A Design Framework for Flexible Automated Warehouses

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Abstract Reducing operational costs in e-commerce logistics by having few distribution warehouses is a competitive approach that requires strategic investments on automation. But this technology is usually highly specific and implies facing the risk of running a warehouse unable to handle a shifting demand after a period of time. This work addresses flexibility as an issue to be faced when designing automated warehouses. An approach to flexibility in this context and its relation with throughput is given, to finally obtain an eight-step procedure that allows us to include this concept in automated warehouses’ design process.

Keywords: E-commerce, Automated Warehouse, Flexibility, Warehouse Design, Material Handling

1 Background, Objectives and Methodology

Flexibility in distribution warehouses has become more important than ever. Customer requirements are continuously changing while demanding low costs and high-rate service in terms of quality and time. The range of products sold on-line has widened to almost everything that we can need. All this makes e-commerce business quite demanding for logistics, and automated distribution warehouses are options to be considered due to their high throughput, fulfillment quality and compact storage. Flexibility is an additional objective that has become increasing-

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ly interesting, but seems to be difficult to achieve within the rigid, specific and specialized world of automation.

Gaining insight to face the flexibility-throughput trade-off and including it in a warehouse (re) design process are the aims of this research work, and thus two objectives are targeted: to develop a theoretical model to define flexibility and explain its sources within warehouses, and to translate it into a procedure to (re) design warehouses. The method applied is based on two pillars: one is the authors’ professional experience on a real case of design of an automatic warehouse, the other are the insights provided by the review of scientific papers. This combination of hands-on experience and scientific framework has enabled us to get the best out of each approach.

This paper is organized as follows: in section 2, state-of-the art in academic research is provided in a Literature Review which covered scientific databases (IEEE Xplore, Web of Science ISI, Elsevier), leading to a gap identification after comparing the needs of professional practice and the answers given by academic literature. In sections 3 and 4 we propose our conceptual model for defining flexibility and its relationship with throughput via item’s characteristics. In section 5 a self-developed methodology for including the flexibility in warehouse design is deployed, based on the previous framework. Finally, our conclusions and further research are presented in section 6.

2 Literature Review and Gap Identification

We have reviewed academic papers dealing with the following issues: (1) literature devoted to flexibility in supply chains or specifically in warehouses, (2) references that mention flexibility in the design process of warehouses, and (3) papers that discuss automation and material handling selection. Information systems and pure organizational issues that may not involve automation are excluded from this study.

Christopher and Peck (2004), discuss the need to create resilient supply chains and mention robustness and resilience as synonyms of flexibility and adaptability. Resilience is defined as “the ability of a system to return to its original state or move to a new, more desirable state after being disturbed”. On the other hand, Brockmann and Godin (1997) define flexibility as the capability to easily adapt to change, mentioning specifically warehouses. The idea of flexibility in a system in general is then understood as the ability to cope with external changes keeping integrity, while adaptability is related to change internally in order to react to those external changes. Manzini (2005) and Brockmann & Godin (1997) study the multiple, rapid external changes that warehouses face, that can take place in cost or in customer demand, meaning shifting items, increasing the number of SKUs and including high variability in products’ shape, dimensions and weight. Richardson
(1998) identifies new products, new customer demands or volume growth as changes to be faced. Customization is a trend that impacts warehousing, especially in e-fulfillment for business to consumer (B2C), as Lederer, Mirchandani and Sims (2001) observe. The ability to cope with those changes is clearly conditioned in the warehouse design process, which includes decisions about level of automation and selection of handling material. Rouwenhorst et al. (2000) present a reference framework and classification of warehouse design and control problems, in which processes, resources and organization have to be defined. Brockmann and Godin (1997) analyze and compare different options in material storage and handling equipment and rank automated systems as the less flexible and more expensive option, while offering the highest storage density and selectivity in case of unit load or small items. Bartholdi and Hackman (2008) describe the equipment that serves to automate warehouses and how it is linked with product characteristics, and also point out the lack of flexibility as a main characteristic of automatic devices. Naish and Baker (2004) study pros and cons of automation, and claim that those systems can cope very well with changes within a limited range in throughputs and order profiles, but there is a dramatic lack of flexibility out of the set of scenarios considered during design. Related to the specifics of material handling selection Eldemir, Graves and Malmborg (2004) identify a set of parameters to be considered in developing APS, a sort of complex automation systems, and Wong (2007) addresses how automated material handling systems (AMHS) can be designed with reconfiguration features to maximize utilization and to enhance its flexibility. Centered on specific configurations, Yu and De Koster (2008) study the effects on performance of varying certain constructive parameters and operational alternatives in a so called pick-and-pass system composed by conveyor systems and pick stations.

After this literature review we concluded that, although flexibility is considered a desirable characteristic of warehouses, the concept has not yet been clearly defined in academic literature. However, we can identify different views of the flexibility as the capacity to absorb product’s physical changes, accommodate variations in the volume of orders in the short and long term, deal with changes in the scheduled inputs or outputs of products and re-organize internally the resources to surmount system failures. Flexibility is considered to be related to performance, and thus it is expected to be fairly conditioned at design stage, when the automation degree is determined and resources are selected. Nevertheless, we have not found works that establish a measurement of the flexibility itself nor the relation between this and other design parameters like performance or storage capacity, thus regarding flexibility the following issues have to be addressed: what is flexibility in automatic warehouses, what flexibility depends on and how are flexibility and throughput inter-related.
3 A Proposal of a Conceptual Model to Study System’s Flexibility

In this work we will face flexibility studying the response of a warehouse to changes in inputs like products, order profiles and work volume, being focused on the adaptation of a warehouse to specific product characteristics. This requires a deep understanding of how item characteristics influence or condition processes and systems. Besides, the design task consists in deciding what processes, systems and organizational policies are to be implemented, thus the relations between product, system and process have to be the driving forces in design and operation of a warehouse. As a consequence, and as illustrated in Fig. 1, the guide for studying a system’s flexibility is a three-axis frame model of products, systems and processes that helps us to cover all the relationships and interfaces between them.

Fig. 1 Model to analyze the impact of changes of products (self production)

Based on systems, we will consider that flexibility can be evaluated through two quantitative aspects (feasibility and impact in throughput) and two qualitative ones (adaptability and scalability):

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3 We consider subsystems or modules as the basic working cells (i.e. a picking station, a palletizer, an AGV…) that can be arranged into systems on which branch processes take place, being the warehouse a combination of systems.
• **Strict feasibility.** Referred to the physical limits and maximum capacities of the system, it is related to the question: Is the system able to decant/pick/store a new item?

• **Impact in throughput** due to changes in items or orders. It is related to the question: How a new item or order profile will condition the throughput?

• **Scalability.** It is the possibility to increase or decrease the capacities of the system in the short term according shifting needs.

• **Adaptability:** it means the easy re-configuration of the modules or elements of the system – which impact on scalability also. Pure element adaptation is closely related to match tool parameters and item characteristics, as for example could happen in a variable grip handling device.

### 4 Influence of Item Characteristics on Throughput

Changes in items’ characteristics may limit the path or ‘branch’ of the process that products can follow. Weight, dimensions, fragility or surface affect item handling and may lead to operative decisions; each handling-related parameter has a specific contribution in the total time of the activity, affecting the throughput. Besides, items in automated systems are generally moved on re-usable containers or pallets, called transport elements, whose design will depend on item’s dimensions, weight, fragility or rigidity. Certainly, the nature of items imposes various conditions on the handling in basic processes and on the transport element definition.

Within this frame, warehouse operations can be classified according to two categories of basic activities: manipulation and transportation processes. Decanting, picking or sorting are examples of manipulation processes, and imply the direct handling of products by operators or machines leading to changes in the packing entities. The relationship studied here is that between item (units, packs or cartons) and handling process. Manipulation can also mean the transference of entities between source and target transport elements, studying the relationship that links them (pallets, dollies, totes or cartons) with items’ characteristics. On the other hand, transportation means transference of transport elements within sub-systems, where the grip transport element – system should be studied. Any process in a warehouse can be then de-composed in a sequence of manipulation and transportation processes. In manipulation processes, changes in strict feasibility can be measured evaluating if the item may be handled with the grip item-handling unit (automatic or manual), and also if the item fits into the source and target transport elements, while throughput could be measured as number of units processed in a time period. This will condition the number of transport elements that are inducted into the transportation system. A fictitious item representative of the whole order can be defined (profile item), which is equivalent to assume that only one type of item is managed in the order. With the average processing time per item, a total
processing time per order can be obtained, and having capacity constraints (i.e: total or maximum processing time per day) the throughput can be calculated. Then providing a measurement of the impact of variations in item/order characteristics on manipulation process’ throughput is feasible, and can be propagated downstream to transportation subsystems with a simple evaluation, reaching to a measure for the whole system.

5 Designing for Flexibility: a Framework Proposal

A flexibility-oriented design of systems starts in the evaluation of the possible changes that the warehouse may suffer from the standpoint of items and orders. Derived from the description of interactions between warehouse’s entities shown in Fig. 1, we may think in propagating product’s changes impact on processes and systems: traveling along the figure counter-clockwise it is possible to make a pre-selection of systems, while a second round reviewing the interactions system-product, product-process and process-system will lead us to know the impact of product changes on throughput, and give us the basis to carry out what-if analysis with different change scenarios. Fig. 2 depicts the steps proposed in our design for flexibility framework.

![Diagram of the evaluation process](image)

**Fig. 2** Complete evaluation process. Linked by letters and colors to the first and second round on the three-axis model (self production)
1. (Step A) Order profile / item characteristics. The type of items to be managed, the order profile and the number of orders per time period have to be clarified:
   - To develop a list of item characteristics and evaluate them in order to find limitative properties that may branch the activity in different processes, as well as to identify those ones that may impact on handling. Dimensions and weight are ranged from minimum to maximum levels in order to pre-select suitable systems and evaluate strict feasibility once we select the handling resources.
   - To have an average throughput as a design objective. Here a ‘representative or fictitious item’ with average dimensions and weight, plus variation ranges on them is required to simplify calculations.

2. (Step B) Process branches. Deciding what items are handled automatically in some or all parts of the flow, and what are to be derived to manual processes is required. This deep impact decision will condition the flows in the warehouse, but will also narrow the range of products inducted in the automatic system, thus reducing variability.

3. (Step C) Sub-systems selection. Once we know what is expected to be handled in the warehouse, the systems can be chosen from commercial catalogs and the identification of manipulation and transportation modules is done.

4. (Step D) Transport element definition. Selected systems will limit the dimension and type of transport element to be used. With this and the requirements imposed by items’ characteristics, the transport element should be defined. Besides, it has to be looked for the suitability of the transport element for further processes (i.e. the container may require to be stackable, to admit separators or to allow ergonomic manual handling).

5. (Step E) Manipulation model. The throughput calculation can be done on the already identified manipulation processes, requiring a previous estimation or measurement of the time impact of each item characteristic on this specific handling process. The limitation in throughput for the process must be known.

6. (Step F) Transportation model. Transportation needs can be expressed as number of transport elements to be moved per time period, and are derived from the results of manipulation model. Applying this with the aid of a net flow model, bottlenecks can be identified.

7. (Step A’) Order profile / item characteristics. What-if analysis. With reference values for the ‘order type’ and ‘item type’ already calculated, scenarios of variation can be forecasted. Changes can be intended in volume or in the average representative item (as a result of changes in the order profile), and may mean a shift in the average manipulation time.

8. (Step A’’) Measure impact in throughput. The last step is to evaluate the throughput again for every scenario generated in the previous point, comparing the results with the reference ones. The impact on throughput and possible shifts in bottlenecks can be calculated, leading to possible re-design decisions.
6 Conclusions and Further Research

The general aim of this research work was to set a methodology to include flexibility within the (re) design process of automated warehouses, and has been deployed after reviewing academic literature and developing a framework to understand the meaning and sources of flexibility in warehousing. The drivers that led us to address the flexibility issue were the interactions system-product-process in a warehouse. We have concluded that flexibility in warehouses is the capacity to absorb external changes in products and orders with little or none internal reconfiguration and moderate impact in throughput. Flexibility is evaluable through four dimensions: strict feasibility, impact in throughput, adaptability and scalability. The first two ones are deeply dependent on item and order characteristics and are closely related to the transport elements to be used. Changes in manipulation times due to changes in characteristics of the items are propagated downstream on the process and changes the number of circulation transport elements, thus affecting the throughput. Based on all this, a procedure of eight steps has been proposed to include and evaluate flexibility in warehouse design or re-design process.

New questions arise after this work opening complementary or new research lines. Tools are needed to decide when to split the process into manual branches and when to consolidate manual and automatic paths, looking for an impact in throughput for the whole warehouse. To include item rotation or class categories in the study could also help to split class categories in different ‘parallel’ systems or aggregation groups in order to improve flexibility. Adaptability and scalability haven’t been addresses in this work, and could be assessed or benchmarked after a wide comparative analysis of warehousing integrators’ portfolio and published references of real installations.

7 References


