacts of critical factors and to optimize system performances. In particular, this optimization approach is necessary to support decisions on flexible systems, which operate in strongly evolving markets.

4. Parametric modeling of the OPS

Malmborg and Al-Tassan (2000) describe four basic types of system parameters which influence operating performances of a generic OPS:

1. *item features*: items space requirements (Kosfeld 1998), product structure and correlation (Brynzer and Johansson 1996, van den Berg 1999), transaction demand levels, packaging and related packing and cutting problems (Dell'Amico et al. 1997).
2. Functional specifications of *storage equipment* concerning material handling systems patterns, such as automated (or product to picker) warehousing facilities, for which the literature referred to is wide (Rosenblatt et al. 1993, Pan and Liu 1995, Sharker and Babu 1995, van den Berg and Zijm 1999, Dallari et al. 2000, Malmborg 2000, Malmborg and Al-Tassan 2000, van den Berg and Gademann 2000), manual system etc.
3. *System operating rules*. Main operating policies are (Caron et al. 1998):
   - *batching policy*, which determinates the pools of single-orders and the manner in which they are combined for a simultaneous picking in each trip of an OP cycle, as described from literature by Elsayed and Stern (1983), Gibson and Sharp (1992), Gray et al. (1992), Brynzer and Johansson (1995), Pan and Liu (1995), Tang and Chew (1997), Hwang et al. (1998), de Koster et al. (1999);

- *routing and sequencing,* which determine the sequence in which storage and retrieval requests are executed. Literature on routing procedures: Ratliff and Rosenthall (1983), Hwang et al. (1988), Petersen (1997), de Koster et al. (1998), Goetschalckx and Ratliff (1998), Chew and Tang (1999), Vaughan and Petersen (1999), van den Berg and Gademann (2000), Dallari et al. (2000), Caron et al. (1998 and 2000), Roodbergen and de Koster (2001);
- *storage location assignment and fulfilment policies*. Alternative physical storage policies and operating related rules are the focus of a large number of studies (Malmborg and Krishnakumar 1989, Park and Webster 1989, Francis et al. 1992, Brynzer and Johansson 1995, Larson et al. 1997, Caron et al. 1998, van den Berg 1999a, Caron et al. 2000, Dallari et al. 2000, Malmborg and Al-Tassan 2000, van den Berg and Gademann 2000, Ferrari et al. 2002).

4. *Physical configuration of storage area and unit load size.* The role of system layout configuration on warehousing optimization process is described by Gibson and Sharp (1992), Caron et al. (2000), Roodbergen and de Koster (2001)

The basic approach of this research is to quantify principal relationships between these decision levels, thereby presenting an integrated approach to solving global optimization of planning and control processes rather than the iterative procedures which have been developed in a few of the efforts to be found in the literature.

4.1 Multi-parametric model of the OPS

Figure 2 shows a visual interactive dynamic model of the parametric OPS. The longitudinal storage system consists of multiple parallel aisles with two high bay pallet racks alongside each aisle. Two sided and single-deep shelving is adopted. Materials enter and exit the warehouse at a single input/output (I/O) area.

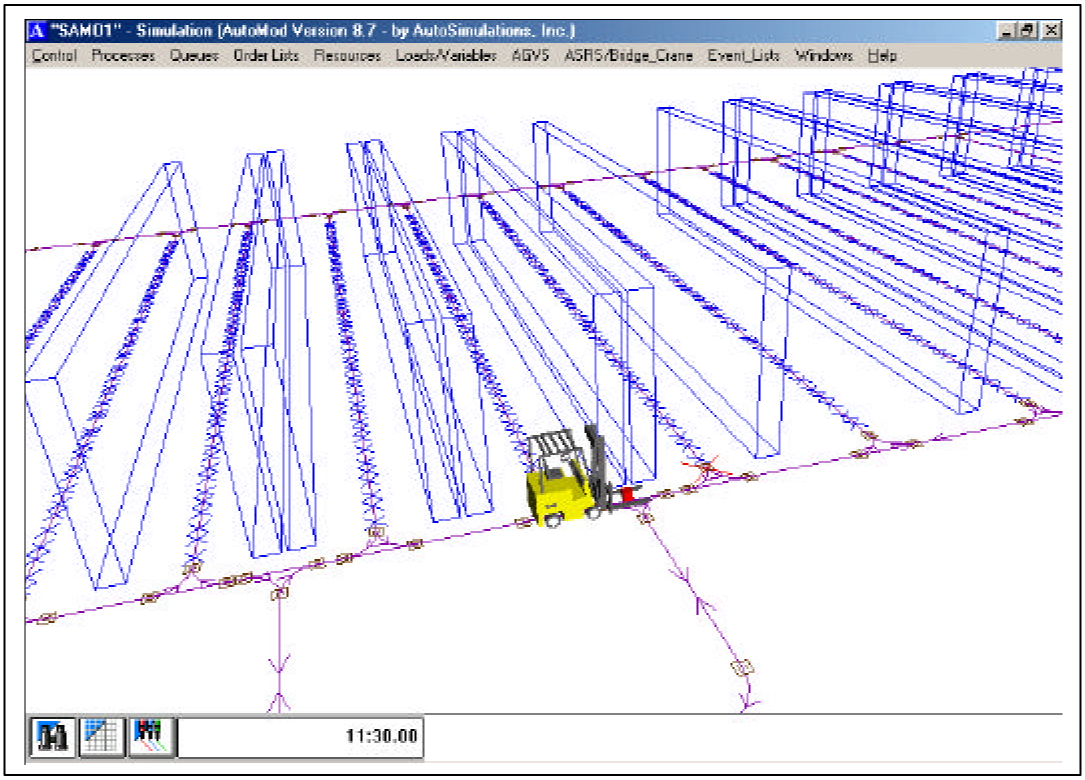

Figure 2. Dynamic model of the OPS.

Each configuration object of a specific simulation run corresponds to a special parametrization of the system and to a related choice of values, which are assigned to all modelled factors. The following compose the set of factors, which are the object of the modeling process, and it is this set of names which is used in subsequent sections and figures.

1) *Shape* (ratio p&q). The layout of inventory area is rectangular. Different values of ratio between the two dimensions (respectively frontal p and longitudinal q) are associated with this factor. Values range between 4&1 to 1&1, where p&q notation indicates the ratio between frontal and longitudinal dimensions.

2) *Curve*. The adopted storage location assignment policy is known as *class based storage*. It partitions all products between a number of classes and reserves a physical warehouse portion for each class, where items are located randomly. This policy is generally managed according to a famous dispatching rule based on Cube per Order Index (COI) introduced by

Haskett (1963). It is defined as the ratio of the number of storage addresses allocated to an item, to the number of transaction per period: the rule is applied by routing incoming items with lowest values to the most accessible storage addresses of a facility (near the I/O point). The CL-K notation denotes the number of classes with K. Studies on class based storage assignment policy by Kallina and Lynn 1976, Frazelle 1989, Park and Webster 1989, Francis et al. 1992, Gibson and Sharp 1992, Caron et al. 2000, Dallari et al. 2000, van den Berg and Gademann 2000, show that better results are achievable with three classes. According to the implementation of a three classes (A, B and C) storage assignment (CL-3), the analysis could be effectively based on a COI - Pareto ABC curve that is related to physical stocks and movement frequencies. This is given the name of Cube per Order Index curve (COI-curve). An example of COI-curve is illustrated in Figure 3 where cumulated values are reported on two axes. Through an analysis of different real cases, it emerges that generally there are many items with small index of rotation: only a small portion of stock is moved with high rotation values. For this reason some values which have been associated with curve factor are 20/95, 20/90, 20/80 etc. where notation x/y indicates that x% of cumulated storage commits y% of material movements.

3) *Class*. In class based storage assignment policy a critical choice on warehouse design is represented by calculation of physical dimension and shape of each class (Ferrari et al. 2002). Class factor could belong to a set of many values, whose examples are 20/50/30, 5/45/55. The notation a/b/c and a, b, c values indicate the portion of total volume (in percentage), which is associated to classes A, B and C respectively.

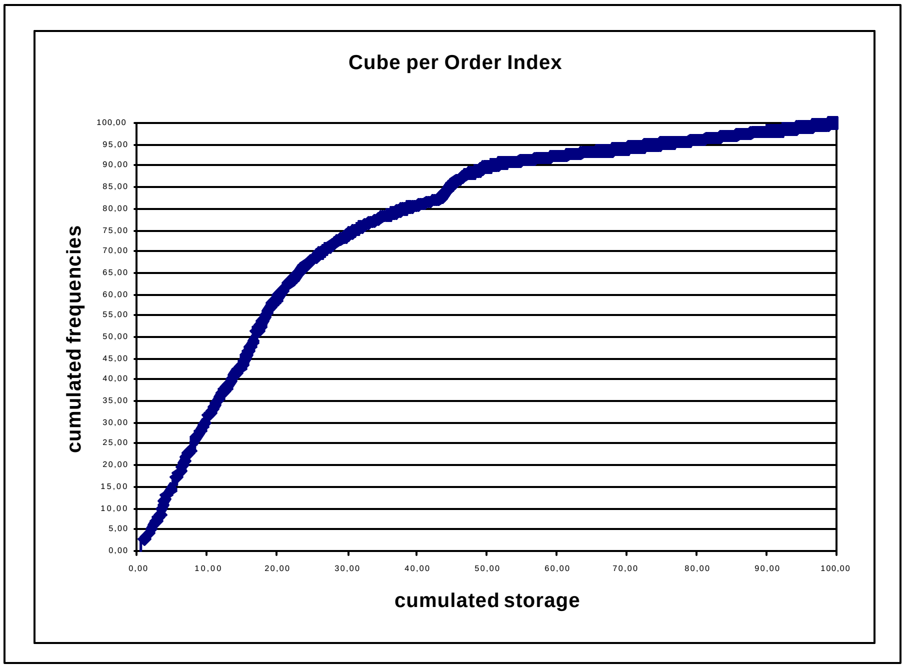

Figure 3. Example of a COI-curve.

4) *Policy.* Different values could be traversal or return according to figure 1 and to the following meanings:
    1. *traversal policy* (TR): the picker enters at one end of an aisle containing at least one pick and exits at the other end;
    2. *Return policy* (RN): the picker enters and exits at the same end of the aisle.
5) *DimList*. This is the number of lines of a picking list and it is associated with a mission of a retrieval vehicle. The generic picker begins and finishes his or her mission at the I/O zone, when he or she reaches the end of the list.
6) *Ratio*. This factor relates the capacity of picking machine to the number of items which are picked at each stop during a vehicle trip. It represents the average number of stops per route.

The number of times the I/O zone is visited during a picking cycle (equal to the number of routes for a picking list) depends upon the values associated with DimList and Ratio parameters: every time a vehicle is saturated or finishes its mission, it reaches this point. The adopted order batching procedure is First-Come-First-Served (FCFS): orders, and related requests and locations, are generated randomly, according to a COI-curve and Class factor value, and they are grouped in pools of DimList parametric size. The adopted order routing policy is associated to the FCFS sequencing of retrieval requests and to the calculation and choice of the Shortest Path (SP) between two generic and consecutive slots to be visited (Papadimitriou and Steiglitz 1982).

A significant study on the optimization of automatic and parametric OPS based on four factors is presented by Dallari et al. (2000). Caron et al. (2000) present a parametric analysis, related to a picker to part OPS, based on analytical modeling and few factors, such as storage capacity of picking system, number of pick stops per tour and shape of COI-based ABC curve. The present research is a new contribution on manual OPS planning and control based on an integrated, dynamic and interactive process. It involves 6 factors for large sets of values and different warehousing system configurations, and these are not the object of in-depth and integrated approach to be found in the current literature.

5. Results

The principal aim of the present research is to plan and develop a parametric simulative model of OP warehousing systems, which are described above. This section provides some guidelines for choosing the best picking strategy for a given subset of system parameters. A set of more than 50000 simulation runs were executed in order to study the impact of physical and managing parameters on the optimization of pickers' horizzontal movements and according to the following hypothesis and ranges of data:

- number of pickers stops = 200;
- dimlist = 5, 10, 15, 20, 25, 30;
- ratio = 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13;
- policies = traversal (TR), return (RN);
- shape: 1&1, 2&1, 4&1;

- curve: 60/20, 70/20, 80/20, 90/20, 95/20;
- classes: random, 5/40/55, 10/50/30, 20/30/50, 20/50/30.

In order to support management optimizing decisions in design and control of real warehousing facilities, the choice of these ranges of values is based on a study of the most widespread OPS configurations.

The global number of simulated scenarios equals 11700; for each one five different runs were executed in order to obtain a set of average performance data. The output of every run is the global picking cycle time. The number of stops belonging to a single run has been optimized on the basis of the calculus of the acceptable percentage error and by a dedicated MSPE (Mean Square Pure Error) analysis. It represents the assessment of the error variance when it is distributed according to a normal distribution with average value equal to zero. If a single simulation run of at least 200 stops is made, the errors are less then 0.3%. All results are in seconds and normalized in respect of the maximum-recorded run time value so as to be able to compare very different scenarios easily. These normalized values are the same as those obtained when considering travelled distance as an output run value because of the existence of a direct proportionality between times and related travelled distances. Following figures present graphs where *Performance ratio* on ordinate-axis is the ratio between the generic picking cycle time and the maximum-recorded one.

6.1 Innovative guidelines to the design

Now a list of principal innovative results obtained is presented in order to offer a set of useful, practical and optimizing guidelines to the warehousing system designer and controller.

The first relevant deduction of note to emerge is the little relevance of the single picking list dimension (DimList) as the graph of Figure 4 clearly illustrates. Figure 4 compares the effect of six dimensions of a hypothetical picking list in terms of performance, considering a system Shape equal to 4&1, a 80/20 Curve, a RN routing Policy and different values of Ratio parameter. For each value of DimList parameter a specula trend of system performance emerges according to the 13 ratio values, which have a measurable impact on cycle picking time because they impact on the saturation of picking machines. Best performance system values correspond to the lower OP cycle time and lower normalized values, which can be seen in the following graphs.

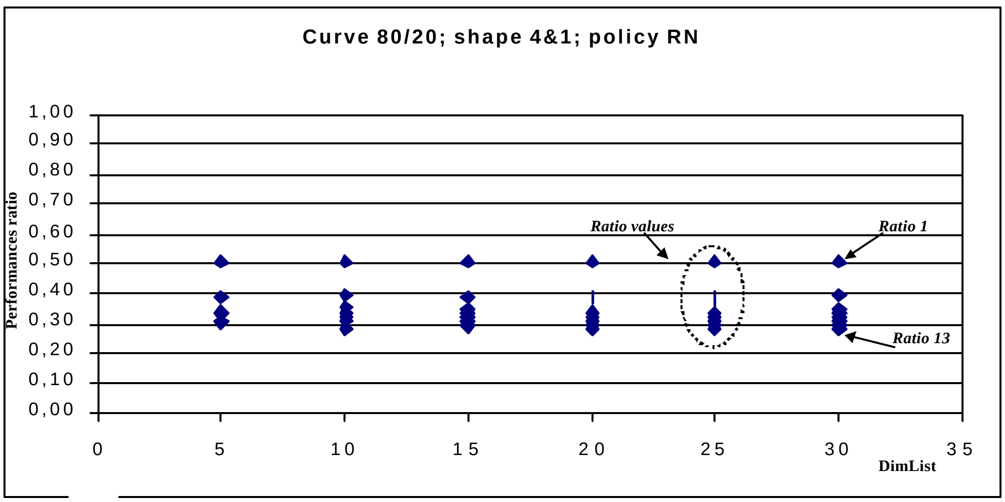

Figure 4. Impact of DimList parameter on system performance. Curve 80/20.Shape 4&1.Policy RN.

In order to study the importance of ratio value and its relationships with the rest of the system design parameters, the graph in Figure 5 compares two routing policies and Ratio values by considering a 80/20 Curve, a Shape equal to 4&1, and different values for Class parameter. First of all, it emerges that Ratio acts independently from routing policies. Secondly, its effect is relevant when considering values of Ratio lower than 3, and thirdly it is reduced and has a constant trend for greater ratios. Lower values ask for greater numbers of visits to the I/O because of the saturation of picking machines. In Figure 6, which is associated to 60/20 Curve, it emerges that Ratio always has the same effect on system performance, but the adopted picking policy importance grows a great deal. RN policy offers an average saving of about 10% compared to TR policy. Although considering a breadthwise picking system (where stocking aisles run either parallel to the warehouse front-end), this conclusion confirms what Caron et al. (1998) demonstrate.

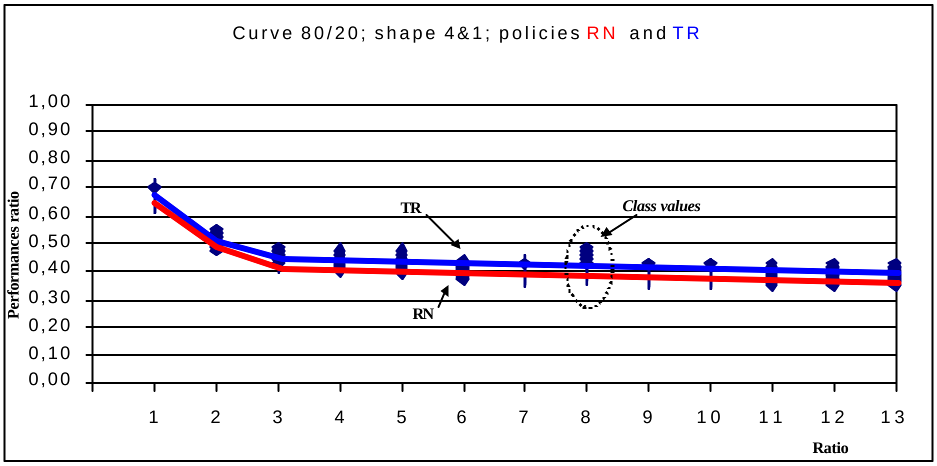

Figure 5. Impact of Ratio parameter on system performance. Curve 80/20. Shape 4&1.

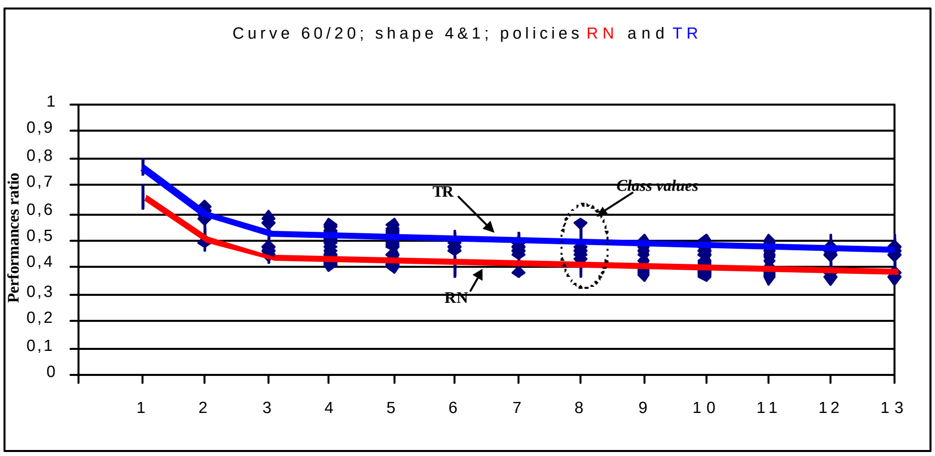

Figure 6. Impact of Ratio parameter on system performance Curve 60/20. Shape 4&1.

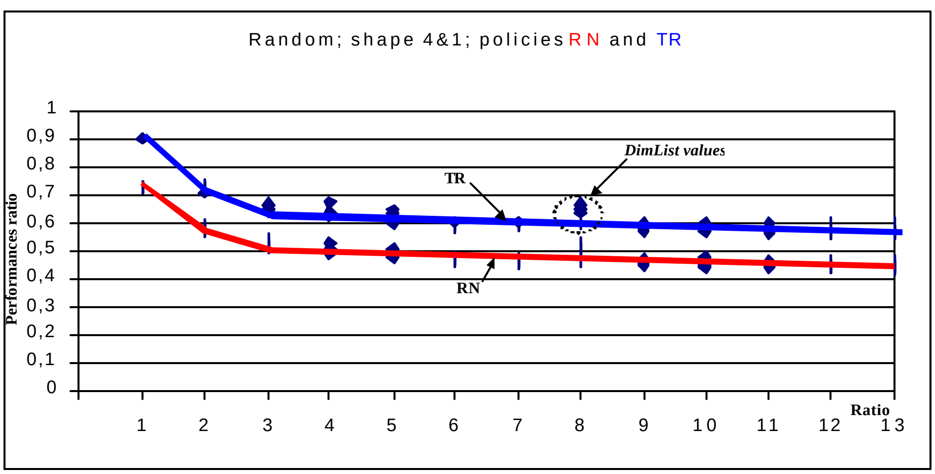

Figure 7. Impact of Ratio parameter on system performance in random storage location policy. Shape 4&1.

When considering a random storage location assignment Policy, it was found that when the system shape is constant (Figure 7), Ratio factor behaves as in previously described scenarios. The TR Policy generates picking cycle times about 13% bigger than RN values. This conclusion is different from studies in the literature on breadthwise OPS where TR always performs equal to or better than RN Policy (Goetschalckx and Ratliff 1988, Hall 1993, Caron et al. 1998). As a set, Figures 5 to 10 describe the effect of warehouse Shape changing when global available plane area is constant. In particular, figure 8, 9 and 10 are in relationship with 5, 6, and 7 respectively. The influence of picking area layout is consistent with Caron et al. (2000). Figure 8 shows that, when Shape is quadratic (1&1) and Curve 80/20, Ratio has a greater impact in TR than in RN routing Policy: RN policy is decisively more advantageous and offers savings greater than 30% in picking of very voluminous items. These results do not change significantly if different kinds of COI-curves are considered: the graph in figure 9, which is based on a 60/20 curve, demonstrates that RN policy guarantees almost 25% minimal savings. The comparison between Figure 6 and 9 shows the quadratic as being the optimal Shape in RN Policy adoption, especially with lower Ratio values. The opposite results are obtained with TR policy: the best performance belongs to the "most rectangular" system (Shape factor 4&1) and savings are about 10% for every Curve.

Figure 10 presents the effects of a random allocation policy in a quadratic system: comparison with graph 7 shows that Shape factor does not affect the RN policy, while performances deteriorate in TR routings. After the analysis of principal implications of DimList and Ratio factors, it is useful to study the impact of different class based storage location assignments on picking cycle times. Figures 11, 12, 13 and 14 show picking system performances when the orderlist dimension is 20 and Ratio value is 5. The lowest value of Shape factor on X-axis represents the quadratic warehousing system: according to previous analysis RN is the best routing policy and offers relevant savings. In rectangular systems based on Shape ratio value over 3, the best routing policy and Class factor need to be chosen together and according to the specific COI curve of products.

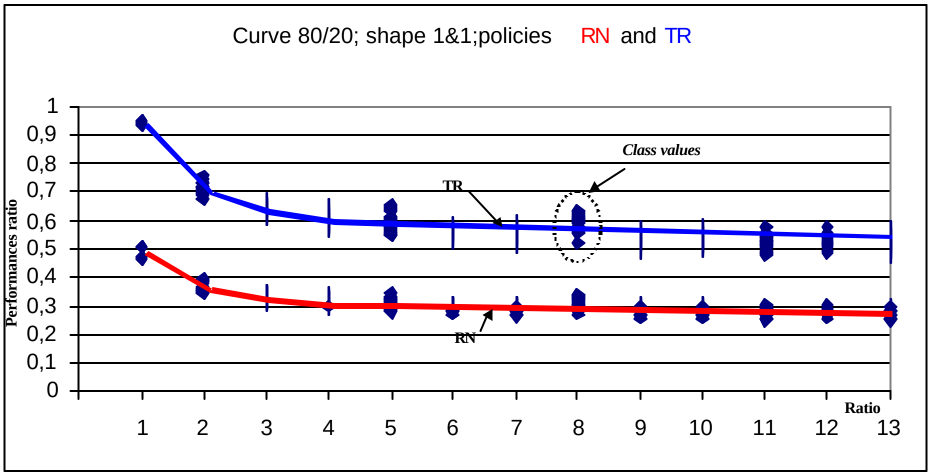

Figure 8. Impact of Ratio parameter on system performance. Curve 80/20. Shape 1&1.

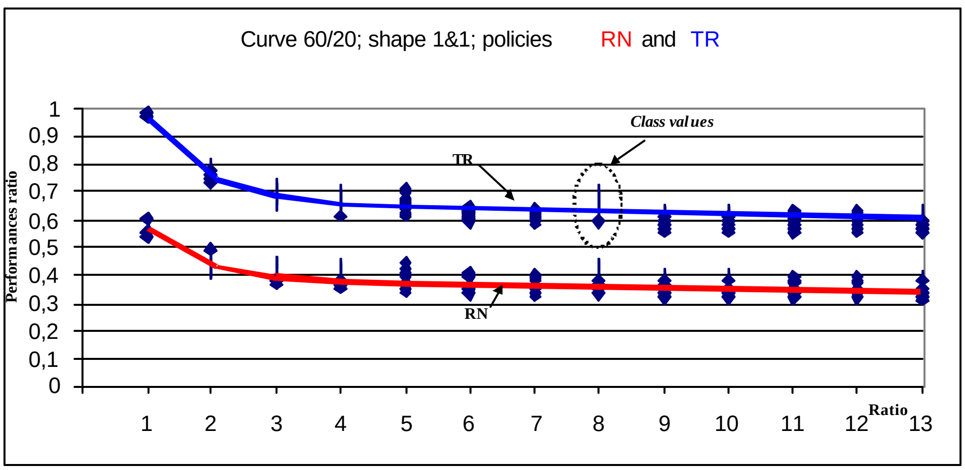

Figure 9. Impact of Ratio parameter on system performance. Curve 60/20. Shape 1&1.

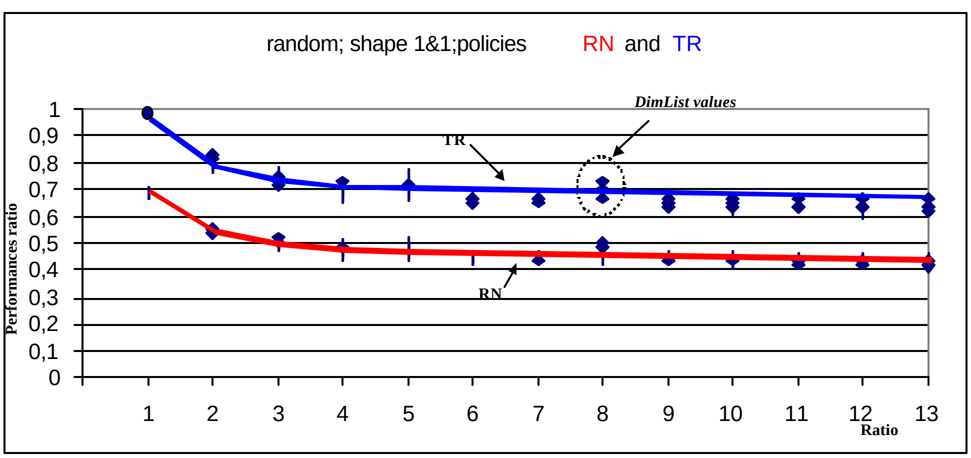

Figure 10. Impact of Ratio parameter on system performance in random storage location policy. Shape 1&1.

Passing from a 60/20 to a 90/20 curve OPS performance can change a great deal (between 10% to 25-30%), while system sub-optimizations based on Class factor choice does not impact more than 5%. This is worst if class based storage location policy is not adopted and products are randomly allocated.

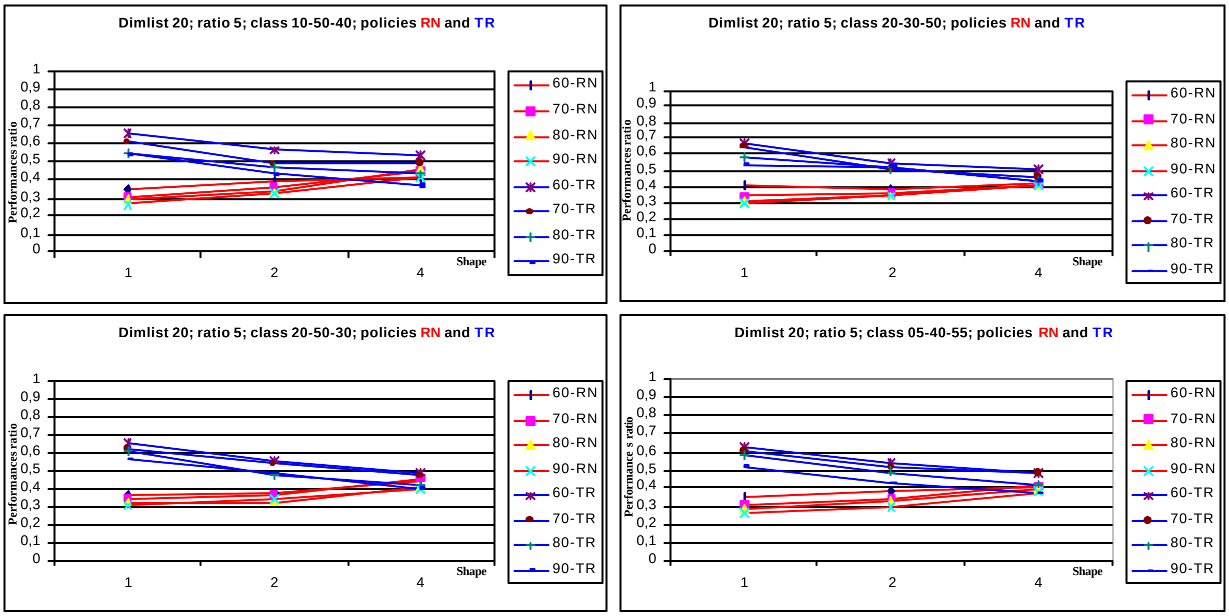

Figure 11, 12, 13, 14. Impact of Shape and Curve factors on system performance with traversal and return routing policies.

By comparing Figure 15, which refers to a random allocation, with previous graphs, particularly with Figure 5, it can be seen that the classes optimization offers average savings in the order of 20% compared to random allocation Policy. Best savings belong to a quadratic system with RN logic and to rectangular systems based on TR routings. Figures 16 & 17 confirm what was just explained: for 2 different system Shape they illustrate system performances according to different classes configuration and random location policy separately. The advantages gained from the adoption of COI-based storage compared to random storage are generally greater with return policy as Caron et al. (1998) demonstrated when considering a breadthwise system, but they depend on Shape factor. For this reason is not possible to extract the best routing policy, not as some of the studies in the literature declare.

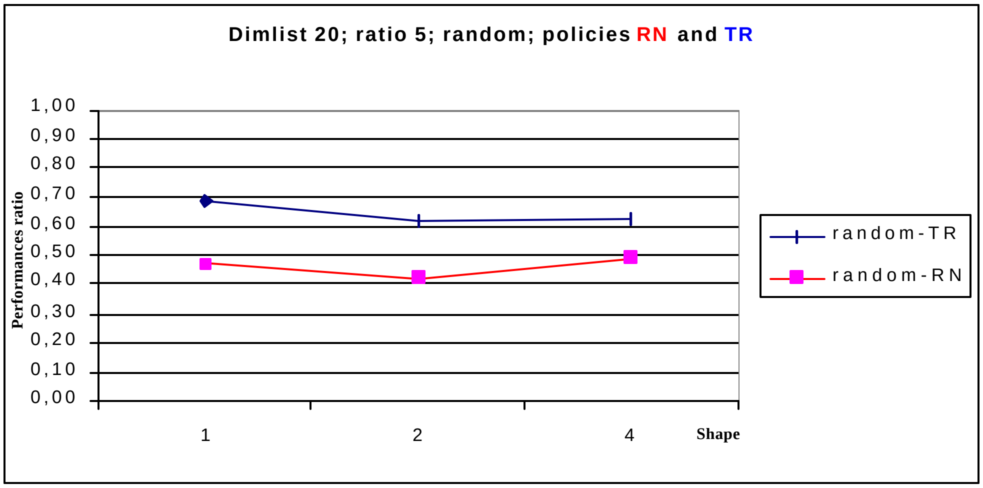

Figure 15. System performance in random storage location policy. DimList 20. Ratio 5.

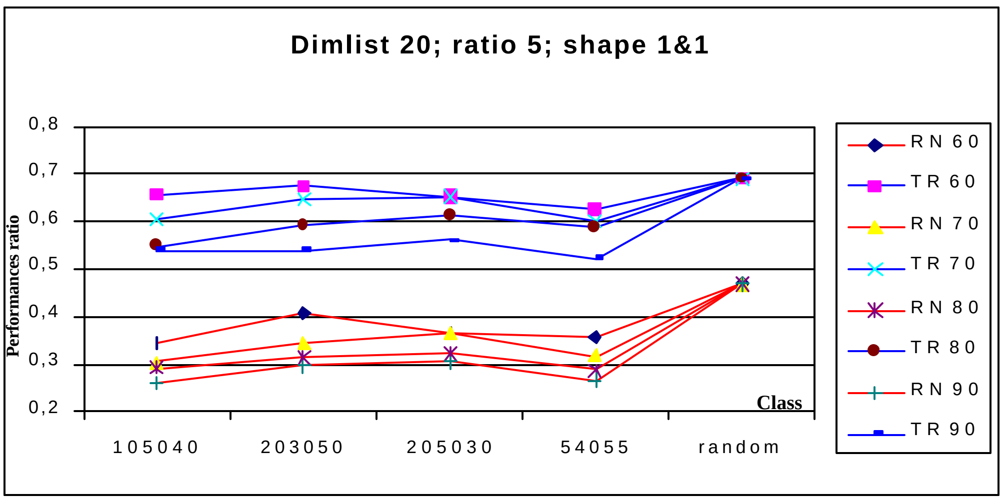

Figure 16. Routing policies effects in class based storage and random location policies. DimList 20. Ratio 5. Shape 1&1.

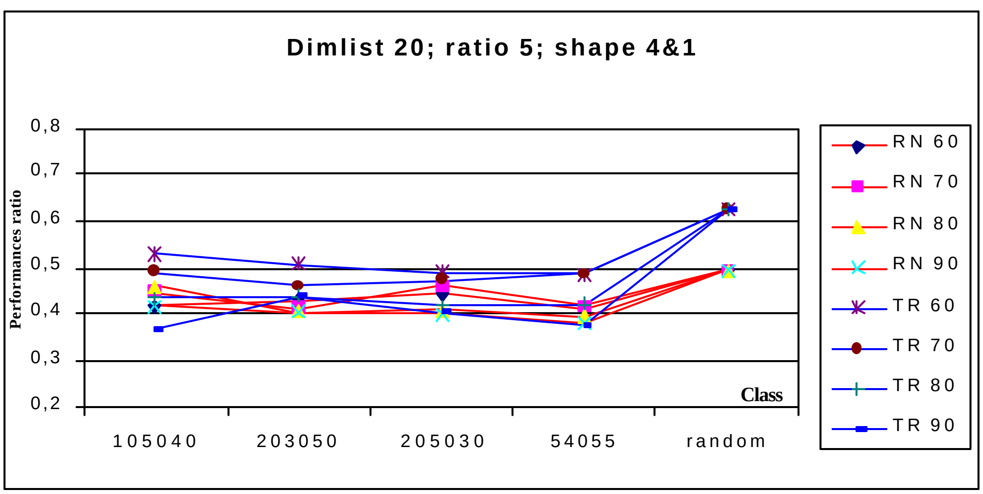

Figure 17. Effects of Routing policies in class based storage and random location policies. DimList 20. Ratio 5. Shape 4&1.

6. Conclusions and further research

A supporting decisionmaking database was created: it picks up a set of more than 50000 simulative runs in agreement with different system scenarios so for a given pool of system input constraints it returns the optimizing values to be assigned to free parameters as output. Some brief conclusions may be drawn from the results of the simulation experiments:

1. in order to involve all crucial and interrelated parameters, the design optimization of an OPS needs to be integrated: system performance depends on the combination of all these values;
2. the dimension of picking list is not as crucial as Policy, Ratio, Shape and Curve factors. In particular Policy and Ratio seem to be the most relevant parameters with respect to OPS performance.
3. Lower Ratio values are more crucial to system optimization than bigger values.
4. COI-based storage policies always yield travel times significantly shorter than the shared storage policy, agreeing with many other studies on manual and not manual OPS in the literature; nevertheless Class factor plays only a secondary role on system optimization;
5. If operating policies and factors are ill defined or may vary over time, intermediate solutions have to be configured through an economic analysis of convenience. They could be the object for further interesting studies on OPS and preferably carried out according to a sensitivity analysis, such as a DOE (Design of Experiment), of system performance relative to all the principal system parameters involved. This is a good way to weigh the influence of factors and their combinations;
6. best savings belong to quadratic system based on RN Policy, and to rectangular system based on TR routings.

Bibliography

Bechtel, C. and Jayaram, J., 1997, Supply Chain Management: A Strategic Perspective, *The International Journal of Logistics Management*, **8**, 15-34.

Brynzer, H. and Johansson, M. I., 1995, Design and performance of kitting and order picking systems, *International Journal of Production Economics*, **41**, 115-125.

Brynzer, H. and Johansson, M. I., 1996, Storage location assignement: using the product structure to reduce order picking times, *International Journal of Production Economics*, **46-47**, *595-603*.

Caron, F., Marchet, G. and Perego, A., 1998, Routing policies and COI-based storage policies in picker-to-part systems, *International Journal of Production Research*, **36**, 713-732.

Caron, F., Marchet, G. and Perego, A., 2000, Optimal layout in low-level picker-to-part systems, *International Journal of Production Research*, **38**, 101-17.

Chew, E. P. and Tang, L. C., 1999, Travel time analysis for general item location assignement in a rectangular warehouse, *European Journal of Operational Research*, **112**, 582-597.

Dallari, F., Marchet, G. and Ruggeri, R., 2000, Optimisation of a man-on-board automated storage/retrieval system, *Integrated Manufacturing Systems*, **11**, 87-93.

De Koster, R., van der Poort, E. S., 1998, Routing orderpickers in a warehouse: A comparison between optimal and heuristic solutions, *IIE Transactions*, **30**, 469-480.

De Koster, M. B. M., van der Poort, E. S. and Wolters, M., 1999, Efficient orderbatching methods in warehouse, *International Journal of Production Research*, **37**, 1479-1504.

Dell'Amico, M., Maffioli, f. and Martello, S., *Annotated Bibliographies in Combinatorial Optimization*, John Wiley & Sons. Chichester 1997.

Elsayed, E. A and Stern, R. G., 1983, Computerized algorithm for order processing in automated warehousing systems, *International Journal of Production Research*, **27**, 1097-1114.

Ferrari, E., Manzini, R., Regattieri, A. and Persona, A., 2001, Application of Operation Research topics and techniques for problem solving in industrial plants, 6th International Symposium on Operational Research in Slovenia, Preddvor, Slovenia, 37-43.

Ferrari, E., Gamberi, M., Manzini, R., Pareschi, A., Persona., A. and Regattieri, A., 2002, Effectiveness of dynamic simulation supporting and optimizing design and management of warehouse facilities, *Proceedings of the Business and Industry Symposium*, 2002 Advanced Simulation Technologies Conference, San Diego, California. April 2002. **34**, 76-81.

Francis R. L., McGinnis L. F. and White J. A., 1992, Facility Layout and Location: an Analytical Approach, Prentice Hall, Englewood Cliffs, New Jersey.

Frazelle, E. H., Hackman, S. T., and Platzman, L. K., 1989, Improving order picking productivity through intelligent stock assignment planning. *Proceedings of The Council of Logistics Management*, 353-371.

Gibson, D. R. and Sharp, G. P., 1992, Order batching procedures, *European Journal of Operational Research*, **58**, 57-67.

Goetschalckx, M and Ratliff, H. D., 1998, Order picking in an aisle, *IIE Transactions*, **20**, 53-62.

Gray, A. E., Karmarkar, U. S. and Seidmann A., 1992, Design and operation of an order-consolidation warehouse: Models and application, *European Journal of Operational Research*, **58**, 14-36.

Hall, R. W., 1993, Distance approximations for routing manual pickers in a warehouse, *IIE Transactions*, **25**, 76-87.

Haskett, J. L., 1963, Cube-per-order index – a key to warehouse stock location, *Transportation and Distribution Management*, **3**, 27-31.

Helo, P.T., 2000, Dynamic modelling of surge effect and capacity limitation in supply chains, *International Journal of Production Research*, **38**, 4521-4533.

Hwang, H., Beak, W. and Lee M., 1988, Clustering algorithms for order picking in an automated storage and retrieval system, *International Journal of Production Research*, **26**, 189-201.

Kallina, C. and Lynn, J., 1976, Application of the cube-per-order index rule for stock location in distribution warehouse, *Interfaces*, **7**, 37-46.

Kim, B. I., Graves, R. J., Heragu, S. S. and St.Onge A., 2002, Intelligent agent modeling of an industrial warehousing problem, *IIE Transaction*, **34**, 601-612.

Kosfeld M., 1998, Warehouse Design Through Dynamic Simulation. *Proceedings of the 1998 Winter Simulation Conference*, Medeiros, D. J., Watson, E. F., Carson, J. S. and Manivannan M. S., 1049-1053.

Larson, T. N., March, H. and Kusiak, A., 1997, A heuristic approach to warehouse layout with class based storage, *IIE Transactions*, **29**, 337-348.

Lawler, E. L., Lenstra, J. K., Rinnooy Kan, A. H. G., Shmoys, D. B., 1985, The Traveling Salesman Problem. John Wiley & Sons, New York.

Lawler, E. L., Lenstra, J. K., Rinnooy Kan, A. H. G., Shmoys, 1993, Sequencing and Scheduling: Algorithms and Complexity. S. C. Graves et al., Handbooks in OR & MS, vol.4, Chapter 9, 445-522. Elsevier Science Publishers.

Lin, C. H. and Lu, I. Y., 1999, The procedure of determining the order picking strategies in distribution center, *International Journal of Production Economics*, **60-61**, 301-307.

Malmborg, C. J. and Altassan, K. M., 1998, Analysis of storage assignment policies in less than unit load warehousing systems, *International Journal of Production Research*, **36**, 3459-3475.

Malmborg, C. J. and Krishnakumar, B., 1989, Optimal Storage Assignment Policies for Multiaddress Warehousing Systems, *IEEE Transactions on Systems, Man, and Cybernetics,* **19**, 197-204.

Malmborg, C. J., 2000, Interleaving models for the analysis of twin shuttle automated storage and retrieval systems, *International Journal of Production Research*, **38**, 4599-4610.

Malmborg, C. J. and Al-Tassan, K., 2000, An integrated performance model for orderpicking systems with randomize storage, *Applied Mathematical Modelling*, **24**, 95-111.

Pan, C-H and Liu, S-Y, 1995, A Comparative Study of Order Batching Algorithms, *Omega, International Journal of Management Science*, **23**, 691-700.

Papadimitriou, C., Steiglitz, K., Combinatorial optimization, Prentice Hall, Englewood Cliffs, New Jersey, 1982.

Park, Y. H. and Webster, D. B., 1989, Design of class-based storage racks for minimizing travel time in a three-dimensional storage system, *International Journal of Production Research*, 9, 1589-1601.

Petersen, II, C.G., 1997, An evaluation of order picking routing policies, *International Journal of Operations & Production Management*, **17**, 1098-1111.

Ratliff, H. D. and Rosenthall, A. S., 1983, Order picking in a rectangular warehouse: a solvable case of the travelling salesman problem, *Operations Research*, **31**, 507-521.

Riddalls, C.E., Bennett, S. and Tipi, N. S., 2000, Modelling the dynamics of supply chains, *International Journal of Systems Science*, **8**, 969-976.

Roodbergen, K. J. and de Koster R., 2001, Routing order pickers in a warehouse with middle aisle, *European Journal of Operational Research*, **133**, 32-43.

Rosenblatt, M. J., Roll, Y. and Zyser, V., 1993, A combined optimization and simulation approach for designing automated storage/retrieval systems, *IIE Transactions*, **25**, 40-50.

Rouwenhorst, B., Reuter, B., Stockrahm, V., van Houtum, G.J., Mantel, R.J., Zijm, W.H.M, 2000, Warehouse design and control: Framework and literature review, *European Journal of Operational Research*, **122**, 515-533.

Sarker, B. R. and Babu, P. S., 1995, Travel time models in automated storage/retrieval systems: A critical review, *International Journal of Production Economics*, **40**, 173-184.

Simpson, N. C. and Erenguc, S. S, 2001, Modeling the order picking function in supply chain systems: formulation, experimentation, and insights, *IIE Transactions*, **33**, 119-130.

Tang, L. C and Chew E.P., 1997, Order Picking Systems: Batching and Storage Assignement Strategies, *Computers and Industrial Engineering*, **33**, 817-820.

Tompkins, J. A., White, J. A., Bozer, Y. A., Frazelle, E. H., Tanchoco, J. M. A. and Trevino, J., 1996. *Facilities Planning* (New York: Wiley).

Van den Berg, J. P., 1999, A literature survey on planning and control of warehousing systems, *IIE Transactions*, **31**, 751-762.

Van den Berg, J.P. and Zijm, W. H. M., 1999, Models for warehouse management: Classification and examples, *International Journal of Production Economics*, **59**, 519-528.

Van den Berg, J. P. and Gademann A. J. R. M., 2000, Simulation study of an automated storage/retrieval system, *International Journal of Production Research*, **38**, 1339-1356.

Vaughan, T. S. and Petersen, C. G., 1999, The effect of warehouse cross aisles on order picking efficiency, *International Journal of Production Research*, **37**, 881-897.

Yoon, C. S. and Sharp, G. P., 1995, Example application of the cognitive design procedure for an order pick system: Case study, *European Journal of Operational Research*, **87**, 223-246.

Yoon, C. S. and Sharp, G. P., 1996, A structured procedure for analysis and design of order pick systems, IIE Transactions, 28, 379-389.