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Research Article

A framework for supporting warehouse design

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Abstract

Paper aims: This paper proposes a warehouse design framework for evaluating the most robust combination of layout alternatives, tactical (picking, storage) and operational (routing) control policies, considering simultaneously the service level, costs and resource utilization criteria.

Originality: We applied an innovative Morphological Analysis to reduce the number of alternatives and evaluate the uncertainties in warehouse design. We also address the effect of congestion and options for configuring the layout of aisles.

Research method: We apply multicriteria decision analysis and discrete event simulation to evaluate the most robust combination between layout alternatives and operational control policies. We also suggest the use of scenario planning to deal with the high uncertainties involved in the order picking activity.

Main findings: Our framework captures the warehouse manager's preference and experience by means of weight elicitation, value functions, scenario planning and an inter-scenario robustness index to provide a robust final solution.

Implications for theory and practice: For theory, we highlight the combination of methods applied to a strategic, tactical and operational warehouse design problem in an environment with uncertainties. For practice, warehouse managers may use the framework to explore and find out which combination of control policies and layout can meet the company's objectives.

Keywords

Warehouse layout. Warehouse control policies. Multicriteria decision analysis. Discrete event simulation. Scenario planning.

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1. Introduction

Warehouse design has gained a more sophisticated and robotized structures when compared with the past (Hashemkhani Zolfani et al., 2023), mainly in the order picking process, which is still the most laborious and expensive process, often suffering from poor ergonomics, and requiring the willingness of high-quality labor to work in shifts (van Gils et al., 2018b; Azadeh et al., 2019). The order picking process performance depends heavily on the layout, storage system, and operational control policies (Tutam & White, 2024), which are crucial warehouse design decisions (Roodbergen et al., 2015).

Strategic operations decisions such as layout (van Gils et al., 2018b), tactical decisions (e.g., storage and picking control policies), and operational decisions (e.g., routing control policies) (Rouwenhorst et al., 2000) are interdependent (De Koster et al., 2007). Since warehouse design decisions are at different planning horizons and there is a strong interrelationship between them, there is a need to analyze them simultaneously (Altarazi & Ammouri, 2018).

Choosing the best combination between the type of layout and the operational control policies depends on the real operating conditions of the warehouse and the company's objectives (van Gils et al., 2018a). The internal operations of a warehouse are stochastic (Roy et al., 2015; Zhou et al., 2022), as orders have different quantities of lines and different items per line to collect (Shqair et al., 2014). The congestion between order pickers (Heath et al., 2013) and the time between order arrivals also matter (Chen et al., 2010). On the one hand, these facts suggest that simulation is a suitable method to address the warehouse performance evaluation during the design phase (Pourhassan & Raissi, 2017), thus evaluating scenarios with variations in the order profile, demand growth, among other variables (Baker & Canessa, 2009). On the other hand, a structured Scenario Planning (SP) method during the design process is suitable to evaluate the alternatives (e.g., the combination of storage policy, picking policy, routing policy and layout) in favorable and unfavorable scenarios that the company may face considering its decision-makers' experience (Ram et al., 2011).

The literature attests to the successful application of simulation and SP to study the performance of warehouses under different design conditions, simultaneously addressing different combinations of the alternatives of two or more decisions, regarding layout, tactical and operational control policies, such as: storage control policies and layout (Petersen & Aase, 2017); routing control policies and layout (Petersen, 1997); picking and storage control policies (Silva et al., 2020); storage and routing control policies (Chan & Chan, 2011; Franzke et al., 2017); picking and routing control policies (Briant et al., 2020; Cao et al., 2023), picking, storage and routing control policies (Chackelson et al., 2013; Chen et al., 2010; van Gils et al., 2019); storage and routing control policies and layout (Altarazi & Ammouri, 2018; Roodbergen et al., 2015; Shqair et al., 2014); and picking, storage and routing control policies and layout (van Gils et al., 2018a).

However, the warehousing literature on order picking mainly considers minimizing the time or distance traveled as a single objective. On the other hand, warehouse design requires evaluating other criteria/objectives (Silva et al., 2015; Montanari et al., 2021), such as total (operational and investment) costs, use of resources (space, equipment and workers), and service level (van Gils et al., 2018b; Ahmadi Keshavarz et al., 2021). Warehouse managers in a supply chain have to look beyond single-dimensional performance and consider trade-offs between different criteria (Chen et al., 2010; Derhami et al., 2020; Silva et al., 2015) to align warehouse efficiency measures with the customers' requirements, since some initiatives to improve one of the previously cited criteria may negatively impact the performance on another criterion (Chackelson et al., 2013; Fontana et al., 2020a). Therefore, the warehouse design can be characterized as a multicriteria problem with conflicting objectives (service level x cost, for example) and many alternatives for analysis and selection (Vieira et al., 2017).

Most studies on warehouse design decisions analyze the interactions of control policy combinations on warehouse performance (van Gils et al., 2018b; Ahmadi Keshavarz et al., 2021). However, to help decision makers (warehouse managers) to evaluate and select the ideal combination between alternatives of control policies and layout for warehouse design when considering real operations conditions, studies on ranking and selection procedures (Chen et al., 2010; Roodbergen et al., 2015) are more useful in practice than interactions studies. The former studies usually offer an ideal combination according to the input data used in contrast with the latter ones. Furthermore, these simulation studies are scarce (van Gils et al., 2018b). Although a Multicriteria decision analysis (MCDA) (operating cost vs service level criterion) has already been combined with simulation by Chen et al. (2010), they do not consider different aisle layouts and picking policies alternatives. On the other hand, Roodbergen et al. (2015) considered one criterion (total travel distance) in their method as a single objective to minimize. Yet, no study has considered congestion picking, which can reduce the order picking performance and efficiency in a multiple order pickers environment (Elbert et al., 2017; Franzke et al., 2017), as far as we know.

Thus, this study proposes a methodology for evaluating, classifying and selecting the most robust combination of layout alternatives (vertical or horizontal aisles orientation) and operational control policy alternatives (picking, storage and routing) considering simultaneously the service level, costs and resource utilization criteria according to the decision-makers' preferences and the picking congestion. We define a more robust alternative as the one that performs reasonably well for a variety of scenarios (Ram et al., 2011). Furthermore, we propose an innovative framework, which is inspired by the combination of MCDA and SP approaches, and Discrete Event Simulation (DES) to provide a generic structure that can be applied to implementing different warehouse design. Therefore, these combined approaches could provide suitable solutions to addressing this problem to consider more aspects simultaneously.

The latest studies in this domain have discussed tactical and operational aspects of the warehouse design to meet market aspects (demand, profitability and sensitivity of the customers towards the products) that influence the warehouse design (Yerlikaya, 2020; Fontana et al., 2020a), and to rank products and assigning them inside warehouses (Silva et al., 2015; Micale et al., 2019), including the order picking (weight, space and demand, time) (Fontana & Nepomuceno, 2017). Differently to these studies that address specific problems applying the MCDA approach in warehouse operations, our proposal provides a more generic framework for warehouse design, based on a set of criteria according to the decision-makers' preferences. Montanari et al. (2021) investigated various routing policies of pickers, criteria, and uncertain aspects using combined methods; however, they did not consider different vertical and horizontal layout aisles and scenarios to address several alternatives.

The contribution unfolds in two aspects:

(1) Although the MCDA and DES have been applied in the ranking and selection procedures in internal warehouse design decisions (Timperio et al., 2020), the combination of those methods for supporting those decisions with SP (Chen et al., 2010) may be useful. For this SP, we applied an innovative Morphological Analysis (MA) to reduce the number of alternative combinations and evaluate the uncertainties at their best (worst) levels.

(2) The literature on the effect of congestion in warehousing design has been overlooked by most of the order picking studies (Silva et al., 2020; van Gils et al., 2018b; Roodbergen et al., 2015; Casella et al., 2023). Our framework also considers the evaluation of the vertical and horizontal layout of aisles as alternatives beyond the number and length of aisles in the previous research.

The remainder of this paper is structured as follows. Section 2 presents a literature review about DES-based warehouse design studies and how MCDA and SP can help deal with warehouse design. Our proposed framework is detailed in section 3. In section 4, a scenario analysis of the application is presented. The paper ends with some conclusions, limitations, and suggestions for future research.

2. Literature review

2.1. DES-based studies in warehouse design

Table 1 summarizes the characteristics of the previous studies that have addressed, simultaneously or not, the evaluation of alternatives of storage, picking and routing control policies in manual order picking warehouse design through DES. Group A studies conduct the evaluation alternatives of one control policy considering the other control policies as fixed. For example, one study considered the total travel distance for the order picker to complete a given pick-list, varying the placement of the cross aisles and considering different storage policies (random, across-aisle and within-aisle) (Petersen & Aase, 2017). Studies that simultaneously evaluate alternatives of two control policies are listed in group B. For example, one analysis identified how the mean throughput time needed to fulfill a single order is affected by the congestion between order pickers under different combinations of storage policies and routing policies for the discrete picking policy (Franzke et al., 2017). Finally, group C studies simultaneously consider alternatives of the three control policies. One example of such group is van Gils et al. (2018a) who evaluated the average travel distance by the order pickers under different combinations of five storage policies (random, diagonal, perimeter, across-aisle and within-aisle), three picking policies (discrete, batch and zone) and five routing policies (traversal, return, largest gap, aisle by aisle and optimal).

The warehouse performance evaluation under different control policy alternatives is generally combined with different warehouse layout alternatives, such as: the layout shape (Petersen, 1997; Petersen & Aase, 2004), the quantity of cross aisles (Petersen & Aase, 2017; Roodbergen & Koster, 2001; Roodbergen et al., 2015), the quantity and length of picking aisles (van Gils et al., 2018b; Petersen, 2002; Roodbergen & Koster, 2001; Roodbergen et al., 2015), the start/end picking route point (Petersen, 1997; Petersen & Aase, 2004; Petersen & Schmenner, 1999), and the aisle layout (Altarazi & Ammouri, 2018). Although different aisle layouts (such as vertical, horizontal, fishbone, etc.) can provide different results in warehouse performance (Altarazi & Ammouri, 2018), evaluating them is less frequent in those studies.

Other factors (or other picking planning problems) are also considered at different levels, such as throughput (Altarazi & Ammouri, 2018; Petersen, 2000; Petersen & Schmenner, 1999), batch capacity, order sequencing (van Gils et al., 2019), time between order arrivals (Chen et al., 2010), the picker zoning policy (van Gils et al., 2019) or the number of order pickers (Altarazi & Ammouri, 2018; Franzke et al., 2017; van Gils et al., 2019).

Control policies, layout alternatives and other factors are commonly analyzed in interaction studies, where the aim is to see how the combination of these decision elements (considering their alternatives or levels, affects warehouse performance, and thus the studies provide general guidance to warehouse managers on how to set up/design their order picking system. Usually, these studies perform a statistical analysis showing tables and graphics for interpretations (see van Gils et al., 2019) for an example). On the other hand, for a more suitable warehouse design solution managers may prefer to use a ranking and selection procedure since the method asks for their warehouse real operation parameters and, as an output, a combination of control policies and layout is presented as an ideal one.

Table 1. Simulation studies on control policy evaluation in warehouses.

Group	Studies	Control policy alternatives			Layout alternatives	Criteria evaluated	Stochastic behavior	Type of work
		storage	picking	routing				
A	Bahrami et al. (2019)	2	1	1	vertical	travel distance	pick list size	interactions
						order lead time		
	Elbert et al. (2017)	1	1	7	vertical	total picking time	no	interactions
	Petersen & Aase (2017)	3	1	1	vertical	distance travelled to pick a list	no	interactions
	Dekker et al. (2004)	1	1	5	horizontal	average route length per order	pick list size	interactions
	Petersen (2002)	3	1	1	vertical	distance travelled to pick a list	no	interactions
	Roodbergen & Koster (2001)	1	1	6	vertical	average travel time to pick a list	no	interactions
	Petersen (2000)	1	4	1	vertical	mean daily labor mean length of day mean percentage of late orders	pick list size	interactions
	Petersen (1997)	1	1	6	vertical	distance travelled to pick a list	no	interactions
B	Franzke et al. (2017)	4	1	7	vertical	mean throughput time to pick a list	no	interactions
	Montanari et al. (2021)	2	1	2	vertical	travel distance	pick list size	interactions
	Altarazi & Ammouri (2018)	2	1	2	vertical	cycle time	pick list size	interactions
					horizontal			
					fishbone		order arrival	
	Roodbergen et al. (2015)	6	1	5	vertical	total travel distance	pick list size	method
	Chan & Chan (2011)	3	1	3	vertical	total travel distance total retrieval time	no	interactions
	Heath et al. (2013)	3	1	2	vertical	total mean congestion time		interactions
						total mean travel time		
	Chen et al. (2010)	3	1	4	vertical	service level	pick list size	method
						operational costs	order arrival	
	Petersen & Schmenner (1999)	4	1	6	vertical	distance traveled to pick a list	no	interactions
	Petersen (1999)	3	1	4	vertical	total route time to pick a list	no	interactions
C	van Gils et al. (2018a)	5	3	5	vertical	average travel distance	pick list size	interactions
	Chackelson et al. (2013)	2	2	2	vertical	order maturity time total picking time	retrieval time	interactions
	van Gils et al. (2019)	5	2	5	Horizontal	total picking time total wait time	pick list size	interactions
	Petersen & Aase (2004)	2	2	3	vertical	total fulfillment time	pick list size	interactions

Chen et al. (2010) pointed out which combination of storage policy, routing policy, batch formation rule and batch capacity is the most efficient (operating cost vs service level) for the warehouse with vertical layout under different scenarios with a variation of time between order arrival and pick list size, using DEA (Data Envelopment Analysis) and Monte Carlo simulation. Roodbergen et al. (2015) proposed a design method to simultaneously determine the vertical layout (number and length of picking aisles and number of cross aisles), the storage and routing control policies, considering data such as: physical limitations (to the building), required storage capacity, systems used (e.g. pallet positions, flow racks and/or shelving), aisle width and cross-aisle width. These studies can be replicated for specific cases (observing the limitations of the studies), and thus they may find a viable solution for warehouse design.

Methods or interactions studies use performance measures related to the time spent or distance traveled in the picking process, usually basing the decision or analysis on a single criterion. For instance, total mean congestion time and total mean travel time are employed by Heath et al. (2013), total order picking time and waiting time by van Gils et al. (2019) and travel distance and order lead time by Bahrami et al. (2019), while Chan & Chan (2011) use the order retrieval time and travel distance performance criteria, reporting that an alternative can have a good performance on one criterion but may perform poorly on other criteria. Chackelson et al. (2013) used order maturity time and total picking time and pointed out the existence of trade-offs between these criteria and that the company's objectives and market conditions must be considered in the decision of the best design alternative.

Moreover, from the point of view of the stochastic behavior of warehouse activities, it is important to consider the congestion problem in the analysis. Picker congestion (or picker blocking) occurs when more than a single order picker works in the same narrow aisle. This has been overlooked in previous works that use only one order picker in their analyzes (e.g., Petersen & Aase, 2017) or that consider multiple order pickers but with large enough aisles to disregard the effects of congestion (e.g. Altarazi & Ammouri, 2018).

Therefore, the literature indicates that few studies address more than one alternative regarding each of the three control policies simultaneously (van Gils et al., 2018a; Petersen & Aase, 2004; Chackelson et al., 2013). Studies that propose evaluation and selection methods of the best combination of control policies (Chen et al., 2010) and control policies and layout (Roodbergen et al., 2015) are also scarce. Although many layout decisions should be taken in warehouse design, the aisle layout decision is relatively unexplored (Altarazi & Ammouri, 2018) since horizontal layout does not appear often. In addition, congestion is not often considered in the analyzes of previous studies, mainly in the method studies. Finally, the trade-off analysis in the warehouse design phase with multiple performance criteria (Chackelson et al., 2013) has also been neglected.

Our framework fills these gaps by proposing an evaluation and selection method of the most robust combination between storage policy, picking policy, routing policy and aisle layout alternatives at warehouse design phase. Moreover, it addresses the congestion problem from an MCDA perspective, by considering the trade-offs among the company's objectives and market conditions.

2.2. Multicriteria decision analysis and scenario planning as an approach for warehouse design

MCDA aims to help structuring complex problems with multiple and conflicting criteria to support the decision-maker in selecting alternatives (Logullo et al., 2022) in warehouse operations (Fontana et al., 2020b), considering distribution strategy, internal activities, and the characteristics of the distribution operations (Vieira et al., 2017).

The combination of MCDA with scenario planning can be useful in making warehouse design decisions, as warehouses have to adapt to uncertainties from outside their supply chains and from internal warehouse activities. Each source of uncertainty can have an unforeseen impact on strategic, tactical or operational decisions, but they must be met on a daily basis in practice (Gong & Koster, 2011; Yerlikaya, 2020). SP uses imaginary future scenarios to help decision-makers reflect on the key uncertainties they face and develop strategies to address these uncertainties (Montibeller et al., 2006). Therefore, scenarios should be relevant to decision-makers' concerns and describe different futures generically, represented by situations where the system may be in a period of time, trying to link the uncertainties that are considered inherent in the future without addressing probabilities for these futures (Ram et al., 2011).

Scenario building can be aided by tools such as: the four quadrant matrix, the Wilson matrix, MA, consistency analysis, and cross-impact analysis (Amer et al., 2013) parabolic aisles-based method (Zhang et al., 2021). MA is suitable for developing scenarios because it can deal with a large amount of quantitative and qualitatively defined uncertainties; it encourages the investigation of multiple combinations of limit values efficiently; and helps to describe scenarios at a level of detail that provides sufficient information to the decision-makers to elicit their preferences (Ram et al., 2011). Hence, MA enables to visualize the various elements and dimensions of the system under analysis, and thus develop scenarios for the future and check if they are plausible to the decision-makers (Amer et al., 2013).

The number of scenarios to develop is also an important issue. It is difficult to establish the ideal quantity, since it depends on the specificity of the application and the objectives of the analysis. However, scenario development must meet certain criteria: at least two scenarios are needed to reflect uncertainties; each scenario must be plausible, that is, they must evolve logically (in a cause/effect manner) from past and present and reflect current knowledge; scenarios must be internally consistent, that is, within scenarios the events must be related through cause/effect arguments, which cannot be flawed; and scenarios should be relevant to the decision-maker's problem. They must be able to generate useful, comprehensive and challenging ideas and provide testing conditions for these ideas against which the decision-maker can consider future business plans, strategies and directions (i.e., course alternatives).

The MCDA and SP combination has been used for decision-making on strategic issues, and therefore for long-term horizons (see Balarezo & Nielsen, 2017 for an overview). The integrated use of SP and MCDA is a powerful combination for strategic decision-making (Stewart et al., 2013). SP is limited in evaluating the alternative strategies generated in its analysis, and MCDA can be useful in this assessment as it is a tool capable of integrating multiple criteria and alternative analysis while considering trade-offs. On the other hand, MCDA does not consider different scenarios in its analysis, and SP can assist in this process.

However, this combination is not trivial as it adds one more dimension to the analysis in the already complex multicriteria decision analysis, as the alternatives must be evaluated and compared in all criteria and scenarios of the analysis (Stewart et al., 2013) to find robust alternatives, which have an adequate performance in all scenarios analyzed (Montibeller et al., 2006).

3. Methodology

Due to the challenges of providing a great combination of the type of layout and the operational control policies, considering the operating conditions of the warehouse, a framework is proposed in Figure 1. Combining the different methods (DES, MCDA and SP) aims to overcome the limitations when these methods are applied alone. Although MCDA can deal with both qualitative and quantitative static performance of alternative (which we call "static criteria"), it is rarely used when the performances of alternatives have a dynamic characteristic (which we call "dynamic criteria"), and DES can help address these criteria. On the other hand, SP is a tool to create future, plausible and relevant scenarios for the decision problem (Schoemaker, 1995), but it fails to evaluate alternatives under the created scenarios, and MCDA can help in this task (Goodwin & Wright, 2004). Moreover, the simulation helps to detail the created scenarios (Baker & Canessa, 2009), quantifying them through the criteria used in the MCDA.

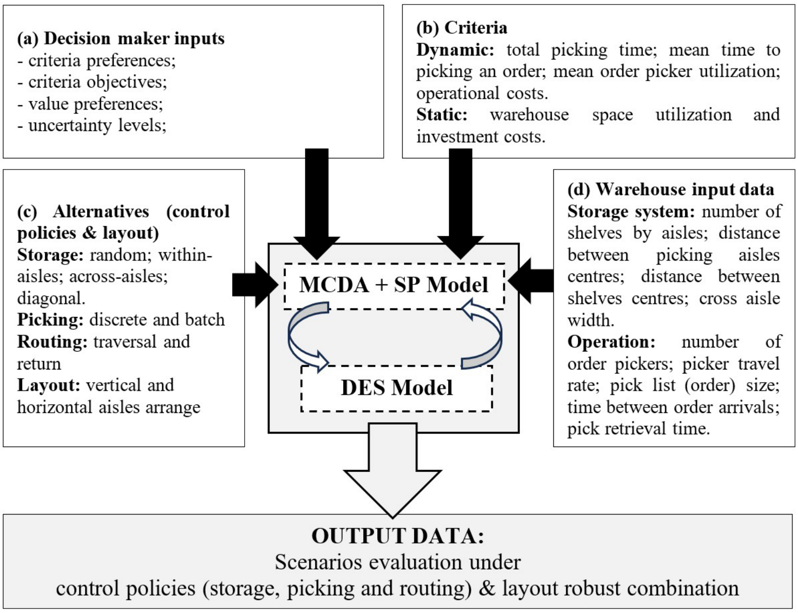

Figure 1. Framework for evaluating and selecting the combination of control policies and layout in warehouses.

As Figure 1 shows, the MCDA+SP model depends on some (a) decision-maker's inputs such as criteria preferences, criteria objectives, value preferences and uncertainty levels, and through the (b) static and dynamic criteria, (c) evaluation of the alternatives defined by SP, of control policies and aisle layouts. A DES model helps the MCDA+SP model in evaluating the dynamic criteria according to the (d) warehouse storage system input data, and the warehouse operation input data. The operation input data, such as the "pick list size" and "time between order arrival" comes from scenario planning (uncertainty levels adopted by the decision-maker's input). The output data of the proposed structure consists of a set of scenarios that present the performance of each combination of storage, picking and routing policies with the horizontal or vertical layout of the aisles (alternatives). Based on comparing the performance of the scenarios, it is possible to find the most robust combination of policies and layout (Montanari et al., 2021).

3.1. Stepwise description of the framework

Our proposal follows an adaptation of the Ram et al. (2011) method for the evaluation of decision alternatives under scenario planning with MA. In the proposed framework, the performances of the dynamic criteria are obtained through a DES model developed according to the principles proposed by Kelton et al. (2007), and the decision-maker's preferences are captured by the Simple Multi-attribute Rating Technique (SMARTS) (Edwards & Barron, 1994). The uncertainties, criteria and alternatives (described below) are obtained from the literature review. In our study, the uncertainties considered are the pick-list size, the time between order arrival and order demand (Fontana & Nepomuceno, 2017).

To support the steps of the proposed framework, a hierarchical structure of the decision-making objectives (with associated criteria that measure the achievement of these objectives) is considered (Figure 2). Some of the criteria were surveyed by the 21 studies (Table 1) and are commonly used in warehouse design (De Koster et al., 2007) or operation.

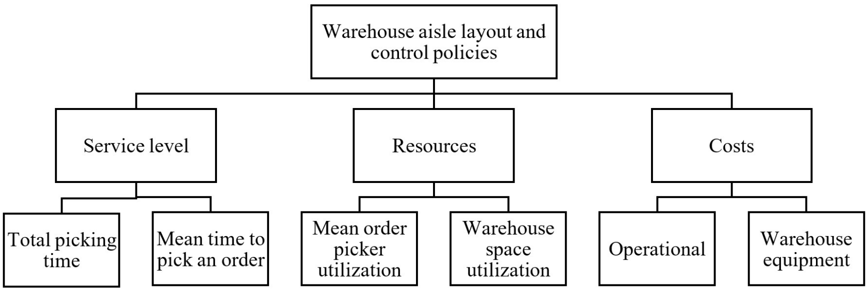

Figure 2. Hierarchical structure of the decision-making objectives.

The hierarchical structure considers three criteria (service level, resources and costs) and their sub-criteria to assist the decision-maker's analysis. Regarding the sub-criteria "total picking time" and "mean time to pick an order", Chackelson et al. (2013) report that they are mainly influenced by the picking and routing policies, as well as the pick-list size (Montanari et al., 2021). Yet, some decisions can improve warehouse performance on one criterion while worsening it on another criterion.

The "mean order picker utilization" criterion assumes that for a fixed number of order pickers, different layout and operating policy combinations will result in different utilization rates. On the order hand, for the same area, different aisle layouts can require different quantities of storage equipment or storage capacity (Derhami et al., 2020), and consequently different occupancy rates, which is captured by the "warehouse space utilization" criterion. Therefore, this criterion forms a trade-off with the "warehouse equipment cost" criterion. Furthermore, there is a trade-off between "warehouse space utilization" and picking time, since the warehouse layout, which provides the maximum utilization of space, is different from one that minimizes handling distance.

Finally, the sub-criterion "operating costs" forms the well-known cost vs service level trade-off (Chen et al., 2010; Min, 2009; Vieira et al., 2017). It is worth observing that this criterion is connected to the "total picking time" criterion but not directly, as the operating costs vary according to working shifts which depend on labor legislation.

Followed by the criteria, the development of alternatives is based on the "value-focused thinking" approach (Logullo et al., 2022; Keeney, 1996). They are created from combinations of aisle layouts and operational control policies. Thus, 32 alternatives were determined based on the combination of 2 x 4 x 2 x 2 layout and operation control policies (2 possibilities for layout and 4, 2, 2, possibilities, respectively for storage, picking and routing policies), as seen in Table 2. Two aisle-layout alternatives are considered: vertical or horizontal. Storage control policy alternatives are classified into random or class-based (within-aisle, across-aisle or diagonal) (Roodbergen et al., 2015). Picking policies can be discrete or batch (Chackelson et al., 2013; van Gils et al., 2018a), considering batch formation using the First Come First Served (FCFS) method due to its ease of application compared to savings and seed cluster heuristics (van Gils et al., 2018a). Concerning routing control policies, the simplest routing heuristics, traversal or return, were considered for the decision (Franzke et al., 2017; Roodbergen et al., 2015). For example, the index alternative "1111" (see the first line of Table 2) combines vertical layout, random storage policy, discrete picking policy and transversal routing policy.

Table 2. Possible alternatives.

Layout		Operational control policies					
		Storage		Picking		Routing	
Vertical	1	Random	1	Discrete	1	Traversal	1
Horizontal	2	Within-aisle	2	Batch	2	Return	2
		Across-aisle	3				
		Diagonal	4				

The proposed framework consists of the following four steps, employed later in a hypothetical case. See the Supplementary Material (SM) for more details, please.

Step 1: Development of the scenarios. Scenario development is supported by MA in the framework to drastically reduce the number of criteria combinations. The technique consists of asking decision-makers to think about the uncertainties at their best and worst levels. To maintain consistency, the decision-makers should consider only the levels they believe are plausible. In order to decrease the number of possible combinations for analysis, it is recommended to assume all uncertainties at their best (worst) levels and swing each uncertainty at a time to their worst (best) level. This helps the decision-maker observe possible trade-offs and thus find new opportunities. Each combination of levels of uncertainty will represent a scenario for the analysis. Further details on the technique can be found in Amer et al. (2013) and Ram et al. (2011). (Also, can be seen in Step 1 in SM for details).

Step 2: Criteria weight elicitation. Weight elicitation is done by the swing weighting technique from a decision-maker´s point of view. Operationally, the technique starts from a hypothetical situation where the decision-makers indicate a hypothetical alternative with the worst performance in all attributes. This chosen attribute (criterion) is set to 100 points (representing the best level). The decision-maker then sequentially chooses the remaining attributes, one by one, comparing each of them to the first selected (see Step 2 in SM for details).

Step 3: Overall assessment of each alternative. This step aims to measure the performance of each alternative in each scenario. Therefore, a weighted average is made of the performances attributed to an alternative in each criterion, considering the weights of each criterion. This allows us to calculate how an alternative performs across all criteria together in each scenario. More specifically, the performance of an alternative *k* under scenario *r* [denoted Performance (a_k, y_r)] using the SMARTS method considering scenarios, follows Equation 1 (Ram et al., 2011), where each scenario is considered separately for a set of *j* criterion.

$$Performance\left(a_k, y_r\right) = \sum_{j=1}^{n} (v_{kir} \, x \, w_{ir}) \tag{1}$$

where w_{ir} is the weight assigned to criterion i at scenario r and v_{kir} is the performance of alternative k in criterion i at scenario r, in other words, the alternative's score. The performance of an alternative on a criterion must be measured by a value function elicited with the bisection method (Goodwin & Wright, 2004). Often, the objectives taken into consideration in warehouse design are to: minimize the total (investment and operational) cost, minimize the total picking time, minimize the throughput time of an order, maximize the use of space (layout), maximize the use of equipment, maximize the use of labor and maximize the accessibility to all items (Chen et al., 2017; De Koster et al., 2007).

The simulation model results for each alternative regarding the dynamic criteria "total picking time", "mean time do pick an order" and "mean order picker utilization" are evaluated with the value functions of these criteria to obtain the performances of the alternative on these criteria. The same can be done for the "operational costs" dynamic criterion and "warehouse space utilization" and "warehouse equipment costs" static criteria.

The discrete event-based simulation model in the hypothetical case in which the framework was tested used the Arena software (academic full version 14.7) to represent a manual warehouse order-picking activity (see flowchart in Appendix A, Figure A1). Arena has been successfully used in other studies to represent warehouse activities (Altarazi & Ammouri, 2018; Chan & Chan, 2011).

The input data is divided into two groups: storage system and operation. The data regarding the storage system are: the number of shelves per aisle; the distance between the centers of shelves; the distance between the centers of picking aisles; the number of picking aisles; and the across aisle width. Operation related data include: the number of order pickers; the picker travel rate; the pick-list size; the retrieval time; and the time between the order arrival. The number of order pickers is a tactical decision correlated to warehouse activity performance (Rouwenhorst et al., 2000) and picking congestion (Franzke et al., 2017). Except for the number of order pickers and picker travel rate, generally these data have a stochastic behavior and can be obtained by collecting them in loco or in a historical database or estimated from an expert in the company (Kelton et al., 2007).

The DES model design allows the configuration of any warehouse shape since it depends on the quantity and length of picking aisles and the number of shelves per aisle. When we have an area restriction and the storage capacity can vary, the 2:1 (width: depth) shape is recommended as it usually offers better performance for picking. On the other hand, when the warehouse capacity is fixed and it is possible to vary the area, it is better to adopt deeper shapes (Petersen, 1997). Moreover, the model is prepared for shelves and flow rack storage systems. For instance, adding vertical speed makes it possible to configure the model for a pallet storage system using a forklift. Finally, the model assumes that the pick/deposit point (p/d) is located in the middle of the front cross-aisle, as this increases the picking performance when compared to the p/d point located in the corner of the front cross-aisle (Petersen et al., 2004). The pick-list size can comprise one or more lines, according to the data inserted, and each line represents a location to visit, where one or more items are collected, also according to the data inserted, which requires identifying an aisle and a position.

The model considers the congestion at the entrance of each picking aisle. The order picker is allowed to enter both sides of the aisle as long as another order picker does not occupy it. If it is busy, the order picker must wait for the aisle vacancy in a queue according to its arrival rank to access it.

Model verification was done by checking the general order-picking activity rules (Tompkins et al., 2010) as in Heath et al. (2013): the random storage policy reduces congestion time; and the class storage policy reduces picking time.

Each alternative resulting from the combination of layout possibilities and storage, picking and routing policies constitutes a scenario to be evaluated employing the simulation model. At the end of the simulation of each scenario, a set of results is exported to an electronic spreadsheet, associated with the layout and policies under evaluation, which allows the performance of all scenarios to be compared.

Step 4: Identify the most robust alternative. After completing all the steps, the alternative which most closely achieves the overall objective can be identified, that is, the alternative whose layout, storage, picking and routing policy combination has the best performance considering its robustness. We adopted the "inter-scenario robustness index" (Montibeller et al., 2006), which considers the robustness of the less robust scenario. The robustness of a given alternative in a given scenario represents the distance between the alternative's performance and the optimal performance (100 points) in that scenario. The longer this distance, the less robust the alternative is to that scenario.

4. Scenario analysis and comparison between methods

After applying the proposed framework in a hypothetical case (see the SM, please), a scenario analysis is conducted using the four-step procedure. Apart from the "1311" alternative, another six alternatives have an inter-scenario robustness index up to 20 points. Within these alternatives, different scenarios can be responsible for each alternative´s inter-scenario robustness index (Figure 3). For example, the WWW scenario reflects the worst performance in "1211" and "1412" alternatives, while the BWB scenario induces the worst performance in "1311", "1222" and "1322" alternatives. This highlights that under different conditions (i.e. different scenarios),

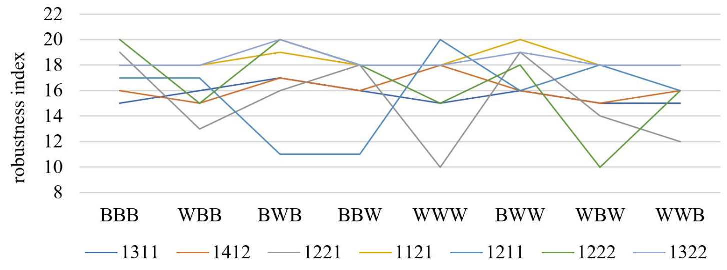

Figure 3. The first seven most robust alternatives in each assessed scenario.

different alternatives (layout and operational policy combinations) may have different performances and a scenario analysis is important to find out which alternative better fits in the company's operation conditions. Therefore, this justifies the need to evaluate the layout and operational control policies simultaneously in different scenarios and criteria. The proposed framework is expected to offer more freedom in selecting any criteria and evaluating different scenarios to be addressed according to the warehousing design, differently from Montanari et al., (2021) that focused only on routing policies of pickers under different allocation methods of items in a warehouse of fixed layout.

Furthermore, the proposed framework can help the decision-maker (DM) to forecast some inferences about the alternatives, criteria, objectives and scenarios considered to make better decisions. By considering our hypothetical case, many operational policy combinations (tactical and operational decisions) could be used (maintaining the strategic layout decision) if the DM is willing to give up to three points in the inter-scenario robustness index (17 to 20 points). For example, for a small decrease in the DM's criteria objectives (which represents, for example, a small increase at the 'operational costs') in some scenarios, the DM could adopt the "1121" alternative, with a random storage policy which is easier to use than other storage methods and results in a more level utilization of all picking aisles (Petersen & Aase, 2004). Fontana et al. (2020a) used a different approach based on MCDA and a multi-objective evolutionary algorithm to solve the storage location assignment problems, considering the warehouse manager preferences and the stock-keeping unit (SKU) characteristics simultaneously. Although their approach considered other criteria and the randomly generated alternatives, demonstrating that the approach can also evaluate the worst possible case, there was no robustness index to measure the consistency in all possible cases in their approach.

Following this reasoning, different results (Table 3) can be found when looking for the best alternative in a comparison between our proposed framework and other studies which seek to minimize single criteria, such as the distance traveled in the order picking activity (Montanari et al., 2021; Fontana et al., 2020a; van Gils et al., 2018a; Petersen, 2002, 1997; Petersen & Aase, 2017; Petersen & Schmenner, 1999; Roodbergen et al., 2015; Shqair et al., 2014), mean time to pick an order (Elbert et al., 2017; Franzke et al., 2017; Petersen, 1999) and the total picking time (Montanari et al., 2021; Chan & Chan, 2011; Heath et al., 2013; Petersen, 2000; Petersen & Aase, 2004). The comparison is made by the largest value found for these criteria among the evaluated scenarios as these higher values can be a way to represent the inter scenario robustness index.

Table 3. Comparisons between our proposed framework and other studies.

Alternatives	Proposed framework (points)	Total distance travelled (x 1000 m)	Total picking time per day (hours)	Mean time to pick an order (minutes)
1311	17	1,418	10.07	3.24
2322	56	656	12.77	5.32
2312	51	893	12.49	2.77
1122	22	1,1167	10.1	6.36

The best alternative regarding the chosen method is bold and underlined. First of all, the "1311" alternative would be the best alternative according to the total picking time, as well as according to our proposal. This is because the DM considered the "operating cost" and "total picking time" sub-criteria to be the most and third most important, respectively. It also considered that both should be minimized. As the operational cost is directly related to the total picking time (in this specific case), therefore the choice for this alternative is the same.

Moreover, “2322” would be the best alternative according to the distance traveled minimization. However, this alternative has a high inter-scenario robustness index (56) compared to alternative “1311”, due to its inferior performance on the criteria considered in the proposed methodology, more specifically “total picking time” and “mean time to pick an order”. This is because the choice based only on the shortest distance does not address the congestion problem, not considering this effect on picking times. Therefore, the choice based only on the shortest distance traveled may be a mistake. To complete the comparison, “the mean time to pick an order” minimization highlights the “2312” alternative. However, its low performance on the “total picking time” and consequently on the “operational costs” leads this alternative to the inter-scenario robustness index (51). Although Chen et al. (2010) and Fontana et al. (2020a) investigated the robustness of single policies in different scenarios, it is more interesting to evaluate the layout and policies combination in all scenarios.

Differently to the previous studies, we consider the congestion approach, which brings more realism to the model. In a manual order picking warehouse, it is common to have multiple order pickers in the same picking area (van Gils et al., 2019). Additionally, to consider the horizontal aisle layout as an alternative may provide a higher practical and managerial relevance (van Gils et al., 2019). In fact, rearranging a warehouse layout has a cost (Chen et al., 2010), which can be reduced by searching for a robust layout in the design phase.

Differently from other studies that consider the characteristics of the products to define the allocation policies in the warehouse based on the time of order picking (weight, space and demand) (Fontana & Nepomuceno, 2017; Micale et al., 2019), our approach offers more freedom in selecting any dynamic/static criteria to be evaluated. In this simulated case, the dynamic criteria were the total picking time, mean time to pick an order, mean order picker utilization and operational costs, and the static criteria were warehouse space utilization and investment costs.

Our elicitation process can be time-consuming; however, Roodbergen et al. (2015) and Chen et al. (2010) methods based on statistical analysis to rank and select an alternative also demand warehouse manager’s time and knowledge to evaluate the order picking process (Fontana et al., 2020a). For example, Chen et al. (2010) adopt Koenig and Law’s method to obtain multiple superior policy sets, which demand input parameters such as the probability of correctly selecting a subset containing the best policy sets, the size of the subset, the number of replications in the first-stage sampling and the indifference-zone width. Yet, their methods are highly applicable.

Chen et al. (2010) scenario planning is based on uncertainties such as ‘time between order arrival’ and ‘pick list size’, and Montanari et al. (2021) also investigated various routing policies for the picking process. We added the MA to develop and analyze scenarios and also ‘daily order demand’, which the warehouse’s daily operation may face. Additionally, our approach can consider the workforce level as an uncertainty (an operational decision according to van Gils et al. (2018b), since some warehouses accept late orders and quantify the number of human resources to provide a high customer service level, which is considered a complicated task by warehouses supervisors (van Gils et al., 2018b). Our proposal may be relevant to verify how to design the layout and the control policies to minimize the effects of these scenarios.

Regarding the simulation study, the developed model is considered complex as it is prepared to be quickly configured to represent a variety of warehousing policies. This issue required extra effort in the modeling phase to represent the operational rules and determine how these could be easily selected. The performance of picking operations is affected by storage, picking, and routing policies that are represented as closely as possible to real-life operations, using the most frequent policies used by warehouses. As a result, a very generic model was obtained, capable of being used in a variety of studies that consider similar systems through rapid modification of parameters.

In terms of computational effort, in the hypothetical case evaluated, representative scenarios of the warehouse operation were tested over one month in a 10-replication mode. Under the conditions evaluated, the simulation of the scenarios took around 3 minutes to run an experiment. This period was considered quick and adequate for studying the combinations predicted in the hypothetical case. Obviously, larger instances, in facilities with a greater number of aisles and more storage positions will require more time to be executed.

Yet, our method captures the warehouse manager’s preference and experience by means of weight elicitation, value functions, scenario planning and inter-scenario robustness index to provide a robust final solution. Silva et al. (2015) also used SMARTER, a variant of the SMART, to position the stored products in locations closer to the I/O point, contributing to cost reductions in order picking and minimizing delays in product deliveries. Silva et al. (2015) suggested the use of other multicriteria methods, with other criteria in a different scenario to the warehousing design problems.

Finally, in addition to what has already been discussed related to its practical implementation, our proposed framework also can be used: i) to consider the number of order pickers as an uncertainty (e.g., due to labor turnover) increasing the number of scenarios to verify; ii) as a tool to evaluate which combination of control policies are suitable for an existing vertical or horizontal layout (but the simulation model has to be validated and the warehouse space utilization and equipment cost criterion disregarded in such case).

5. Conclusions

Our framework proposal is new, as the existing scientific literature offers a very limited number of approaches to simultaneously address the complexities of warehousing design. The new framework determines the most robust combination of the three control policies (storage, picking and routing) and aisle layout (horizontal and vertical) simultaneously at the warehouse design phase. Our framework considers multiple criteria that the warehouse design phase must meet such as costs, service level and resource utilization. The company's objectives and preferences are considered to evaluate the existing trade-offs. Furthermore, scenarios based on uncertainties, which a warehouse's daily operation can face, are simulated to see how the alternatives perform. In this case, we added the MA to reduce the number of alternative combinations and evaluate the uncertainties, as well as to reduce the number of alternative combinations, evaluate the uncertainties, and provide a robustness index. None of the methods available in the literature can be directly compared to the approach proposed in this paper, either focusing on non-compensatory/compensatory MCDA approaches for evaluating the criteria. We can highlight the combination of methods (DES, MCDA and SP) applied to a strategic, tactical and operational warehouse design problem and the use of MA as our conceptual contribution for supporting warehouse design problems.

Considering the approach to representing warehouse operations using the DES technique, the proposed modeling properly enabled the representation of the scenarios under evaluation and provides a structure capable of being adjusted to other specific cases, with some flexibility. The most significant difficulty in representing warehouse operations via simulation lies in predicting, in the modeling phase, the possible rules to be followed in warehouse operations. In our specific case, the configurations of each storage, picking and routing policies, and the layout possibilities (and their implications) need to be known in advance. However, most of these policies are classic, widely used by practitioners and well reported in the literature. If previously considered in modeling, the policies can be quickly configured in the model, by simply changing parameters before running each scenario. Specific characteristics of picking operations, such as the number and length of aisles, spacing, number of order pickers, etc., also constitute easy parameters to configure, allowing the model to be used in similar warehouse systems.

Therefore, as a practical contribution, warehouse managers or planners can use the framework to determine which combination of control policies and layout can meet the company's requirements. Our methodology has managerial relevance since it approaches real operation data and a trade-off analysis. Specifically considering warehouse operations and their representation through a DES model, two new features were included as an evolution of previous studies: aisle congestion and the possibility of configuring the warehouse layout horizontally or vertically.

Some limitations can be mentioned regarding our framework: i) the case study in which we tested the framework is based on a hypothetical case; a real-world application is necessary to validate the framework, as also stated by Micale et al. (2019) and Fontana et al., 2020a); ii) the time consumed during the modeling due to the elicitation process; and iii) the lack of qualitative criteria in the assessment(such as safety). These limitations provide further opportunities for future research, with real-world case studies, streamlined elicitation protocols and the inclusion of qualitative criteria for the analysis.

We suggest other potential avenues for further research as follows: i) the aggregation of more layout alternatives such as flying V and fishbone (Zhou et al., 2022; Pohl et al., 2011) as well as cross-aisle layouts (Roodbergen et al., 2015) and different depot locations; ii) the aggregation of a mezzanine floor (layout) with productivity and cost impact analysis; iii) the addition of a high level picking for analysis considering vehicle properties, costs and productivity; iv) the adoption of more performance measures as criterion such as tardiness and makespan since different companies may evaluate their operations differently (Ahmadi Keshavarz et al., 2021); v) the aggregation of other control policy alternatives such as zone picking policy, the largest gap or composite routing policy (van Gils et al., 2018a); vi) the adoption of more warehouse internal activity on the evaluation such as receiving, unloading, putting away, storing, loading and shipping (Altarazi & Ammouri, 2018); vii) the aggregation of human factors such as fatigue, learning, routing variations or picking errors (Destro et al., 2023); viii) the extension of the proposed framework by considering the inventory stochastic problem; and ix) the extension of the proposed framework by adding a method of weight aggregation, since warehouse design usually has more than one decision maker.

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Appendix A. Simulation studies on control policy and additional information about step-by-step for the proposed framework.

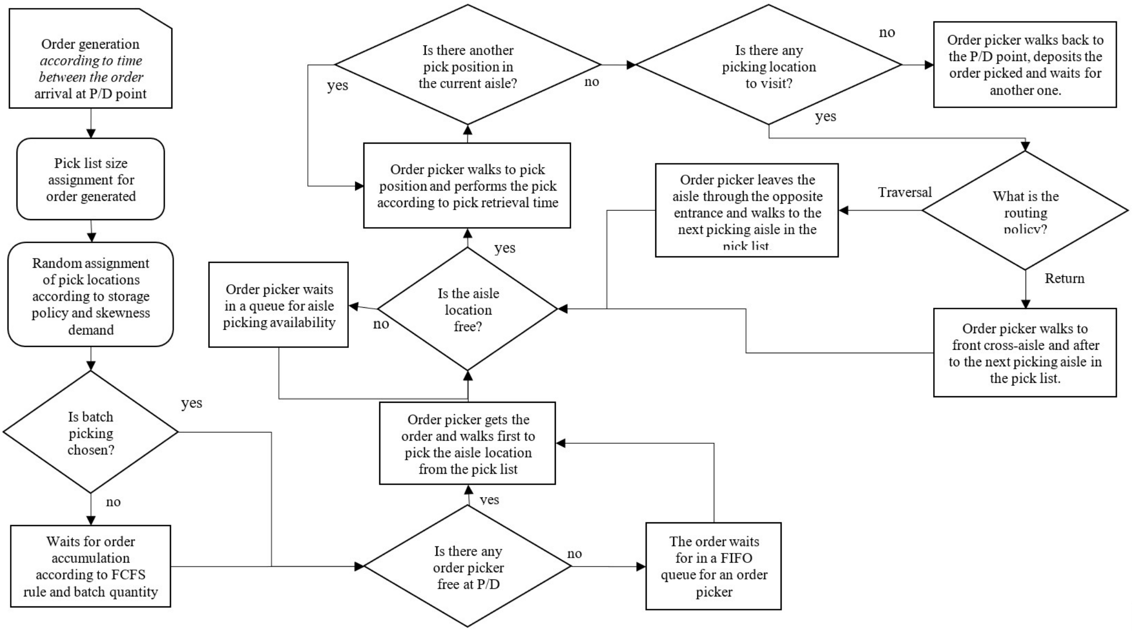

Figure A1. Manual order picking flowchart from DES model.

Supplementary Material

Supplementary material accompanies this paper.

A framework for supporting warehouse design.

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