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A NEW CROSS ABC ANALYSIS PROPOSAL FOR INVENTORY CLASSIFICATION: A FABRIC WAREHOUSE CASE STUDY

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Keywords

Cross ABC Analysis; Warehouse layout; Operational efficiency; Inventory management

Abstract

One of the most important decisions regarding warehouse management is the assignment of raw materials or products to the shelves. Effective shelf management is the key to continuity and efficiency in production. ABC analysis is one of the most preferred methods for material classification in warehouses. In this study, an enhanced cross-ABC analysis is proposed as an alternative to the traditional multi-criteria ABC analysis scoring for the assignment of raw materials to the shelves. In order to simplify the application, instead of taking into account all the criteria in the classification, it is suggested as a new approach to consider the first two criteria whose weights are the highest. Another difference is in determining the importance scores to be obtained as a result of this classification and used for the mathematical assignment model. When the application results are evaluated, by comparing the Analytical Hierarchy Process (AHP) weighted ABC analysis and classical ABC analysis results with the results obtained from the proposed method, it is seen that the proposed method can make a more detailed classification with less processing load and complexity.

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ENVANTER SINIFLANDIRMASI İÇİN YENİ BİR ÇAPRAZ ABC ANALİZİ ÖNERİSİ: KUMAŞ DEPOSU ÖRNEK ÇALIŞMASI

Anahtar Kelimeler	Öz
Çapraz ABC analizi, Depo yerleşimi, Operasyonel etkinlik, Envanter yönetimi	*Depo yönetimiyle ilgili en önemli kararlardan biri hammadde veya ürünlerin raflara atanmasıdır. Etkin raf yönetimi, üretimde sürekliliğin ve verimliliğin anahtarıdır. ABC analizi depolarda malzeme sınıflandırmasında en çok tercih edilen yöntemlerden biridir. Bu çalışmada, hammaddelerin raflara atanmasında geleneksel çok kriterli ABC analizi puanlamasına alternatif olarak geliştirilmiş bir çapraz ABC Analizi önerilmektedir. Uygulamayı kolaylaştırmak amacıyla sınıflandırmada tüm kriterlerin dikkate alınması yerine ağırlıkları en yüksek olan ilk iki kriterin dikkate alınması yeni bir yaklaşım olarak önerilmektedir. Bir diğer farklılık ise bu sınıflandırma sonucunda elde edilecek ve matematiksel atama modeli için kullanılacak önem puanlarının belirlenmesindedir. Uygulama sonuçları değerlendirildiğinde, AHP ağırlıklı ABC analizi ve klasik ABC analizi sonuçları ile önerilen yöntemden elde edilen sonuçların karşılaştırılmasıyla, önerilen yöntemin daha az işlem yükü ve karmaşıklıkla daha detaylı bir sınıflandırma yapılabildiği görülmektedir.*

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1. Introduction

Warehouse design and management play a key role in many aspects of production efficiency. Due to the difficulty of stock-free production, determining the most appropriate stock amount is an issue that needs to be emphasized. While holding less stock than needed causes it to sell out, holding more than needed leads to holding costs and time losses.

The warehouse management aims to minimize product movements and holding costs by saving transportation and time. To achieve better warehouse management, various techniques commonly used in other management problems, such as value stream mapping, spaghetti diagram analysis, 5S tools, and other lean methodologies, have been used in many previous studies.

The key element in effective and efficient warehouse management is to carry out the processes of storing and distributing the goods in the shortest time and with the least error. This is why inventory classification is important for effectiveness.

ABC analysis is one of the most used methods for inventory classification, easy to use and understand by average materials managers. Commonly, raw materials are classified by annual demand, average unit price, or annual value in use. While Class A items are relatively few in number, they make up a relatively large part of the annual value in use or average unit price, the opposite is true for Class C. Items between these two classes also constitute Class B (Ramanathan, 2006).

It is generally accepted that traditional ABC analysis cannot, in practice, provide an ideal result for the classification of inventory items, especially as the product range increases. Also, to decide the importance of an inventory item, many criteria could need to be taken into account, such as inventory cost, criticality of parts, lead time, substitutability, scarcity, durability, reparability, stockability, demand distribution, etc., different from the annual value or unit price. That's exactly what multi-criteria ABC analysis is used for. Certainly, multi-criteria ABC analysis requires more processing steps than a single one. In this case, it is clear that the subjective evaluation of experts determining criteria weights will be effective in classification (Hatefi and Torabi, 2015).

At this stage, weighting techniques such as AHP are often preferred. Cross-ABC analysis is also used in practice, especially for two-criterion evaluations. This study is aimed to provide convenience and simplification, especially in multi-criteria ABC analyses using more than two criteria.

The contributions of this study to the existing literature can be summarized as follows:

I. Inventory items with similar characteristics were gathered under the same roof by averaging the quantitative values of the evaluation criteria. Thus, in the evaluation, it is aimed to create an easy basis at the first stage.

II. Once more, in order to simplify the application, instead of taking into account all the criteria in the classification, it is suggested as a new approach to consider the first two criteria whose weights are the highest.

III. Another difference is proposed in determining the importance scores to be obtained as a result of this classification and used for assignment in the mathematical model. This suggestion makes it possible to make a more detailed and homogenous score, different from the classical ones.

IV. For the mathematical assignment model, class scores are included in the model as a coefficient, which is different from the current literature.

In the continuation of the study, some similar studies in the literature on warehouse design/layout and optimum shelf planning are given in Section 2. While the general framework of the methods used in the study is given in Section 3 and the application of the study is given in Section 4 and the results are discussed in the last Section.

2. Related Literature on Inventory Management and ABC Analysis

A warehouse design is a complex problem. Warehouse processes involve many interrelated decisions between warehouse resources and warehouse organizations. Warehouse design and planning problems are classified at three decision levels: strategic, tactical, and operational. At the strategic level, various decisions are made, from determining the number, size, and location of warehouses to the design of the warehouse and the selection of the necessary material handling equipment. Decisions such as the determination of manpower to run the system, the allocation of products to functional areas, the development of order picking and supply policies, capacity planning, etc. take place at the tactical level (Heragu, Du, Mantel, and Schuur, 2005).

For the solution of the assignment problem of products in the warehouse, in the literature, a solution can be provided either with heuristic methods or mathematical optimization models (Gül et al., 2016). Heragu et al. (2005) have developed both a mathematical model and a heuristic algorithm that determines product distribution according to the size of each area in warehouse design and product placement. Roodbergen and Vis (2006) developed a model for warehouse layout and compared different routing techniques to minimize the average transport times.

Ramanathan (2006) proposed a weighted linear optimization model for classifying inventory items in the presence of multiple criteria which is a very simple model that can be easily understood by inventory managers. Ng (2007) proposed an alternative weight linear optimization model which could automatically calculate the weights of each criterion with such each item can achieve the maximal score and compared the results by Ramanathan' s study (Ramanathan, 2006).

Chen, Li, Kilgour and Hipel (2008) proposed a case-based distance model to handle Multi Criteria ABC problems using weighted Euclidean distances which can be easily understood by a decision maker and a quadratic optimization program was used for optimal classification thresholds.

Silvestri, Falcone, Forcina and Pacitto (2011) suggested using the AHP method instead of cross-ABC analysis because of its ability for evaluation of different criteria. Kiriş (2013) applied the fuzzy Analytical Network Process (ANP) approach in the study comparing traditional ABC analysis and fuzzy ANP approach, for more flexible decision making in uncertain environments. Hatefi and Torabi (2015) proposed a methodology based on a common weight linear optimization model to solve the multiple criteria inventory classification problem that could make the classification of inventory items via a set of common weights which is very essential in a fair classification.

Çolak, Keskin, Günel and Akkaya (2016) proposed a two-stage solution approach to ensure an efficient layout of the raw material warehouse in a chemical factory. Depending on multi-criteria ABC analysis, 47 types of raw materials were normalized according to four criteria effective in raw material placement (periodic usage amount, unit price, supply period, and service life). These normalized values were multiplied with the criterion weights obtained from the AHP method and the weighted normalized values were found. According to the results of the multi-criteria ABC analysis, it was determined that 17% of 47 raw materials belong to Class A, 32% to Class B, and 51% to Class C. The mathematical model aims to minimize warehouse transportation by considering the importance of coefficients obtained from the integrated ABC and AHP analysis.

Accorsi, Bortolini, Gamberi, Manzini and Pilati (2017) used a multifunctional mathematical model to optimize the carbon footprint in addition to the total cost and cycle time for warehouse design.

On the other hand, Öztürk, Özer, Gülen, Çiçek and Serttaş (2019) examined the situation where more than one warehouse meets the needs of more than one factory, and proposed a mathematical model in which the distance of raw materials to the factories and the number of shelves used is minimized, and solved it using a heuristic method. Şahin, Ekmekçi, and Yürekli (2020) proposed two separate mathematical models and two separate layouts, taking into account shelf areas and transport vehicle dimensions, for the effective placement of semi-finished products in the welding section of a machinery factory.

Karagiannis (2021) compared the results obtained with the method based on the concept of mean cross productivity, which they applied to the ABC inventory classification problem, with the results obtained by four methods based on information theory: Shannon entropy, distance-based, least squares difference weighted method and maximum deviation methods. The empirical results conclude that there is a consensus on the inventory items belonging to the alternative methods class A, but there are minor differences between them that are relatively more obvious.

Demircioğlu and Özceylan (2021) applied ABC Analysis to determine Class A raw materials among 121 types of raw materials, firstly. They determined the nine raw materials with the A degree of importance, that is, the highest degree of importance. Then, using the Fuzzy ANP, the criteria weights were calculated according to the importance of these A group raw materials, based on the opinions of four experts, under the criteria of consumption amount, rate of presence in the finished product, access status, storage conditions, analysis, and delivery adequacy. These weights obtained are the coefficients of the variables in which the positions and quantities of the raw materials are shown in the shelf cells where they can be located, and are used in the objective function of the mathematical model in which the benefit is maximized.

Mohammed and Workneh (2020) performed a comparison study with a combination of ABC and Vital, Essential, and Normal (VEN) analysis to determine whether there was a relatively high expenditure on low-priority drugs and also Gizaw and Jemal (2021) used ABC-VED-FNS (Fast, Normal, and Slow) matrix to identify the types of items that require focused managerial control, priority, and replenishment intervals for pharmaceuticals.

The inventory management process of a railway logistics operator is improved by Vidal, Caiado, Scavarda, Ivson and Garza-Reyes (2022)'s novel framework that combines Multi Criteria Decision Making (MCDM) and machine learning approaches. In the initial stage, it integrates fuzzy logic and AHP to rank over 16.000 stock units based on their criticality and significance. It then employs the VIKOR method to rank the alternatives based on FAHP-defined weights. The Genetic Algorithm - Artificial Neural Network (GA-ANN) method is employed in the second stage to estimate the demand for the selected stock units. As a result, a structure is proposed in which the company is less reliant on high safety inventories, which results in high costs.

Yılmaz Kaya (2022) also proposed a novel approach through inventory control practices integrated ABC-VED analysis to determine the item group with the utmost relation to possible Occupational Health and Safety (OHS) risks and dangers and the highest investment percentages.

In their study, Khanorkar and Kane (2023) divided the stock items into three clusters A, B, and C using the unsupervised machine learning technique K-Means clustering method and then compared them to Hadi-Vencheh and classical ABC analysis results to check the algorithm's effectiveness. The criteria for multiple ABC analysis were delivery time, annual usage value, and unit average cost. They concluded that the K-Means approach can cluster the data set with an accuracy rate of around 74.4% by bypassing the extensive calculations required by MCDM techniques to classify inventory.

Mehdizadeh (2020) introduced a novel approach that employs rough set theory and ABC analysis to simulate retailers who send stock orders to distributors based on the number of vehicles sold and their kilometers. The objective of this approach is to establish a system that ensures good distributor service and the minimum inventory amount and age. Personal experience and discernment are absent from this data-driven decision-making model. To classify and manage spare parts, Gong, Luo, Qiu and Wang (2022) implemented Failure Mode Effect and Criticality Analysis (FMECA). They expanded the ABC classification economic index by taking into account the Risk Priority Coefficient (RPN) value and criticality of each system element, thereby combining the FMECA, entropy weight, and ABC classification methods. The comparison between the traditional

ABC classification and the proposed method demonstrated that the enhanced classification method reduced the number of A and B parts, thereby enhancing system security and reducing inventory control costs.

Zhang, Li and Guo (2020) established a methodology that differed from previous studies in the literature to address the possibility of misclassification in the inventory information managers put forward. They estimated the model's parameters using the maximum likelihood method, and ratios were utilized to identify potential misclassifications in the sample data. Both simulated and real-world datasets validated the suggested technique. The findings revealed that the proposed method works better in terms of classification accuracy and that experts can learn the classification rules from the training set and use them to categorize new things. Chawla, Itika, Singh and Singh (2024) investigated multiple MCDM methods and suggested a model to improve traditional ABC analysis using the Pythagorean Fuzzy TODIM approach. This methodology uses fuzzy integers to represent the uncertainty in real data, and they discovered that the proposed method can classify with 76.6% accuracy.

In comparison to previous studies, this study performed frequent interval scoring for cross-ABC analysis classes and used the results as coefficients in the shelf assignment model. The most notable aspect of this study is that it integrates cross-ABC analysis with AHP and bases it on the two most important criteria among the criteria determined by AHP, resulting in ease of operation and practicality in the use of cross-ABC analysis, the calculation difficulty of which increases as the number of criteria increases. When the acquired findings are evaluated, it is clear that the classification results are comparable to both classic multi-criteria ABC analysis and ABC analysis weighted with AHP. In this situation, the Cross-ABC analysis generated comparable classification findings by selecting the two criteria with the highest weight.

3. Methodology

3.1. Analytical Hierarchy Process

AHP is the widely applied multi-criteria decision-making method based on pairwise comparison to determine the weights of the criteria and the priorities of the alternatives Šarić, Šimunović, Pezer and Vjesnik (2014). AHP, proposed by Saaty (1988), has been extensively applied to evaluate complex multi-criteria alternatives in several domains. It performs well, favoured by ease of use, systematically structuring problems, and calculating both criterion weights and alternative priorities.

3.2. ABC Analysis

Materials management has to deal with thousands of transactions each year. Materials managers prefer to separate items that require close control from those that require less control in order to concentrate on important matters rather than dealing with trivial details to do their job effectively. One of the most frequently used methods for this purpose is ABC Analysis.

3.3. Single Criteria ABC Analysis

ABC Analysis is built on the basis that a small fraction of materials makes up a large part of the total stock value. In this method, which is based on the Pareto Analysis, also known as the "80/20 Rule", while the main valuable and important inventory items constitute only 20% of the total; the logic that it has 80% of the total value is operated. Therefore, it is possible to collect stocks in three classes, A, B and C, depending on these importance values.

Class A materials consist of 15-20% of all materials, which corresponds to 75-80% of the total stock value. Class B consists of 20-25% of the total materials and 10-15% of the total stock value. Class C, on the other hand, consists of 60-65% of the total materials and constitutes 5-10% of the total stock value.

3.4. Multi-Criteria ABC Analysis

In one-factor ABC analysis, the evaluation process is carried out by considering only one factor. Often this factor is the annual cost or the average unit cost. However, since there are many important factors apart from these factors, multi-criteria ABC analysis, in which multiple criteria are evaluated together, is often preferred. In multi-criteria ABC analysis, more than one factor as amount of use, value in use, lead time, unit price, lifetime, substitutability and criticality etc. can be taken into account for evaluation purposes at the same time.

For each criterion, stock classes are first determined. Then, these classes are scored. The scoring here is subjective. The relevant stock item, which class is assigned to a criterion, is multiplied by the percentage value given to that extent. Then, the values obtained in the same way for other criteria are collected and the total score of the related stock item is calculated. Finally, according to the scoring obtained, inventory items are reordered from largest to smallest and an ABC classification is made according to the cumulative percentage values. As can be seen, it requires a more complex calculation.

The method of traditional ABC analysis either with one or more criteria, has some disadvantages (Abdolazimi, Shishebori, Goodarzian, Ghasemi and Appolloni, 2021). Due to these deficiencies, in this study, a different approach is proposed in ABC analysis to improve grouping and inventory control decisions.

3.5. Vital, Essential and Desirable (VED) Analysis

VED analysis is a technique for classifying inventories according to their functional importance and prioritizing them according to their criticality. The lack of things under the "vital" classification can seriously hinder or impair the proper functioning of activities. The "essential" classification incorporates stock, which is close to being indispensable. The "Desirable" classification of stock is the most un-significant among the three, and their inaccessibility might bring about minor stoppages. The ABC-VED matrix method is especially one of the most suitable methods for pharmacies.

3.6. Cross ABC Analysis

To identify items that have a significant impact on the overall inventory, the cross ABC analysis is an alternative method that combines information from two different ABC analyses with a single criterion. Flores and Whybark (1987) proposed the cross-tabulation matrix model for two-criterion inventory classification. However, the methodology becomes more complex when three or more criteria are included in the evaluations.

Cross ABC Analysis allows items to be further divided into classes to make a more detailed analysis. In this method, raw materials are divided into AA, AB, AC, BA, BB, BC, CA, CB and CC classes. It is a preferable way to have a complete set of information to prioritize items to focus on and allocate appropriate places in the warehouse.

Here, for example, AA products may be the best selling and most frequently transported products, or they may be the products with the highest unit cost and the most difficult to substitute. Therefore, they are placed in the most suitable position in the warehouse. If CC products are for the same example, they can be classified as the least sold and less transported products or the products with the lowest unit cost and the most easily substituted products. For this reason, the control and placement options may also be different.

There are not many studies on cross ABC analysis in the literature. Although ABC-VED matrix analysis is mostly used for stock management in the pharmaceutical industry (Pund, Kuril, Hashmi, Doibale and Doifode, 2016) there has been no detailed study on cross ABC analysis in general terms. Mbakop and Kevine (2018) used the classical ABC analysis to analyse the sales and order frequency values of the products separately, in their study to reveal the effectiveness of cross-ABC analysis in the placement of products in the warehouse. Then, starting from the items of the first analysis and comparing the classification with the second analysis, they crossed the previous two analyses and classified the products as AA, AB, AC, BA, BB, BC, CA, CB and CC.

This study complied with research and publication ethics.

4. Case Study

In this study, different types of ABC analysis are used for the placement of fabric balls in the fabric warehouse of a textile company and the effectiveness and simplification of these types are compared based on the obtained results.

4.1. Analysis of Current Situation

In the textile factory where the study was carried out, raw material entry and exit to the fabric warehouse is made through a single door and a forklift is used for this process. The control process of the fabrics that are shipped in the fabric warehouse is carried out by using two machines. As seen in Figure 1, raw materials are placed randomly in the warehouse, without a specific order. The lack of a warehouse rack system makes stacking difficult and reduces the volumetric utilization efficiency. This study aims to design warehouse shelves and improve the layout based on minimizing transports in the fabric warehouse in practice.

Figure 1. Current Layout of the Warehouse

4.2. General Flow of the Proposed Approach

The main focus in warehouse layout is that not all products or raw materials have the same level of importance among themselves. There are many studies using ABC analysis to group raw materials, as mentioned before multi-criteria ABC analysis is frequently used when more than one criterion is considered. However, in multi-criteria analysis, it is not clear which priority or importance weight of the criteria will be evaluated. In this context, weighting many studies with MCDM methods, especially the AHP method is preferred.

Figure 2 explains the flow of the study. In this study, three different approaches to ABC analysis are compared. The first one is multi-criteria ABC analysis, where the criteria are considered equally weighted and the second one is also multi-criteria ABC analysis with AHP weighted criteria. Lastly, AHP weighted Cross ABC Analysis with selected two criteria and detailed scoring scale is proposed.

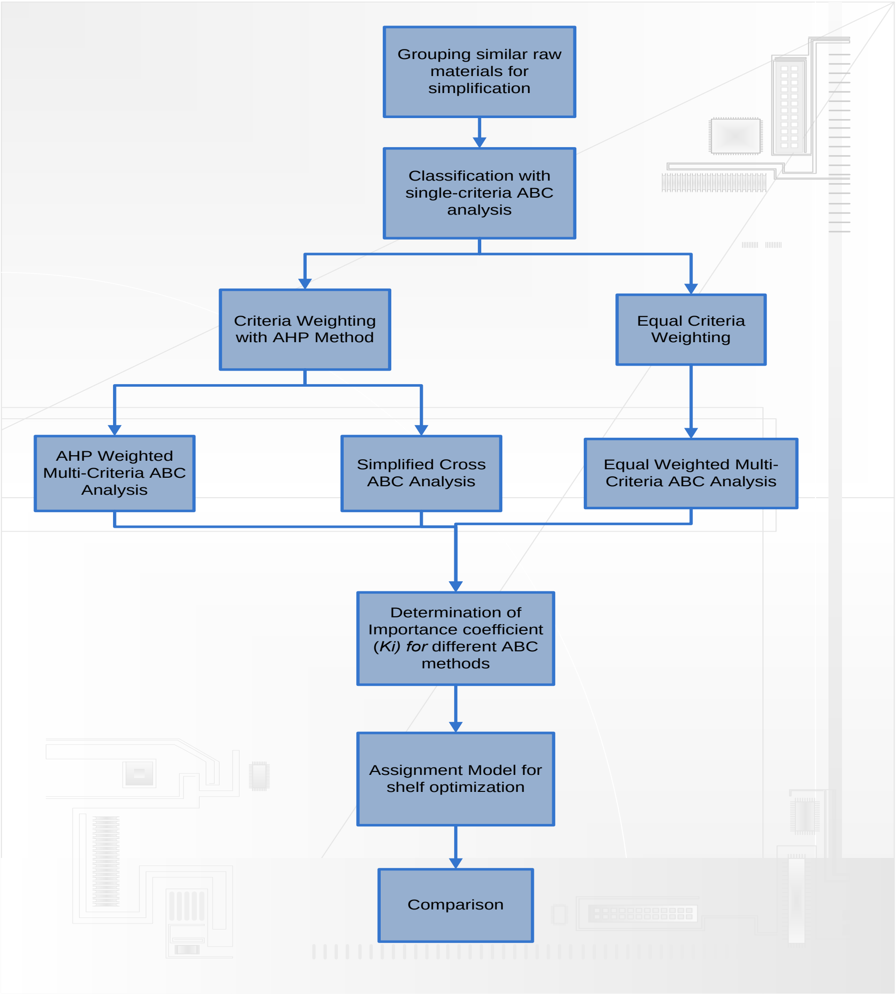

Figure 2. The General Flow of the Proposed Approach

4.3. Calculations for ABC Analysis

Raw material data regarding the unit price, weight, transportation cost and width*length criteria of the fabric rolls in the factory are given in Table 1.

Table 1

Raw Materials Data

Order No	Raw Material Name	Unit Price	Trans. Cost	Weight	Width*Length
1	Inspection Summary 1st ball	40.34	1.698	80.10	208.98
2	Inspection Summary 2nd ball	40.34	1.698	73.75	140.94
3-9	...	40.34	1.698	...	...
10	Sharabati 1st ball	92.00	1.417	69.30	179.12
11	Sharabati 2nd ball	92.00	1.417	72.60	129.98
12-21	...	92.00	1.417	...	...
22	Nebraska Gots Organic 1st ball	32.40	1.084	61.20	132.61
23	Nebraska Gots Organic 2nd ball	32.40	1.084	68.30	133.40
24-34	...	32.40	1.084	...	...
35	Dubai poplin 1st ball	65.00	0.788	50.76	359.12
36	Dubai poplin 2nd ball	65.00	0.788	43.41	302.59
37-45	...	65.00	0.788	...	...
46	Scharabati Presley Ocean Blue 1st ball	71.80	1.287	79.80	191.18
47	Scharabati Presley Ocean Blue 2nd ball	71.80	1.287	73.95	173.80
48-52	...	71.80	1.287	...	...
53	Eleven Ecru Organic 1st ball	31.30	1.126	97.00	238.58
54	Eleven Ecru Organic 2nd ball	31.30	1.126	98.00	232.84
55-61	...	31.30	1.126	...	...
62	Coldow Blue 1st ball	31.00	2.046	67.50	225.00
63	Coldow Blue 2nd ball	31.00	2.046	80.10	262.50
64-68	...	31.00	2.046	...	...
69	Martinez Gabardin 1st ball	22.40	1.721	43.50	112.50
70 -73	...	22.40	1.721	...	...
74	Martinez Gabardin 6 th ball	22.40	1.721	41.18	60.00
	Total:	**3738.96**	**98.84**	**4977.18**	**14239.63**

There are 74 types of fabric balls. However, when the unit price and transportation costs of fabric rolls are examined, it is seen that fabrics with the same properties have the same values. For this reason, ABC analysis is deemed appropriate by dividing 74 fabric balls into 8 groups according to their properties. The width-length and weight values have different values for each fabric ball. Therefore, the mean values of these criteria for each group are taken into account for this analysis.

The values of all fabric balls divided into eight groups are as in Table 2.

Table 2

Grouping Data for Raw Materials

Order No	Raw Material Name	Weight (Average)	Width*Length (Average)	Unit Price	Trans. Cost
1	Inspection Summary	72.40	171.50	40.34	1.698
2	Sharabati	74.60	182.23	92.00	1.417
3	Nebraska Gots Organic	65.89	153.91	32.40	1.084
4	Dubai poplin	43.93	306.01	65.00	0.788
5	Scharabati Presley Ocean Blue	75.24	179.40	71.80	1.287
6	Eleven Ecru Organic	94.11	226.80	31.30	1.126
7	Coldow Blue	68.94	203.69	31.00	2.046
8	Martinez Gabardin	39.04	69.95	22.40	1.721

First, traditional single criterion ABC analysis is performed for each criterion. The results of the ABC analysis performed separately for the unit price, weight, transportation cost, and aspect criteria are given in Table 3.

Table 3

Classification Results for Each Criterion Separately with Single-Criteria ABC Analysis

Order No	Raw Material Name	Width * Length	Transportation Cost	Unit Price	Weight
1	Inspection Summary	C	A	B	B
2	Sharabati	B	B	A	A
3	Nebraska Gots Organic	C	C	B	C
4	Dubai poplin	A	C	A	C
5	Scharabati Presley Ocean Blue	B	B	A	A
6	Eleven Ecru Organic	A	C	C	A
7	Coldow Blue	A	A	C	B
8	Martinez Gabardin	C	A	C	C

4.3.1. Equal Weighted Multi Criteria ABC Analysis

Using the classification results in Table 3 and assuming that the criteria weights are equal (0.25), the results of the multi-criteria ABC analysis performed is as in Table 4.

Table 4

Equal Weighted Multi-Criteria ABC Analysis Results

Order No	Raw Material Name	Score	Percent	Cumulative Percent	Class
2	Sharabati	6.50	0.17	0.17	**A**
5	Scharabati Presley Ocean Blue	6.50	0.17	0.33	
7	Coldow Blue	6.00	0.15	0.49	
4	Dubai poplin	5.50	0.14	0.63	**B**
6	Eleven Ecru Organic	5.50	0.14	0.77	
1	Inspection Summary	4.25	0.11	0.88	**C**
8	Martinez Gabardin	3.25	0.08	0.96	
3	Nebraska Gots Organic	1.50	0.04	1.00	
	Total:	**39.00**	1.00		

In this study, in order to ensure homogeneity in all conventional ABC analyses, the scores of classes A, B and C are taken as 10, 3 and 1, respectively. Of course, other values between 1 and 10 could be taken, provided that the class points gradually decrease. An example of score calculation for Table 4 is given below:

A-C-A-C classifications are made in single analysis for Dubai poplin type fabric. The score is calculated as (10+1+10+1) * 0.25 = 5.5

It should also be noted that since the number of raw materials decreased due to grouping, the 80/20 ratio is not used exactly in the ABC classification. In the evaluations, approximately 50-60% of the total value is included in the A class, while the C class is mostly classified as 80% and above of the cumulative value. The same assumptions apply for all analyses.

4.3.2. AHP Weighted Multi-Criteria ABC Analysis

To determine the importance of the criteria, the comparison matrix is filled in by taking the opinions of the engineers and warehouse managers in the workplace. According to the calculations in *Appendix A*, the criteria weights are determined as 0.6328; 0.1665; 0.1068, and 0.0937 for width * length, transportation cost, unit price, and weight criteria, respectively. As seen the highest value is for the width*length criterion and transportation cost is the second one.

Once more, using the analysis results in Table 3, the values obtained from the AHP method are used for ABC classification with the same scores, as mentioned before. The AHP-weighted multi-criteria ABC analysis results are as in Table 5.

Table 5

AHP Weighted Multi Criteria ABC Analysis Results

Order No	Raw Material Name	Score	Percent	Cumulative Percent	Class
7	Coldow Blue	8.38	0.21	0.21	**A**
4	Dubai poplin	7.66	0.20	0.41	
6	Eleven Ecru Organic	7.54	0.19	0.60	
2	Sharabati	4.40	0.11	0.72	**B**
5	Scharabati Presley Ocean Blue	4.40	0.11	0.83	
1	Inspection Summary	2.90	0.07	0.90	**C**
8	Martinez Gabardin	2.50	0.06	0.97	
3	Nebraska Gots Organic	1.21	0.03	1.00	
	Total:	**39.0**	**1.00**		

An example of score calculation for Table 10 is given below for Dubai poplin-type fabric. A-C-A-C classifications are made in a single analysis and the weights are taken from AHP then the score is calculated as:

$$10 * 0.6328 + 1 * 0.1665 + 10 * 0.1068 + 1 * 0.0937 = 7.66$$

4.3.3. Proposed Cross ABC Analysis

The Cross ABC analysis, based on the principle of categorizing the items into classes AA, AB, AC, BA, BB, BC, CA, CB and CC is used to combine the two criteria in order to determine the degree of importance and categorize them accordingly. This method, which compares the management factors selected in pairs, allows stocks to be divided into more detailed classes with the same characteristics (Silvestri et al., 2011).

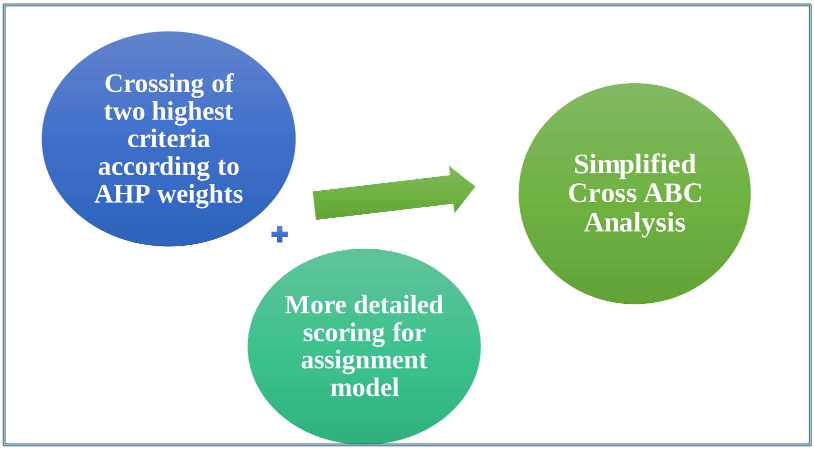

Figure 3. Components of Simplified Cross ABC Analysis

The proposed contributions for cross ABC analysis in this study are as summarized in Figure 3. First of all, the criteria are weighted with AHP in order to eliminate the criticisms about subjectivity in the weighting of the criteria in the classical multi-criteria ABC analysis. Then, in the weighting of this criterion, in order and the raw materials are classified as AA, AB …, CC.

For more than two criteria, in the proposed method, the first two criteria with the highest weight is to be crossed with each other. For this case study, the width*length and transportation cost criteria, which have the highest weight value, are crossed together, while the unit price and weight criteria, which have less importance and for the elimination of complexity, matrix representation could also be used as in Table 6.

Table 6

Matrix Representation of Cross ABC Analysis Pairwise

Width* Length AND Transportation Cost	Unit Price - Weight								
	AA	AB	AC	BA	BB	BC	CA	CB	CC
AA								Coldow	
AB									
AC			Dubai				Eleven		
BA									
BB	Sharabati Scharabati								
BC									
CA					Inspection				Martinez
CB									
CC						Nebraska			

With the proposed cross-ABC analysis, the classes of the two criteria with the highest weight are crossed without needing to do any extra calculation as seen in Table 7 in which all of the results are compared.

Table 7

Comparison of Three Method Classes

Order No	Raw Material Name	Classes for Equal Weighted Multi Criteria ABC Analysis	Classes for AHP Weighted Multi Criteria ABC Analysis	Classes for Proposed Cross ABC Analysis
7	Coldow Blue	A	A	AA
4	Dubai poplin	A	B	AC
6	Eleven Ecru Organic	A	B	AC
2	Sharabati	B	A	BB
5	Scharabati Presley Ocean Blue	B	A	BB
1	Inspection Summary	C	C	CA
8	Martinez Gabardin	C	C	CA
3	Nebraska Gots Organic	C	C	CC

As seen in Table 7, the classification order is similar, especially for C class inventories. Also a more detailed scoring can be made due to the cross ABC analysis. In addition, the scores obtained from the ABC analysis will be used for shelf assignment in the mathematical model. In this simplified ABC analysis approach, a different scoring method from the traditional approach is also suggested. The score scales used both in the traditional and the improved methods are shown in Table 8.

Table 8

Score Scales

Proposed Cross ABC Analysis Score Scale		Traditional ABC Analysis Score Scale	
Classes	Scale	Classes	Scale
AA	10	A	10
AB	9	B	3
AC	8	C	1
BA	7		
BB	6		
BC	5		
CA	4		
CB	3		
CC	2		

Although not necessarily, in traditional analysis, this type of scoring is generally preferred. Whereas it is seen, in the proposed cross ABC analysis, that the suggested scoring is more detailed.

The score calculations for the three methods whose results are compared are as in Table 9. As can be seen, the proposed approach shows a homogeneous distribution on the 1-10 scale, while the point value in the classical method is limited to only 3 numbers.

Table 9

Comparison of Scores

Order No	Raw Material Name	Equal Weighted Multi-criteria ABC Analysis Scores	AHP Weighted Multi-criteria ABC Analysis Scores	(Proposed method) Simplified Cross-ABC Analysis Scores
1	Inspection Summary	1	1	4
2	Sharabati	10	3	6
3	Nebraska Gots Organic	1	1	2
4	Dubai poplin	3	10	8
5	Scharabati Presley Oc. Blue	10	3	6
6	Eleven Ecru Organic	3	10	8
7	Coldow Blue	10	10	10
8	Martinez Gabardin	1	1	4

4.4. Mathematical Model

Within the scope of the application, a mathematical model is created to place the raw materials on the shelves so that the transportations are minimized according to the ABC analysis.

4.4.1. Notation List:

Sets (Indices)

i: Index of inventory items (fabric rolls), $i \in I = (1, 2, ..., i)$

j: Index of shelves for assignment, $j \in J = (1, 2, ..., j)$

Parameters

k_i*:* Importance coefficient (score) of fabric ball i according to different ABC methods

b_i*:* Total number of shelves to which raw material i can be assigned

d_j*:* Distance of shelf j to the control machine (Table 10)

Decision Variables

$$X_{ij} = \begin{cases} 1, & If\ raw\ material\ i\ is\ assigned\ to\ shelf\ j \\ 0, & other\ wise \end{cases}$$

Objective Function

$$\text{Min} \quad \sum \sum k_i * d_j * X_{ij} \qquad (1)$$

The objective function, Equation (1), minimizes in-warehouse shipments by taking into account the classification scores obtained from the ABC analysis of raw materials. The main purpose is to place the fabric balls with higher importance scores on the shelves closer to the fabric inspection machine according to the importance coefficients obtained from the ABC analysis.

Constraints

$$\sum_{\mathrm{i=1}}^{\mathrm{I}} X_{ij} \leq b_i \qquad \mathrm{j} = 1, \dots, \mathrm{J} \qquad (2)$$

Equation (2) indicates the maximum number of fabric rolls assigned to shelf i.

$$\sum_{\mathrm{j=1}}^{\mathrm{J}} X_{ij} = 1 \qquad \mathrm{i} = 1, \dots, \mathrm{I} \qquad (3)$$

Equation (3) indicates that a fabric roll can only be assigned to one shelf.

$$X_{ij} = \begin{cases} 1, & If\ raw\ material\ i\ is\ assigned\ to\ shelf\ j \\ 0, & other\ wise \end{cases} \qquad (4)$$

Equation (4) indicates that X_{ij} is 0 -1 binary variable.

Table 10

The Distances between Quality Control Machine and the Shelves

Shelf Number	Distance
1	490
2	320
3	560
4	160
5	550
6	360
7	190
8	420
9	280
10	430
11	500
12	240

Since A class fabric rolls will be used more often, they are placed closer to the fabric inspection machine and since C class fabric rolls are used less, they could be placed farther from the fabric inspection machine, thus providing efficiency in terms of time and cost.

As represented in Figure 4, shelving optimization is aimed for the fabric rolls, taking into account the scores obtained from the ABC analysis with the assignment model and the distances of the shelves to the machine.

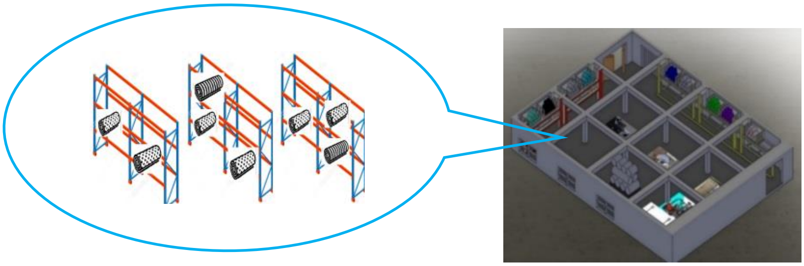

Figure 4. Representative Warehouse Layout

4.4.2. Assumptions of the Model

In this study, after classification with ABC analysis, class scores are included in the model as a coefficient, different from Çolak et al. (2016) and Demircioğlu and Özceylan's (2021) studies as they used the weight values directly in the assignment model.

In the sample application, a mathematical model with ABC analyses coefficients is used for shelf assignment of raw materials has the following assumptions.

- 74 fabric balls are gathered under 8 main headings in order to avoid complexity in calculations.
- Assuming that similar balls will be assigned to the same area, the number of fabric balls (b) that can be assigned to a shelf is accepted as 1.
- The area of the fabric warehouse is fixed and cannot be changed.
- The area of the fabric warehouse is divided into 12 equal-sized shelf areas and the fabric balls are placed in these allocated areas.
- When calculating the transport distances, the distances of the fabric balls to the fabric inspection machines are taken into account.
- It is assumed that the transport of fabric rolls takes place only from fabric inspection machines to their places on the shelf and from their places on the shelves to fabric inspection machines.

When the results in Table 11 are evaluated, it is seen that the assignments made with the scores obtained from AHP weighted classification, in which all criteria are taken into account, assign values very close to the assignment results of the proposed model.

Table 11

Assignment Results for Three Methods

No	Raw Material Name	Equal Weighted Multi-criteria ABC Analysis Shelf Assignment	AHP Weighted Multi-criteria ABC Analysis Shelf Assignment	Proposed Simplified Cross-ABC Analysis Shelf Assignment
		Assignment of Shelves		
1	Inspection Summary	10	10	8
2	Sharabati	12	2	2
3	Nebraska Gots Organic	8	8	10
4	Dubai poplin	2	12	12
5	Scharabati Presley Oc. Blue	7	9	9
6	Eleven Ecru Organic	9	7	7
7	Coldow Blue	4	4	4
8	Martinez Gabardin	6	6	6
	Objective Function Value	***8910***	***8910***	***12620***

Although the minimization objective function values of the assignment model of two classical methods, gave a lower result than the recommended one, it is obvious related to the importance score (k_i), which is included as a coefficient in the objective function. As can be seen in Tables 8 and 9, since the scoring values of the proposed method are determined at more frequent intervals compared to the other two methods, the objective function value is higher. When Table 11 is examined, it is seen that while the shelves assigned in the lower classes are the same as in the other methods, assignments are made to shelves with values that are somewhat close to the upper classes. The contribution that is emphasized here is that a more detailed classification can be made with a more simplified method. In particular, it makes it possible to make effective assignment results without straining the calculation limits of warehouse managers.

5. Discussion and Conclusions

Many methods have been used for inventory classification. ABC Analysis is proposed to identify items that have a significant impact on the overall inventory. While it is very simple and technically feasible to implement a single-criteria-based analysis, it ignores some very important criteria. To overcome the limitations of traditional classification analysis, many researchers have focused on incorporating multi-criteria judgments such as average unit cost, criticality, and lead time into the inventory classification procedure. Cross-ABC analysis has some advantages over traditional ABC analysis as it allows a more detailed examination of inventory items based on multiple criteria.

This study proposes an inventory classification system for shelf assignment minimizing the transport distance in a warehouse. By applying the presented methodology to the warehouse of a textile factory, we show that it represents a useful tool to systematically and dynamically improve the raw materials classification and shelf assignment. Indeed, the application of the approach to the factory leads to a facilitator proposal for warehouse management.

It can be stated that the model proposed here has two main contributions. The first of these is to provide simplification in the operations as a result of crossing the two criteria with the highest AHP weight value without considering all the criteria in the multi-criteria ABC analysis. Such that, as shown in Appendix 1, once the criteria weights are calculated and the two most important criteria are determined, warehouse personnel who do not have a technical background, that is, not a production engineer, can easily apply the proposed method.

The second is that the scores of the cross-classes added as coefficients to the assignment model are more detailed, more homogeneous scoring can be done, and the score scale has been diversified. As a result of these contributions, almost the same results were obtained with the classical AHP weighted method.

When the scores obtained from all three ABC analyses are compared with the results of the assignments, as mentioned above, assignments made with the scores obtained from AHP weighted classification, in which all criteria are taken into account, are very close to the assignment results of the proposed model. Once more, the important point to be considered is that the proposed classification method can make an appropriate, similar, practical and simple classification compared to others.

Due to the complexity of the analytical multilevel method of multi-criteria evaluation, the proposed methodology can be used effectively in practice. Given the time-sensitive nature of inventory management, the aspect of practicality becomes crucial in guaranteeing efficiency and can greatly enhance inventory management.

In the mathematical assignment model, the amount of fabric roll *i* is not included in the model, and that each roll is assumed to be assigned to a single shelf can be evaluated as limitations of the model. Furthermore, the fact that the current and proposed situations are not compared in practice due to the transportation of the textile factory for ground conditions can be evaluated as a weakness.

In future studies, different MCDM methods can be used for criterion weighting, as well as suggestions for evaluating the criteria to be paired together as the number of criteria increases.

Conflict of Interest

There is no conflict of interest to declare.

Contribution of Researchers

In this research, first and only author (YO) was responsible for conceptualization, literature review, methodology, software, data curation, writing- original draft preparation, validation, writing- reviewing and editing.

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Appendix 1. Weighting of Criteria with AHP Method

Step 1: A comparison matrix is created to determine the importance of the criteria.

The comparison matrix is filled in by taking the opinions of the engineers and warehouse managers in the workplace. Comparisons using the AHP method are made according to the importance scale.

Table 1

Binary Comparison Matrix

	Weight	Width*Length	Transportation Cost	Price
Weight	1	0.20	0.33	1
Width*Length	5	1.00	5.00	7
Trans. Cost	3	0.20	1.00	1
Price	1	0.14	1.00	1

Step 2: Normalization: Priority values are calculated.

A normalized comparison matrix is obtained by dividing each element of the comparison matrix by its column sum. Priority values will be used in ABC analysis.

Table 2

Normalized Comparison Matrix

	Weight	Width* Length	Transportation Cost	Price	Normalized Row Sum	Priority Values
Weight	0.1000	0.1299	0.0450	0.1000	0.3749	0.0937
Width* Length	0.5000	0.6494	0.6821	0.7000	2.5315	0.6328
Trans. Cost	0.3000	0.1299	0.1364	0.1000	0.6663	0.1665
Price	0.1000	0.0909	0.1364	0.1000	0.4273	0.1068

Step 3: The weighted total vector and eigenvalues are calculated.

The weighted total vector is found by multiplying the pairwise comparison matrix with the relative priority value vector.

Table 3

Calculation of the Weighted Total Vector

	Weight	Width*Length	Transportation Cost	Price	Total
Weight	1*0.0937=0.0937	0.2*0.6328=0.1265	0.33*0.1665=0.0549	1*0.1068=0.1068	0.3819
Width* Length	5*0.0937=0.4685	1*0.6328=0.6328	5*0.1665=0.8325	7*0.1068=0.7476	2.6814
Transp ortation Cost	3*0.0937=0.2811	0.2*0.6328=0.1265	1*0.1665=0.1665	1*0.1068=0.1068	0.6809
Price	1*0.0937=0.0937	0.14*0.6328=0.088 5	1*0.1665=0.1665	1*0.1068=0.1068	0.4555

The eigenvalue vector is calculated by dividing the elements of the weighted sum vector by their corresponding relative priority values.

Table 4

Calculation of the Eigenvalue Vector

	Total weight / Relative priority value	Eigen Value
Weight	0.3819 / 0.0937	4.0757
Width*Length	2.6814 / 0.6328	4.2373
Transportation Cost	0.6809 / 0.1665	4.0894
Price	0. 4555 / 0.1068	4.2649

Step 4 and 5: The consistency ratio is calculated.

The value of λmax is found by taking the arithmetic average of the eigenvalue vector values. The consistency index value is calculated. The ratio of the consistency index to the randomness index gives the consistency ratio and this ratio is expected to be less than 0.1.

$$\lambda_{max} = \frac{4.0757 + 4.2373 + 4.0894 + 4.2649}{4} = 4.1668$$

Where n is the number of criteria, CI is the consistency index and CR is the consistency ratio then CR is calculated as follows:

$$CI = (\lambda_{max} - n)/(n - 1) = (4.1668 - 4)\ /\ 3 = 0.0556$$

$$CR = \frac{CI}{RI} = \frac{0,0556}{0,9} = 0.0617$$

As a result, it is said to be consistent because CR<0.1. As a result of the calculations, the weight value of the width-length criterion, which is the most important criterion, is 0.6328. Weight values of other criteria are 0.1665 for transportation cost; it is 0.1068 for price, and 0.0937 for weight.