

## SUPPLEMENTARY MATERIAL

### A framework for supporting warehouse design

This supplementary material encompasses the proposed framework applied in a hypothetical case.

#### The proposed framework applied in a case

We aim to apply the proposed framework using the four steps (Methodology – Section 3).

We use the database from an automotive parts distributor in Brazil and the experience of a decision-maker (DM) who works with warehouse design to indicate to the company the most robust combination between control policies and layout for warehouse design.

Warehouse storage system (shelf system chosen) data are:

- $N_{sa} = 10$  shelves (vertical layout) (Figure SM1) or 12 (horizontal layout).
- $D_s = 1.00$  m
- $D_{pa} = 3.00$  m
- $N_{pa} = 10$  aisles
- $W_{aa} = 2.00$  m

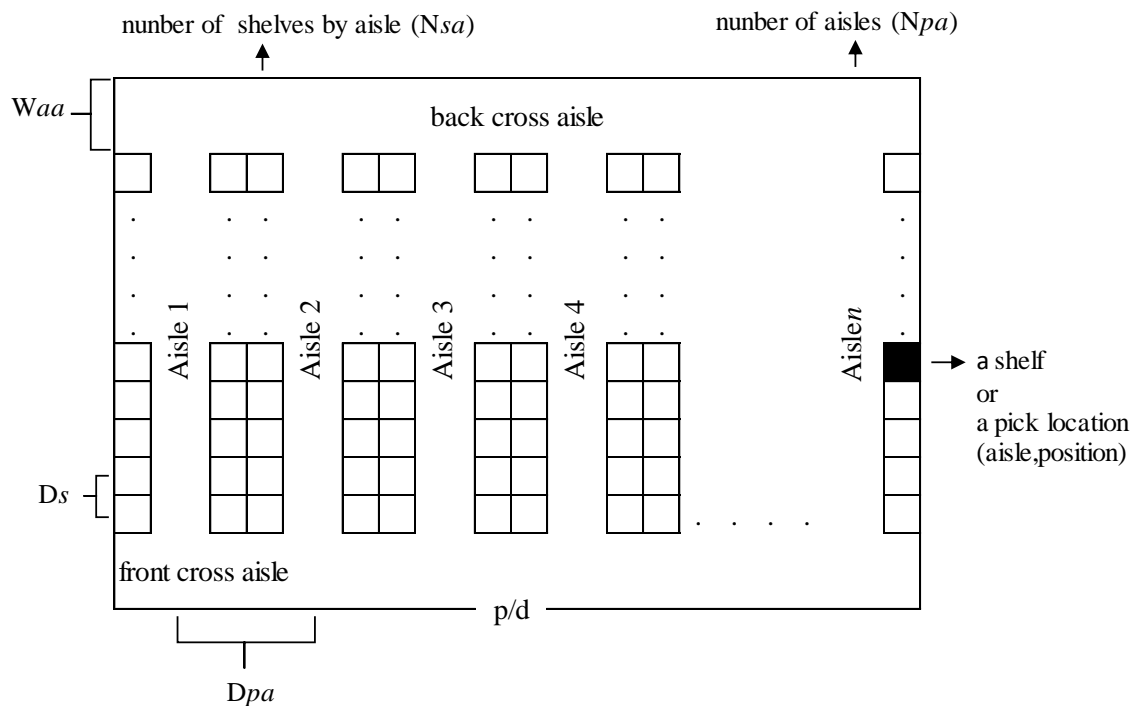


Figure SM1. Vertical layout characteristics.

To illustrate, a vertical layout is presented in Figure SM1 and the horizontal layout follows the same idea. Input data is divided into two groups: storage system and operation. The data regarding the storage system are: the number of shelves per aisle (Nsa); the distance between the centers of shelves (Ds); the distance between the centers of picking aisles (Dpa); the number of picking aisles (Npa); and across the aisle width (Waa). These are strategic decisions related to the storage system chosen and the desired storage capacity to meet the company's target service level and inventory policy (Rouwenhorst et al., 2000). Moreover, these data depend on handling equipment that will be used, such as carts, forklifts, etc.

These data represent 420 m<sup>2</sup> of a warehouse picking area for small and medium parts. The picking activity is not considered a replenishment operation. In this case, 12 shelves per aisle in a horizontal layout are considered in order to take advantage of the area while respecting the Waa, Npa, Dpa and Ds restrictions for both layouts.

The operation data considered are:

- Number of order pickers = 5;
- Picker travel rate = 0.75 m/s (Chan and Chan, 2011; Chen et al., 2010; Franzke et al., 2017);
- The retrieval time = TRIA (10,20,30) s;
- Demand skewness = 80%
- Pick-list size = according to the uncertainty level defined by DM;
- Time between order arrival = according to the uncertainty level defined by DM.

The database evaluation is shown in Table SM1 with theoretical and empirical distributions for a time between order arrival and pick-list size, respectively, obtained according to Kelton et al. (2007) procedures. Moreover, the daily demand is presented.

Table SM1. Company historical database evaluation.

Time between order arrival		Picklist Size	Daily Order demand
Period	value (minutes)	(units)	(units)
8:00 to 8:40	1+ERLA(4.62,2)	DISC (0.000, 1, 0.425, 2, 0.619, 3, 0.721, 4, 0.787, 5, 0.834, 6, 0.866, 7, 0.890, 8, 0.910, 9, 0.925, 10, 0.936, 11, 0.947, 12, 0.955, 13, 0.962, 14, 0.968, 15, 0.973, 16, 0.977, 17, 0.981, 18, 0.984, 19, 0.987, 20, 0.989, 21,	500 ± 64
8:40 to 9:40	1.01+WEIB(1.03,2.32)		
9:40 to 12:00	0.59+ERLA(0.0913,3)		
12:00 to 13:00	1+ERLA(4.62,2)		
13:00 to 14:40	1.01+WEIB(1.03,2.32)		
14:40 to 18:00	NORM(0.866,0.091)		

0.991, 22, 0.993, 23, 0.995, 24, 0.996, 25,  
0.997, 26, 0.998, 27, 0.999, 28, 1, 30)

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Mean	1.2	3.4	500
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In **Step 1 (Scenario development)**, Ram et al. (2011) suggest the following steps:

A - Define the limits of each uncertainty. In determining the limits, the following steps are useful:

- Consider the best and worst possible achievement levels for the criteria that can be perceived.

For instance, service level can be measured by the number of orders picked within a period, with figures of 100% and 80%, respectively, for best and worst levels.

- Extend these further while keeping them within plausible levels and trying to envisage what uncertainty levels might lead to that situation. These levels define the limits.

For example, considering the hypothetical order picking time, the level of uncertainty that could cause 100% of the Service Level would be x% (below the current level) and the level of uncertainty that could cause 80% of the Service Level would be, hypothetically, y% (above the current level). These order-picking time levels define the limits for the analysis.

- Combinations of conditions (one condition from each uncertainty) represent different scenarios.

B – Test for consistency. Consistency analysis is used to check the compatibility of combined variations of various scenarios uncertainty (Amer et al., 2013). Only those combinations the DM is certain about should be included (Ram et al., 2011).

The DM explained that a 10% variation up or down is acceptable to the company because the operation is dimensioned to absorb these variations, regarding the uncertainty levels. In these cases, he explains that the warehouse cost is known and will be the same as there is no overtime worked, for example. However, when the variation is greater than 10%, the cost of the warehouse increases as a function of overtime worked, for example, in which case new working methods should be developed. These considerations are based on the DM's experience.

After the historical database analysis, the DM considered the time between the order arrival's uncertainty to be the best level, with a constant mean of 1.2 minutes over the picking time activity, as this would provide better order picker utilization and fewer

queues in the system. Conversely, using the theoretical distributions, the time between the order arrival variation was considered the worst level. For the pick-list size uncertainty, the DM considered the empirical distribution as the best level and an addition of one item (one line) over the empirical distribution as the worst level as this would represent a rise of 50% over the most common pick list size, once 42.5% of them have one line. Finally, for demand uncertainty, 500 orders per day were considered as the best level and 600 (20% higher) orders per day as the worst level. Thus, eight scenarios (2 pick list size variations x 2 times between order arrival variations x 2 daily demand variations) can be developed according to MA (Table SM2).

BBB is the best and WWW is the worst possible scenario according to uncertainty levels and it represents situations in which the system (order picking activity) can be found.

Although it is possible to establish intermediate levels for each uncertainty (Ram et al., 2011), if the DM had included 550 orders per day as an additional demand uncertainty beyond the plausible limits considered as best and worst level, 12 scenarios would be developed (an increase of 25%) for analysis but unnecessarily since MA implies the use of best and worst plausible scenarios of an uncertainty to drastically reduce the number of scenarios combinations.

Table SM2. Scenario development.

Scenarios	Pick List Size	Time between order arrival	Daily demand
BBB	Empirical distribution	1.2	500
WBB	1+ Empirical distribution	1.2	500
BWB	Empirical distribution	Theoretical distribution	500
BBW	Empirical distribution	1.2	600
WWW	1+ Empirical distribution	Theoretical distribution	600
BWW	Empirical distribution	Theoretical distribution	600
WBW	Empirical distribution	1.2	600
WWB	1+ Empirical distribution	Theoretical distribution	500

In Step 2 (**weight elicitation**), the DM was asked about his criteria preferences regarding the problem under consideration by means of the swing weighting elicitation method. See the procedure below as an example:

**Analyst:** Imagine that you have a hypothetical alternative that has the worst performance in all attributes, that is, it has 10 units in attribute “X”, 80 units in attribute “Y” and 20 units in attribute “Z” (see Figure SM2). Now, if you could improve only one attribute, from worst to your best level, which attribute would you choose?

**Tomador de decisão:** O atributo “X”.

**Analyst:** Considering this first improvement from 10 to 50 units of the “X” attribute represents 100 points (max. value).

**Analyst:** Chosen the second attribute to be improved (i.e., 80 units in the “Y” attribute or 20 units in the “Z” attribute), from your worst level to best?

**Decision maker:** The “Y” attribute, that is, reducing the “Y” attribute from 80 to 10 units.

**Analyst:** If the first improvement in attribute “X” was valued at 100 points, how much would you value this second improvement?

**Decision maker:** Around 60. This procedure must continue until the attributes are complete.

In this way, the normalized weights are calculated in Figure SM2.

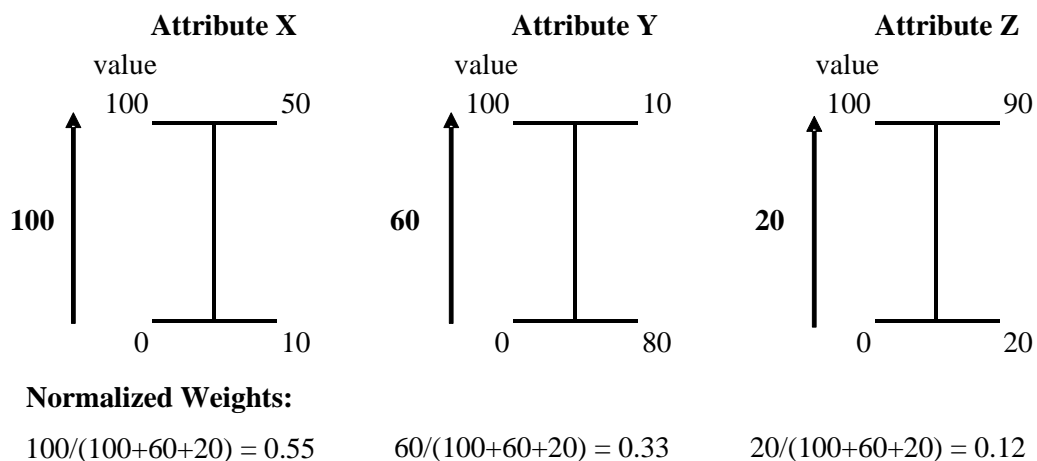


Figure SM2. Example of swing weighting application.

In Step 3 (**assessment of each alternative**), to measure the performance of each alternative in a criterion in each scenario, the DM elicited value functions for each criterion in the analysis. As the value function elicitation must consider the range of values that a criterion may reach regarding all alternatives (Montibeller and Franco, 2007), we ran the simulation model for 30 days to obtain the performance of the alternatives in the dynamic criteria and then captured the range of values that each dynamic criterion could reach. For the same reason, we calculated the performance of each alternative in the static criteria and then verified the range of values that each static

criterion could reach. The value function of each criterion is presented in Figure SM3, after DM elicitation, according to Montibeller and Franco (2007).

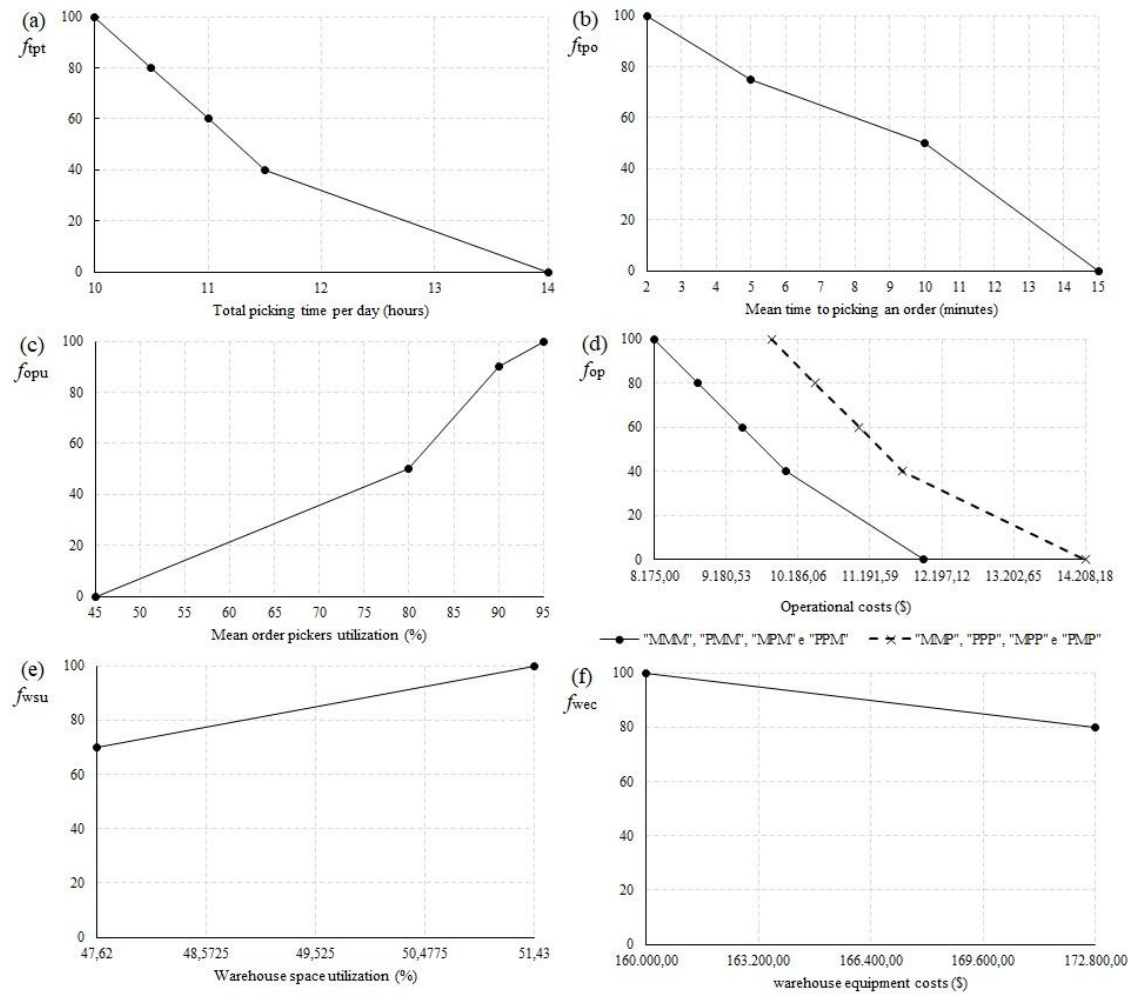


Figure SM3. Value functions.

The DM's objectives (maximize or minimize) are in accordance with Chen et al. (2017) and Koster et al's. (2007) point of view. In Figure SM3a, it can be observed that the alternatives took from 10 to 14 hours per day to fulfill the picking order and the DM assigned a value of 100 points to 10 hours and zero to 14 hours. Yet, according to his preferences, the alternative that completes picking in 11 hours has a score of 60 points, having 40 points less than one which fulfills the picking in 10 hours. The other value functions follow the same idea.

To compare different layouts, one must consider the handling equipment costs and the order picker salary costs as the other costs remain the same. As we are dealing with a manual order-picking process (Figure SM4), only the order picker salary costs remains, which is a function of the hours worked. In Figure SM3d, two curves are presented because the scenarios have different amounts of orders for picking. The demand

uncertainty at a low level is 15,000 orders (30 days x 500 orders/day) and at a high level it is 18,000 orders (30 x 600). Thus, different total order picker costs resulted.

Warehouse space utilization (Figure SM3e) is a function of the amount of storage equipment distributed in the layout. Once the horizontal layout has 216 shelves, the space utilization results in 51.43% (216 m<sup>2</sup>/420 m<sup>2</sup>). On the other hand, the vertical layout has 200 shelves resulting in 47.62%. Finally, the warehouse equipment costs (Figure SM3d) are directly proportional to the number of shelves in each layout alternative.

To complete **Step 3 (assessment of each alternative)**, by means of equation 1 the performance of each alternative in each scenario is presented in Table SM3. For example, the “1311” alternative (1 = vertical layout, 3 = across-aisle storage, 1 = discrete picking and 1 = traversal routing) scored 85 points at scenario BBB, 84 points at scenario WBB, and so on.

At **Step 4 (the identification of the robust alternative)**, the robustness of each alternative in each scenario is presented in quotation marks (Table SM3). The “1311” alternative robustness at scenario BBB is 15 points, at scenario WBB it is 16 points, and so on.

**Table SM3.** Performance of alternatives (robustness) against scenarios.

Alternatives	Scenarios															
	BBB		WBB		BWB		BBW		WWW		BWW		WBW		WWB	
1111	84	(16)	85	(15)	85	(15)	84	(16)	85	(15)	79	(21)	85	(15)	84	(16)
1112	85	(15)	85	(15)	83	(17)	84	(16)	85	(15)	85	(15)	85	(15)	77	(23)
<b>1121</b>	<b>82</b>	<b>(18)</b>	<b>82</b>	<b>(18)</b>	<b>81</b>	<b>(19)</b>	<b>82</b>	<b>(18)</b>	<b>82</b>	<b>(18)</b>	<b>80</b>	<b>(20)</b>	<b>82</b>	<b>(18)</b>	<b>82</b>	<b>(18)</b>
1122	82	(18)	82	(18)	82	(18)	81	(19)	78	(22)	82	(18)	82	(18)	82	(18)
1211	83	(17)	83	(17)	89	(11)	89	(11)	80	(20)	84	(16)	82	(18)	84	(16)
1212	83	(17)	76	(24)	85	(15)	92	(8)	75	(25)	89	(11)	74	(26)	73	(27)
1221	81	(19)	87	(13)	84	(16)	82	(18)	90	(10)	81	(19)	86	(14)	88	(12)
1222	80	(20)	85	(15)	80	(20)	82	(18)	85	(15)	82	(18)	90	(10)	84	(16)
<b>1311</b>	<b>85</b>	<b>(15)</b>	<b>84</b>	<b>(16)</b>	<b>83</b>	<b>(17)</b>	<b>84</b>	<b>(16)</b>	<b>85</b>	<b>(15)</b>	<b>84</b>	<b>(16)</b>	<b>85</b>	<b>(15)</b>	<b>85</b>	<b>(15)</b>
1312	85	(15)	82	(18)	84	(16)	84	(16)	79	(21)	83	(17)	84	(16)	83	(17)
1321	82	(18)	82	(18)	77	(23)	82	(18)	74	(26)	82	(18)	82	(18)	78	(22)
1322	82	(18)	82	(18)	80	(20)	82	(18)	82	(18)	81	(19)	82	(18)	82	(18)
1411	84	(16)	85	(15)	79	(21)	84	(16)	84	(16)	80	(20)	85	(15)	85	(15)
1412	84	(16)	85	(15)	83	(17)	84	(16)	82	(18)	84	(16)	85	(15)	84	(16)
1421	82	(18)	82	(18)	76	(24)	82	(18)	81	(19)	82	(18)	82	(18)	77	(23)
1422	82	(18)	82	(18)	82	(18)	82	(18)	75	(25)	82	(18)	82	(18)	82	(18)
2111	85	(15)	86	(14)	49	(51)	86	(14)	52	(48)	45	(55)	86	(14)	53	(47)
2112	86	(14)	86	(14)	51	(49)	86	(14)	49	(51)	47	(53)	86	(14)	49	(51)
2121	83	(17)	83	(17)	47	(53)	83	(17)	49	(51)	43	(57)	83	(17)	49	(51)
2122	83	(17)	83	(17)	44	(56)	83	(17)	51	(49)	42	(58)	83	(17)	52	(48)
2211	94	(6)	73	(27)	49	(51)	94	(6)	57	(43)	47	(53)	73	(27)	58	(42)
2212	94	(6)	69	(31)	52	(48)	94	(6)	57	(43)	48	(52)	69	(31)	58	(42)

Alternatives	Scenarios															
	BBB		WBB		BWB		BBW		WWW		BWW		WBW		WWB	
2221	83	(17)	91	(9)	50	(50)	83	(17)	48	(52)	45	(55)	91	(9)	48	(52)
2222	83	(17)	91	(9)	49	(51)	83	(17)	48	(52)	46	(54)	90	(10)	49	(51)
2311	85	(15)	86	(14)	47	(53)	85	(15)	48	(52)	48	(52)	86	(14)	48	(52)
2312	85	(15)	86	(14)	50	(50)	85	(15)	51	(49)	49	(51)	86	(14)	52	(48)
2321	83	(17)	83	(17)	43	(57)	83	(17)	46	(54)	43	(57)	83	(17)	48	(52)
2322	83	(17)	83	(17)	44	(56)	83	(17)	49	(51)	44	(56)	83	(17)	50	(50)
2411	86	(14)	86	(14)	45	(55)	86	(14)	48	(52)	46	(54)	86	(14)	49	(51)
2412	85	(15)	86	(14)	47	(53)	85	(15)	49	(51)	47	(53)	86	(14)	49	(51)
2421	83	(17)	83	(17)	45	(55)	83	(17)	47	(53)	44	(56)	83	(17)	48	(52)
2422	83	(17)	83	(17)	46	(54)	83	(17)	46	(54)	46	(54)	83	(17)	47	(53)

The inter-scenario robustness index is presented in Figure SM4 in descending order. The “1311” alternative is considered the most robust alternative under the conditions adopted: warehouse system data, warehouse operation data, uncertainties, criteria, DM’s criteria preferences, DM’s objectives, and the alternatives evaluated. This means that under these conditions, the “1311” alternative guarantees a minimum of 83 points as its worst performance (in MPM scenario), in other words, 17 points distance from the ideal (100).

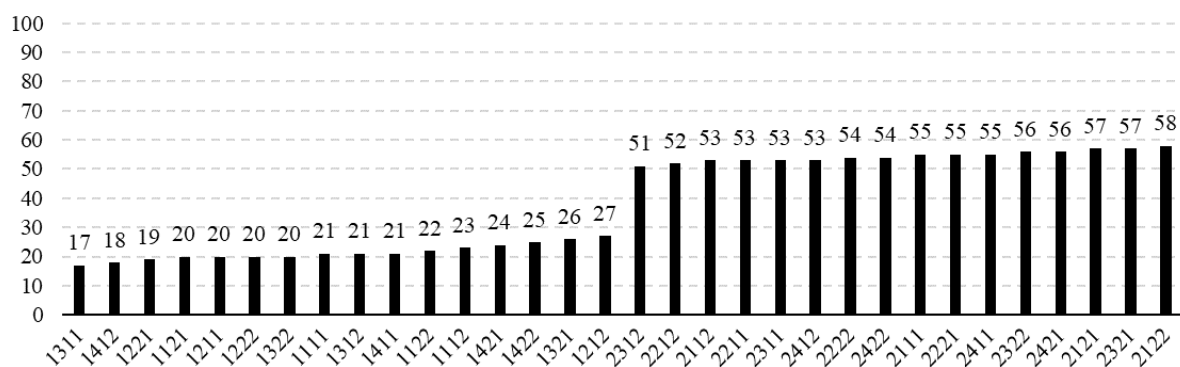


Figure SM4. Inter-scenario robustness index.