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EDITORIAL

Development of Low-carbon and Sustainable Magnesium-bearing Cementitious Materials-based Solidification Approaches for Management of Problematic Soils

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ABSTRACT

The production of traditional cementitious binders such as calcium-based Portland cement poses a serious challenge to the environment and society. Therefore, low-carbon, green and sustainable magnesium-based cementitious materials are developed to replace fully or partly Portland cement and reduce the consumption of natural resources and CO_2 emissions. Three interesting techniques, including reactive MgO-activated industrial solid wastes, MgO-based cement and carbonation of magnesium-bearing materials, are elucidated to point to the necessity for developing novel magnesium-based cementitious materials. In the coming future, the carbonation of magnesium-rich industrial solid wastes or its combination with reactive MgO for application in various construction sectors such as soft ground improvement and concrete fabrication would be a promising approach to generate high-value products based on industrial solid wastes.

Keywords: Mg-bearing binder; Solidification; Soil; Carbonation

The uninterrupted population growth and economic development would unavoidably require more living space and infrastructure construction, especially in the coastal, lake, valley and river regions. In these areas, soft soils with high water content, high compressibility, low bearing capacity and low strength pose a serious challenge that must be addressed before the infrastructure construction. To overcome efficiently the intractable issue, a commonly accepted approach—Portland cement-based solidification

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method is being developed and attracting more and more attention worldwide [1-4]. However, in general, producing 1 ton of traditional Portland cement must generate 0.94 tons of CO_2 (0.55 tons of chemical CO_2, 0.39 tons of CO_2 from fuel emissions) [4,5]. The quantity of CO_2 emitted from the cement industry has been estimated to be about 5%-7% of the world's total CO_2 emissions [6]. Consequently, developing low-carbon, sustainable and high-efficiency binders for the solidification of problematic soils is an important and promising issue that deserves to be probed to replace partly or fully calcium-based Portland cement.

The magnesite deposit in China is an abundant reserve that occupies the first place in the world. It provides a great opportunity to synthesize magnesium-bearing cementitious materials, which are generated at lower calcination temperatures and less energy and resource consumption in contrast with Portland cement. For soil solidification, reactive MgO has been incorporated to activate the pozzolanic properties of industrial solid wastes such as granulated blast furnace slag and fly ash [7,8], generating C-S-H or M-S-H gels at high alkalinity that are essentially the micromechanisms for soil improvement. In fact, the incorporated MgO plays a duel role in the process of MgO activated industrial solid wastes: (i) Similar to lime (CaO), MgO dissolves in water to form brucite ($Mg(OH)_2$) that fills into pore space and cements fines grains together, and (ii) MgO reacts with active components (SiO_2) contained in solid wastes in the presence of water to produce M-S-H or provides an alkaline environment to facilitate the production of C-S-H gels. Nevertheless, it is observed that the strength development is relatively slow at an early age and the activation efficiency of solid wastes by reactive MgO is unstable due to the complexity of chemical composition in various solid wastes [8,9]. To synthesize MgO-based cement that is more highly effective in enhancing the early and long-term strength of solidified soils, several blocks of cement with a significantly higher quantity of magnesium have been developed and introduced in soil solidification [4,10-13]. They exhibit many superior characteristics such as fast hardening, high early strength and excellent fire/abrasion resistance and so on. As an air-hardening cement, magnesium oxychloride cement (MOC) is prepared from reactive MgO and chemical reagent $MgCl_2$, and the hydration of MOC occurs in a through-solution reaction, generating the major hydrated products including brucite ($Mg(OH)_2$), phase 5 crystals ($5Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$) and phase 3 crystals ($3Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$). Besides, magnesium phosphate cement (MPC), prepared by dead burned magnesia (MgO) and potassium dihydrogen phosphate (KH_2PO_4) or ammonium dihydrogen phosphate ($NH_4H_2PO_4$) in the presence of water is one of the most promising alternatives to substitute Ca-based Portland cement, and generated $KMgPO_4 \cdot 6H_2O$ (struvite-k) or $NH_4MgPO_4 \cdot 6H_2O$ (struvite) by an acid-base neutralization reaction. According to the above discussions, it can be concluded that the performance of Mg-based blocks of cement in soil solidification depends greatly on the ratio between components, affecting directly the number of hydrated products and the strength development of solidified soils. The optimal ratio where the strength reaches the peak should be determined before the application of Mg-based blocks of cement in soil solidification.

With the development of Mg-based blocks of cement, an innovative combination of CO_2 carbonation and reactive MgO or MgO-bearing materials was proposed and is attracting more and more attention for the beneficial use in soil solidification [14-17]. In fact, reactive MgO has an excellent capacity to absorb CO_2 emitted from industrial activities such as cement production and mineral calcination, and thus reduce CO_2 emissions by capturing and transforming them into a series of stable hydrated carbonates such as nesquehonite, dypingite and hydromagnesite [16,17]. This can realize us to transform CO_2 gas from industrial emissions to solid Mg-based carbonate minerals that are permanently stable at ambient temperature. For application in soil solidification field, CO_2 carbonation combined with reactive MgO or MgO-bearing materials can not only improve the mechanical performance (strength, bearing capacity etc.) of solidified soils, but also reduce their permeability and porosity owing to the combined physic-chemical impact of pore filling-cementation-skeleton construction. Furthermore, to cut the material cost for CO_2 carbonation and recycle industrial solid wastes that are difficult to be reused on large-scale, various industrial solid wastes with high MgO content such as granulated blast furnace slag, steel slag and fly ash were innovatively introduced in CO_2 carbonation-based solidification approach [17,18]. A portion of MgO originally contained in industrial solid wastes was proved to be efficiently carbonated, but there is still an important fraction of residual MgO in these wastes tested that do not take part in the CO_2 carbonation process. Therefore, how to activate efficiently these MgO residuals in solid wastes and carbonize them to form stable and permanent carbonates is deemed as an intractable problem to address in the future. Some preliminary attempts at the dissolution of magnesium from solid wastes to facilitate its combination with CO_2 have already been made for the moment, but it still requires many more efforts on this topic to develop a cost-effective and efficient approach to carbonize as much as possible these MgO minerals contained in solid wastes. It would become a crucial and innovative research issue in the soil solidification field that deserves to be systematically investigated in the coming future. Especially, the environmental compatibility between Mg-based carbonation and treated soils should be also considered for the potential application in various construction domains including ground improvement and concrete fabrication etc.

The above discussions summarized the research motivation and development process of green, low-carbon and efficient Mg-bearing cementitious binders oriented for soil solidification in the domains of soft ground improvement and waste sludge treatment. Especially, concerning the prospective research, the carbonation of industrial solid wastes and their combination with reactive materials such as MgO would be a promising and high-valued waste recycling technique for soil solidification and the green construction sector.

Conflict of Interest

There is no conflict of interest.

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REVIEW

A Comprehensive Overview of the ELECTRE Method in Multi-Criteria Decision-Making

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ABSTRACT

The ELECTRE (ELimination Et Choix Traduisant la REalite) method has gained widespread recognition as one of the most effective multi-criteria decision-making (MCDM) methods. Its versatility allows it to be applied in a wide range of areas such as engineering, economics, business, environmental management and many others. This paper aims to provide an overview of the ELECTRE method, including its fundamental concepts, applications, advantages, and limitations. At its core, the ELECTRE method is an outranking family of MCDM techniques, which allows for the direct comparison of alternatives based on a set of criteria. The method takes into account the preferences and importance of decision-makers and generates a ranking of the alternatives based on their relative strengths and weaknesses. The ELECTRE method is a powerful tool for decision-making, and its applicability to a wide range of fields demonstrates its versatility and adaptability. By understanding its concepts, applications, merits, and demerits, decision-makers can use the ELECTRE method to make informed and effective decisions in a variety of contexts.

Keywords: Decision making; Multi criteria decision making; ELECTRE method; ELimination Et Choix Traduisant la REalite method; Multi attribute decision making

1. Introduction

The ELECTRE (ELimination Et Choix Traduisant la REalite) method is a non-compensatory multi-attribute decision making (MADM) method that works based on alternatives' comparison considering individual criteria [1]. The main point that distinguishes the ELECTRE from compensatory methods

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such as simple additive weighting (SAW) [2] is that in the ELECTRE method, the weights are not criteria substitution rates instead the weights are coefficients of importance. Furthermore, in this method, it is not possible to offset a very bad value on a criterion with good ones on other criteria. It should be added that a few references consider the ELECTRE as a partially compensatory method and argued for placing it in the non-compensatory subgroup [3].

The initiated ELECTRE evaluation method was introduced in 1966 by Benayoun et al. [4]. This was the report of a real word problem in the European consultancy company SEMA, although the first journal article was published by Roy in 1968 to describe the method in detail and it was renamed later as ELECTRE I [5]. Then, different authors published manifold studies on this method based on similar theories to establish preference and outranking relations, and also to support decision-makers by making consistent exploration and analysis. Different ELECTRE versions were introduced by several scholars such as ELECTRE I, II, III, IV, IS, TRI, TRIB, and TRI-C. In this paper, the process steps of three methods that are between the most commonly used versions including ELECTRE I, II, and III are described in detail. ELECTRE I was developed as one of the earlier versions of ELECTRE methods, and ELECTRE II was developed in 1971 by Roy and Bertier as an improved and promoted version of ELECTRE I. ELECTRE III was developed based on the main principles of ELECTRE II, but instead of classical true criteria, it applies the pseudo-criteria and makes the presentations of the outranking relations in a fuzzy form possible [3,5,6]. These methods work based on selecting a desirable option between different alternatives meeting two separate demands including:

- Concordance preference above many evaluation benchmarks;
- Discordance preference under any optional benchmark.

The ELECTRE I method contains three concepts including a threshold value, concordance, and discordance indexes. In the ELECTRE II method, the concepts of concordance and discordance indexes incorporate weak and strong relationships that are extremely opposite relationships and result in two final rankings known as weak-ranking and strong-ranking [6]. On the other hand, ELECTRE III outperforms the former ones as it can deal with uncertain, imprecise, and inaccurate data using the fuzzy concept [7]. To sum up, although the ELECTRE method's versions differ in several aspects, for example some are designed for utilization in selection problems (such as ELECTRE I) and some are applicable for ranking purposes (such as ELECTRE II and III), and even for assignment problems (using ELECTRE TRI) all of them are included in the outranking multi-criteria decision making (MCDM) methods' family [1,3,5].

While there have been previous reviews on ELECTRE methods, this review provides a fresh perspective by consolidating and presenting up-to-date information on the topic. This review aims to provide an up-to-date understanding of the ELECTRE method and to discuss the basic concepts, principles, and steps of the ELECTRE method, along with variations and extensions proposed by researchers. Additionally, the review provides process steps of the ELECTRE method and suggests potential areas for future research. The following sections are provided to discuss the application areas of the ELECTRE methods, their advantages and disadvantages, and finally the ELECTRE principles and process steps. This comprehensive analysis provides a valuable resource for researchers, practitioners, and decision-makers seeking to explore the potential of ELECTRE methods in various domains and make informed choices about their implementation.

2. Application areas

The ELECTRE evaluation methods have manifold application areas and are widely used decision-making methods that can be applied in a vast range of areas from transport to environmental protection programs [6]. Here, to gain a better overview of the application areas, the results of a comprehensive review by Govindan and Jepsen [5] are summarized. They analyzed the literature worked based on the ELECTRE method considering different categories. The applied papers are considered here that focus on numerical research studies using the ELECTRE, developing algorithms, etc. **Table 1** shows a summary of the 13 categories of the ELECTRE application areas, and the description of the articles are included in the categories. In this study, they introduced "natural resources and environmental management (NRE)" as the most popular application area.

3. Advantages and disadvantages

The ELECTRE method is known for its various advantages, although it also exhibits certain weaknesses. This section presents a concise list of the merits and demerits associated with the ELECTRE evaluation. Considered as one of the best Multiple Criteria Decision Making (MCDM) methods, ELECTRE possesses the following strengths: it employs a simple logic; it fully utilizes the information contained in the decision matrix; it incorporates a refined computational process [8]; it utilizes an outranking approach [9]; it models imperfect knowledge by considering indifference and preference thresholds; it avoids compensating for a very poor criterion value with good values on other criteria; and its non-compensatory nature is not as extreme as other methods [9].

On the other hand, the literature identifies several

Table 1. Application areas of ELECTRE methods [5].

No	Category	Description
1	Natural resources and environmental management	The articles are between for example geology and cartography; water, land, and waste management; forestry, ecotourism, and natural reserves sub-categories.
2	Business management	The sub-categories are for instance human resources, investment decisions, performance and benchmarking, etc.
3	Energy management	The articles are about energy management within a building or for a small set of customers, etc.
4	Design, mechanical engineering, and manufacturing systems	The articles focus on product design, equipment and material selection, the setup and maintenance of production lines, and manufacturing systems.
5	Structural, construction and transportation engineering	For example, includes articles on infrastructure and housing, transportation networks' management and development, etc.
6	Logistics and supply chain management	This application area includes different sub-categories for logistics and management of supply chain, selection of supplier and location, facility layout, etc.
7	Information technology	This includes four sub-categories including e-commerce and m-commerce, software evaluation, selection of the network, etc.
8	Financial management	The articles are about for example investment and portfolio management.
9	Policy, social, and education	This category includes mainly public planning and policy decision.
10	Chemical and biochemical engineering	This category includes different problems related to designing the chemical processes and bacteria identification, etc.
11	Agriculture & horticulture	This category includes different areas related to assessing the agricultural cropping systems, crops, land-use types; animal production, etc.
121	Health, safety, and medicine	The articles are about safety management and health sector problems.
13	Other areas and non-specific applications	Other application areas (excluded from the other 12 categories) such as destination assessment in the tourism industry, architectural design, selection of cars, evaluating movies, etc.

disadvantages of the ELECTRE method, which are as follows: The use of threshold values that may be arbitrary but significantly impact the final solution [8]; the time-consuming nature of the method [10]; the uncertainty in the accuracy of the ranking obtained through ELECTRE I [11]; the inability of the method to handle purely ordinal scales, as it requires a metric scale for the discordance index to compare differences. Consequently, ELECTRE I should only be employed when numerical scales are used to code the criteria; and the possibility of encountering the rank reversal phenomenon in ELECTRE II and III methods, wherein adding or removing an alternative can reverse the ranking between two alternatives [9].

4. Principle of ELECTRE methods

In this method, a decision-making problem is considered including m alternatives (known as $A_i : i = 1, 2, ..., m$) and n criteria ($X_j : j = 1, 2, ..., n$) and n weighting factors ($w_j : j = 1, 2, ..., n$). This can be shown as an $m \times n$ decision matrix (with x_{ij} elements). Also in these methods $\sum_{j=1}^{n} w_j = 1$. A decision problem aims to select the best alternative as a result. For this, the ELECTRE methods use outranking relations between each pair of alternatives. That is to say, these methods work based on preferring an alternative to another one. This concept is shown as:

$A_i \rightarrow A_k$ (*or* A_iSA_k) *means* A_i *is preferred to* A_k

For this, A_i should:

- Be at least as good as A_k for the majority of the criteria;
- Not be significantly worse when other criteria are considered.

The second factor can be examined by using a predefined threshold. This process aims to detect the dominated and non-dominated alternatives, although it is problematic in complex problems and when the matrix does not have crisp data due to their uncertainties. For this, two kinds of comparison sets are required among the criteria in which:

- $X_j(A_i)$ is superior to $X_j(A_k)$;
- $X_j(A_i)$ is not superior to $X_j(A_k)$.

Therefore, this method separately investigates the criteria that vote and veto the preference of A_i to A_k, and these sets are called concordance and discordance tests. Concordance tests are binary tests for ELECTRE I and II which use 0 and 1 index when the test is failed and passed; respectively. Consider a criterion that aims to minimize A_i, as an example. In this situation:

- *If* $A_i < A_k$, *results in a passed concordance test;*
- *If* $A_i > A_k$, *results in a failed concordance test.*

On the other hand, the outranking relations in the ELECTRE III method are fuzzy with the values between 0 and 1 based on how far an alternative is better than another when considering a criterion.

The second test known as discordance aims to evaluate the existence of a very high opposition between alternatives and to be intended for the criteria in which the performance of A_i is worse compared to A_k. This test also can be binary or fuzzy in nature.

Both tests are necessary to gain a true outranking relation between pairs of alternatives. The results can be finalized as:

- A_i *is preferred to* A_k ($A_i \rightarrow A_k$ *or* A_iSA_k): *If both tests are passed*;
- A_i *is incomparable to* A_k ($A_i\ R\ A_k$): *Neighter* $A_i \rightarrow A_k$ *nor* $A_k \rightarrow A_i$;
- A_i *is indifferent to* A_k ($A_i\ I\ A_k$): *One is not preferred over another alternative.*

The main and fundamental concept of the ELECTRE methods is discussed above. However, there are some differences in the steps of conducting different versions of the ELECTRE due to the differences in their application of them in decision-making. For example, ELECTRE I is used for the selection problems, and ELECTRE II and III are designed for ranking purposes. The following section aims to discuss the process steps of the different ELECTRE methods more specifically [3,7].

5. Process steps

Different ELECTRE methods can differ from each other in different aspects such as the process of determination of concordance and discordance matrices, the type of outranking relations (for example binary or fuzzy), etc.

5.1 ELECTRE I process steps

Step 1. Normalizing the Decision Matrix

The $n \times m$ decision matrix X is shown in Equation (1):

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1m} \\ \vdots & \ddots & \vdots \\ x_{n1} & \cdots & x_{nm} \end{bmatrix}_{n\times m} \quad (1)$$

This step is similar to the first step in The TOPSIS method, and the attributes with various scales are transformed into comparable scales using Equation (2). This makes all the attributes similar in terms of the unit length of the vector.

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{m} x_{ij}^2}} \quad (2)$$

Step 2. Weighting the Normalized Matrix (V)

This step also is similar to TOPSIS, and aims to add the effect of weight to the decision matrix using the following method:

$$V = (v_{ij})\ \mathrm{n} \times \mathrm{m} \quad (3)$$

where $v_{ij} = w_j r_{ij}$. (4)

Step 3. Determining the Concordance and Discordance Sets

This step aims to separate the decision criteria set into two distinct subsets (C_{kl} (Concordance) *and* D_{lk} (Discordance) : $l \neq k$) for each pair of alternatives. That is to say, when two alternatives are considered, the alternatives are compared considering the type of criteria (cost or benefit types), and then based on which one is better or worse, the concordance and discordance sets are determined. For example, in a 4 × 6 matric if all attributes are positive (benefit attributes), when $C_{12} = [3,4,5,6]$, and $D_{12} = [1,2]$, then it means:

- $v_{11} < v_{21}$; $v_{12} < v_{22}$; $v_{13} \geq v_{23}$; $v_{14} \geq v_{24}$; $v_{15} \geq v_{25}$; $v_{16} \geq v_{26}$

Generally, the concordance and discordance sets are:

$$C_{kl} = \{j | v_{kj} \geq v_{lj}\}$$
$$D_{kl} = \{j | v_{kj} < v_{lj}\} = J - C_{kl}$$

Step 4. Building the Concordance Matrix

After recognizing the concordance and discordance sets, in this step, the sum values of the weights associated with the concordance set are considered as the concordance index. Other equations are also recommended by different authors. Here a simple method is introduced:

$$c_{kl} = \sum_{j \epsilon C_{kl}} w_j \quad (5)$$

considering the example in the previous step, for instance, the sum of w_2, w_3, w_4, w_5 must be placed in the c_{12} in the concordance matrix (C). This general (not symmetric) concordance matrix is shown as:

$$C = \begin{bmatrix} - & c_{12} & \ldots & c_{1n} \\ c_{21} & - & \ldots & c_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ c_{m1} & \ldots & c_{m(m-1)} & - \end{bmatrix} \quad (6)$$

Step 5. Building the Discordance Matrix

In this step, the focus is especially on the degree to which an alternative is worse than the other one (considering the pairs of alternatives). For this the discordance index should be calculated using the following equation:

$$d_{kl} = \frac{\max_{j \epsilon D_{kl}} |v_{kj} - v_{lj}|}{\max_{j \epsilon J} |v_{kj} - v_{lj}|} \quad (7)$$

and then the discordance (D) matrix is built similarly to the concordance matrix:

$$D = \begin{bmatrix} - & d_{12} & \ldots & d_{1n} \\ d_{21} & - & \ldots & d_{2m} \\ \vdots & \vdots & \ddots & \vdots \\ d_{m1} & \ldots & d_{m(m-1)} & - \end{bmatrix} \quad (8)$$

In this matrix, higher values of d_{kl} show that A_k is less favorable than A_l for the discordance criteria. In contrast, a lower value implies that A_k is favorable to A_l. In this matrix, the d_{kl} values are between 0 and 1.

Step 6. Determining the Concordance Index (Dominance) Matrix

In this step, a threshold value is considered for the concordance index. That is to say, based on a threshold value, it can be determined whether A_k have the chance of dominating A_l, when C_{kl} exceeds at least a certain value for the threshold ($\overline{c}$). That is to say:

- $c_{kl} \geq \overline{c}$

where the $\overline{c}$ can be determined in different ways. For example, it can be calculated as follows:

$$\bar{c} = \sum_{\substack{k=1 \\ k\neq l}}^{m} \sum_{\substack{l=1 \\ l\neq k}}^{m} \frac{c_{kl}}{m(m-1)} \tag{9}$$

But the threshold can be assumed 0.7 usually. Then a bloomlean matrix (F) must be constructed with the following elements:

- $f_{kl} = 1; if\ c_{kl} \geq \bar{c};$
- $f_{kl} = 0; if\ c_{kl} < \bar{c}.$

Each "one value" for the matrix elements means "the dominance of one alternative with respect to another alternative".

Step 7. Determining the Discordance Index (Dominance) Matrix

On the other hand, a similar process is conducted to build the discordance dominance matrix (G). A threshold value is considered here as well such as:

$$\bar{d} = \sum_{\substack{k=1 \\ k\neq l}}^{m} \sum_{\substack{l=1 \\ l\neq k}}^{m} \frac{d_{kl}}{m(m-1)} \tag{10}$$

Also, $\bar{d}$ can be assumed 0.3 usually. The elements of the matrix are:

- $g_{kl} = 1; if\ d_{kl} \leq \bar{d};$
- $g_{kl} = 0; if\ d_{kl} > \bar{d}.$

Step 8. Determining the Aggregate Dominance Matrix

This step aims to combine f and G matrices, and calculate the intersection of the F and G matrices called Aggregate Dominance Matrix (E) with e_{kl} elements that is gained by the multiplication of f_{kl} and g_{kl} elements in the f and G matrices:

$$e_{kl} = f_{kl} \times g_{kl} \tag{11}$$

So, the elements of the aggregate dominance matrix can have just zero or one value for $k \neq l$.

Step 9. Eliminating the Less Favorable Alternatives

Now it is time to eliminate the less favorable alternatives. The alternatives' partial-preference ordering is given in matrix E. That is to say:

- If $e_{kl} = 1$; for both concordance and discordance criteria A_k are preferred to A_i.

But it is important to note that still A_k can be dominated by other alternatives. Therefore, more comprehensive conditions must be considered to conclude that A_k is not dominated in the whole ELECTRE procedure. These conditions are as follows:

- $e_{kl} = 1$; *for at least one l*;
- $e_{il} = 0$; *for all i*.

In these conditions: $k \neq l, i \neq k, i \neq l, l\&i = 1,2,...m$. Although applying this condition can appear difficult, E matrix can be easily used to identify the alternatives with the following method:

If at least one "element of 1" is existed in any column of the E matrix; it means that "the column is 'ELECTREcally' dominated by the corresponding row(s)". Therefore, the column(s) with at least one element of 1 should be eliminated. In this step, a graphical representation of the over-ranking relationships can be also helpful to illustrate the relationships better. Consider the following $E_{example}$ matrix as the result of Step 8:

$$E_{example} = \begin{bmatrix} - & 1 & 0 & 1 \\ 0 & - & 0 & 0 \\ 0 & 1 & - & 1 \\ 0 & 1 & 0 & - \end{bmatrix}$$

In this example, the graphical representation can be shown in **Figure 1** considering the following relationships given as the result of $E_{example}$ matrix elements:

$A_1 \rightarrow A_2$, $A_1 \rightarrow A_4$, $A_3 \rightarrow A_2$, $A_3 \rightarrow A_4$, $A_4 \rightarrow A_2$

It can be concluded from the figure that A_2 and A_4 are dominated by A_1 and A_3, although the preference relationship between A_1 and A_3 cannot be obtained from this. These results also can be taken from the columns of the $E_{example}$ matrix. As A_1 and A_3 do not possess any element of 1 [3,6,8,11,12].

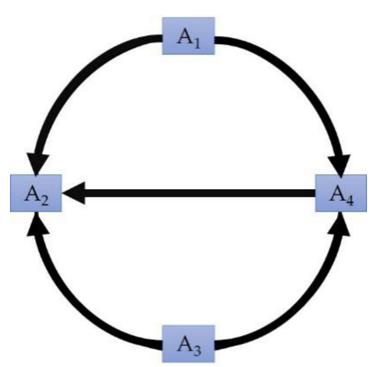

Figure 1. An example for over-ranking relationships [8].

5.2 ELECTRE II process steps

ELECTRE II is similar to ELECTRE I, but the differences are related to the definitions of two outranking relations called "strong outranking" and "weak outranking". Strong outranking and weak outranking have solid bases and questionable grounds, respectively.

Strong outranking relies on solid bases, whereas weak outranking has questionable grounds. Therefore, the result is given as an outranking graph dichotomy in weak and strong outranking graphs. The process steps of the ELECTRE I were defined in the previous sub-section in detail. Here, as some steps are similar to the ELECTRE I (such as decision matrix formation), just the main steps of the ELECTRE II are listed. The main process steps are listed following:

Step 1. Outranking Relationships Definition

This method compares the alternatives pair to pair as discussed in the ELECTRE I. The aim of this step is to define whether A_k outranks $A_l$strongly. Three concordance thresholds (α): high, medium, and low and two non-concordance thresholds (D)are used in this method. For this, the following conditions must be met:

$$\begin{cases} c_{kl} \geq \alpha^{+} \\ and \\ X_j(A_k) - X_j(A_l) \leq D_1(\text{j}), \forall \text{j} \\ \text{and} \\ \dfrac{P^{+}(k,l)}{P^{-}(k,l)} \geq 1 \end{cases} \tag{12}$$

and/or

$$\begin{cases} c_{kl} \geq \alpha^{0} \\ and \\ X_j(A_k) - X_j(A_l) \leq D_2(\text{j}), \forall \text{j} \\ \text{and} \\ \dfrac{P^{+}(k,l)}{P^{-}(k,l)} \geq 1 \end{cases} \tag{13}$$

where:

- P^{+} (k, l) is "the sum of criteria weighting of the k when it is preferable to l (considering the type of the criteria)";
- P^{-} (k, l) is "the sum of criteria weighting of the l when it is preferable to k (considering the type of the criteria)";
- $P^{=}$ (k, l) is "the summation of criteria weighting of the k when the k equals to l".
- $\alpha^{+} \geq \alpha^{0}$ (threshold values) and D_2 (j) $\leq D_1$ (j) (thresholds of discordance).

The above definitions for $P(k, l)$ are similar to Step 4 in the ELECTRE I. Considering these relations A_k strongly outranks A_l if:

- In Equation (12), the outranking equation is "strongly" concordant and "fairly" discordant;
- In Equation (13), it is "fairly" concordant and "weakly" discordant.

On the other hand, the following equation is used as the weak outranking relation to determine A_k weak outranks A_l:

$$\begin{cases} c_{kl} \geq \alpha^{-} \\ and \\ X_j(A_k) - X_j(A_l) \leq D_2(\text{j}), \forall \text{j} \\ \text{and} \\ \dfrac{P^{+}(k,l)}{P^{-}(k,l)} \geq 1 \end{cases} \tag{14}$$

where $X_j(A_k)$ is the evaluation of A_k on criterion j. In Equation (14), $\alpha^{-} \leq \alpha^{0}$, and A_k weakly outranks A_l, if:

- The relation is weakly concordant and fairly discordant.

To discuss the relations more, considering the hypothesis of the problem "A_k outranks A_l" it can be noted that:

- If $X_j(A_k) - X_j(A_l) \leq D_1(\text{j})$, then the criterion j does not possess a major opposition to the considered hypothesis, and the discordance is weak in this situation;
- If $D_2(\text{j}) \leq X_j(A_k) - X_j(A_l) \leq D_1(\text{j})$, then the criterion j does not possess a major opposition to the considered hypothesis, and the discordance is mean in this situation.

Step 2. The Concordance Coefficient Definition

Consider cases A_k and A_l are compared. The concordance coefficient/index can be determined by the following equation (similar to ELECTRE I, but here another equation is used which can be also in ELECTRE I):

$$c_{kl} = \frac{P^{+}(k,l)+P^{=}(k,l)}{P^{+}(k,l)+P^{=}(k,l)+P^{-}(k,l)} \tag{15}$$

Conditions are as follows to accept the concordance test:

$$\begin{cases} \dfrac{P^{+}(k,l)}{P^{-}(k,l)} \geq 1 \\ and \\ c_{kl} \geq \alpha^{+} \; or \; c_{kl} \geq \alpha^{0} \; or \; c_{kl} \geq \alpha^{-} \end{cases} \tag{16}$$

After defining the main concepts in the ELECTRE II, now it is time to enter the classification process.

Step 3. Constructing the Graphs

First, two separate graphs are used to show the relationships between alternatives: Strong and weak outranking graphs.

- In a strong outranking graph (G_F), the nodes of alternatives are liked, if there is a strong outranking relation between them. G_F includes Y as the set of nodes and U_F as the set of arcs between the nodes, and can be shown as $G_F(Y, U_F)$.
- In weak outranking graph (G_f), the nodes of alternatives are liked, if there is a weak outranking relation between them.

The graphs should be modified to remove the circuits which are defined as "A circuit is a set of actions in which we have, for example, action A dominates action B, action B dominates action C and action C dominates action A". In the circuits, finding the best alternatives is not possible, therefore these actions are defined as equivalent for the decision makers. After removing the circuits, a modified graph is shaped. In this graph, the circuit is replaced by one of the fictitious actions(for example instead of the ABC circuit, *A'* is used).

Step 4. Conducting the Direct Classification (Forward Ranking)

Then, the direct classification can be conducted in several iterations. the process simply is shown in **Figure 2**.

Consider **Table 2** for ranking the alternatives completed by the following steps:

1) Firstly, in $t = 1$ consider $Y(1) = Y$;

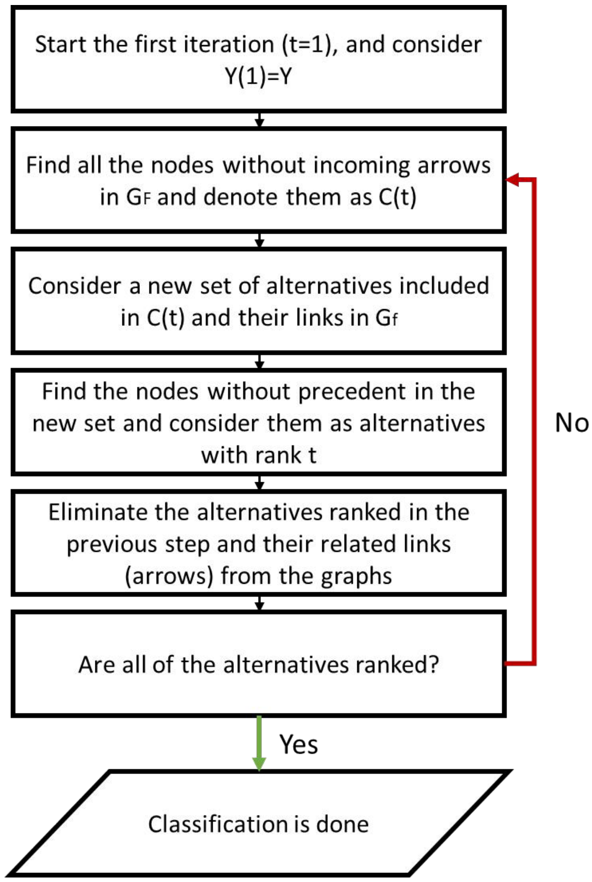

Figure 2. Direct classification process.

2) In G_F find all the nodes (alternatives) without incoming arrows (or not having a precedent). Denote them as $C(1)$.

3) Go to G_f, see the nodes in $C(1)$, and remove all the ties between these nodes and the system (you just consider the connections between the alternatives included in $C(1)$), and add the sets of links as $\overline{U_f}(t)$. Then, construct the $(C(1), \overline{U_f}(t))$ graph, and the nodes that have no precedent in this graph are the set of selected nodes in this iteration ($A(1)$) that is the non-dominated set at the first iteration. It shows the alternatives without precedent in either strong or weak outranking graphs.

4) Eliminate all the nodes and arrows related to the $A(1)$ in $Y(1)$, and consider it as $Y(2)$. Therefore in each iteration $Y(t) = Y(t-1) - A(t-1)$. That is to say, in a new iteration t (step t), the classified actions from the previous steps should be removed from the outranking graph.

5) Continue the iterations until all nodes are

ranked. In this table, lower rank means better performance, for example if *rank* (A_k) < **rank** (A_l) then A_k is better than A_l. Therefore, the action related to r_1 is the best.

Table 2. Process of ELECTRE II.

Step/Iteration (*t*)	***Y*(*k*)**	***C*(*t*)**	$\overline{U_f}(t)$	***A*(*t*)**	r_t
1	$Y(1)$				r_1
2	$Y(1) - A(1)$				r_2
⋮	⋮	⋮	⋮	⋮	⋮
Until all alternatives are ranked and eliminated	∅				r_t

Step 5. Conducting the Reverse Classification

In this step rank the actions similar to the previous step (direct ranking), but first reverse the direction of the all arrows in the strong outranking and weak outranking graphs. The results of the ranking table also must be adjusted. For example, the following equation is used for this purpose:

$$Rank\ reverse\ (A_i) = 1 + Rank(A_i)_{max} - Rank(A_i) \quad (17)$$

Step 6. Determining the Partial Preorder

Using the ranks determined in Steps 4 and 5 a partial preorder should be determined. The following points can be concluded from two classifications:

- A_k is preferred to A_l in the final preorder, if this trend can be seen in both direct and reverse preorders;
- A_k is preferred to A_l in the final classification, if it is preferred in one of the preorders, and the actions are equal in the other one;
- A_k and A_l are incomparable, when A_k is preferred to A_l in one of the preorders, and A_l is preferred to A_k in another one.

Also, special charts can be beneficial to gain global classification based on the reverse and direct classifications. In these charts x-axis and y-axis performs the inverse and direct ranks [3,6,12,13].

5.3 ELECTRE III process steps

This method is similar to the ELECTRE II method; the main difference is using the concept of pseudo-criteria instead of applying classic criteria. In this method two different thresholds are used which are indifference and strict preference thresholds. On the other hand, both concordance index and discordance index are defined in fuzzy form. According to this advantage, the ELECTRE III outperforms previous versions (I and II) in addressing imprecise, inaccurate, and uncertain data. In this method, the concept of a credibility degree or reliability of the outranking also is introduced. The result is not binary, and I is not just a choice between accepting or rejecting the alternatives. The steps are as follows:

Step 1. Determining the Required Values

For criterion j, determine three thresholds known as 1) indifference (q), 2) preference (p), and 3) veto (v) and consider $v \geq q \geq p$. Furthermore, similar to other methods, importance weights (w_j) should be also determined for the criteria. Using these thresholds, strict, indifferent, and weak relations can be identified.

Step 2. Determining Concordance Index

In this step, the concordance index should be determined first. For this the following equation which has a fuzzy form is used for criterion j, and between A_k and A_l alternatives:

$$\begin{cases} c_j(k,l) = \dfrac{X_j(A_k) + p_j - X_j(A_l)}{p_j - q_j}\ if\ q_j < X_j(A_k) - X_j(A_l) \leq p_j \\ c_j(k,l) = 1\ if X_j(A_k) - X_j(A_l) \leq q_j \\ c_j(k,l) = 0\ if\ p_j < X_j(A_k) - X_j(A_l) \end{cases} \quad (18)$$

After calculating all $c(k,l)$ values for all criteria, a global concordance index is calculated using the following equation:

$$C_{kl} = \frac{\sum_j p_j . c_j(k,l)}{\sum_j p_j} \quad (19)$$

Then this process should be applied to all pairs of alternatives, and the result is placed in the elements of a matrix called Concordance Matrix. The elements of this matrix are defined as "the percentage of criteria where one alternative is at least as good as the other". For example, if C_{kl} is 0.5, then half of the criteria A_k is at least as good as A_l.

Step 3. Determining Discordance Index

Discordance index calculation needs to define a veto (v) threshold for each criterion (v_j). When decision makers give no credibility to the outranking of alternative A_k with respect to A_l, the v_j is $X_j(A_k) - X_j(A_l)$. The index of discordance is obtained using fuzzy concept by the following equation:

$$\begin{cases} d_j(k,l) = 1 \; if \;\; v_j < X_j(A_k) - X_j(A_l) \\ d_j(k,l) = \dfrac{X_j(A_k) - X_j(A_l) - p_j}{v_j - p_j} \; if \; p_j \leq X_j(A_k) - X_j(A_l) \leq v_j \\ d_j(k,l) = 0 \; if \; X_j(A_k) - X_j(A_l) < p_j \end{cases} \tag{20}$$

In this step, all discordance indices should be calculated for all pairs of alternatives considering all criteria.

Step 4. Determining the Outranking Credibility Degree and Building Credibility Matrix

Now a concordance and discordance measure is available for each pair of alternatives for each criterion. But, these measures must be combined to gain an outranking degree and assess the reliability of the hypothesis criteria A_k is at least as good as A_l ($A_k SA_l$). This is possible using a credibility degree concept. Credibility is calculated as follows:

$$S(k,l) = \begin{cases} C_{kl} \; if \; d_j(k,l) \leq C_{kl} \\ C_{kl} \cdot \prod_{j \in \overline{F}} \dfrac{1 - d_j(k,l)}{1 - C_{kl}} \end{cases} \tag{21}$$

$\overline{F}$ is the set of criteria by which $d_j(k,l) > C_{kl}$. According to the credibility, it is assumed that when $d_j(k,l) \leq C_{kl}$, the C_{kl} should not be modified, but else the effect of $d_j(k,l)$ should be considered for outranking as the hypothesis should be questioned, and C_{kl} needs a modification. On the other hand, if $d_j(k,l) = 1$, then there is no confidence to say that criteria A_k is at least as good as A_l, and credibility for this criterion and pair of alternatives is zero. The values of $S(k,l)$ can be put into a matrix called Credibility Matrix in this step as well. This matrix then will be used for ranking step.

Step 5. Descending and Ascending Distillations (Exploitation Step)

Similar to the ELECTRE II method, two preorders (descending and ascending distillations) are determined in this step.

Descending distillation process

Similar to the direct outranking in the ELECTRE II, this process is a step-by-step which starts with the first iteration and ends when all the alternatives are ranked. Also, descending distillation determines the best alternative first, and ends with finding the worst one. But, the basic here is to set a qualification score for the alternatives. For this, a discrimination threshold ($s(\lambda)$, $0 < \lambda < 1$) should be set. For example, the following equation can be used for determining $s(\lambda)$:

$$s(\lambda) = 03 - 0.15\lambda \tag{22}$$

Now, Use the following process (shown simply in **Figure 3**) to define the qualifications of alternatives:

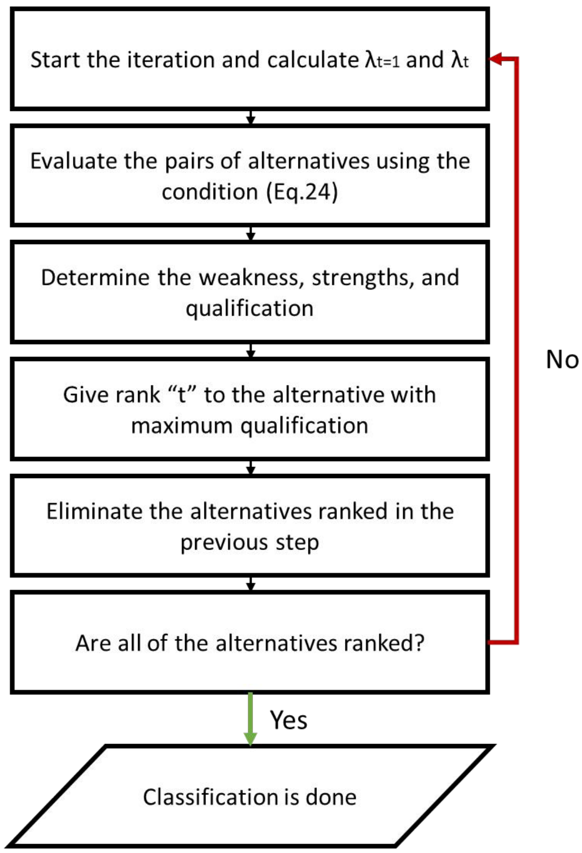

Figure 3. Descending distillation process.

- For the first iteration, set $\lambda_0 = \max_{k,l \in A} S(k,l)$, then use the following equation to gain a cutoff level of outranking (λ_1):

$$\lambda_1 = \max_{k,l \in A} S(k,l) \; where \; S(k,l) < \lambda_0 - s(\lambda_0) \tag{23}$$

That is to say, λ_1 is "the largest outranking score which is just less than the maximum outranking score minus the discrimination threshold".

- Then, consider the following equation for the pair of alternatives in the first iteration:

$$A_k S A_l \; iff \begin{cases} S(k,l) > \lambda_1 \\ and \\ S(k,l) - S(l,k) > s((k,l)) \end{cases} \tag{24}$$

Both conditions should be applied for all pairs of alternatives in this step. For the result of these evaluations, give 1 value (strength) to an alternative every time it outranks another alternative, and –1 value (weakness) when it is outranked by another alternative. The sum of these values in each iteration gives the qualification of the alternatives. The alternative with the maximum qualification is the ranked alternative in this iteration. It must be noted that if there are more than one alternative with similar maximum values, this step must be repeated (but considering a matrix just with the alternatives have the maximum qualification) to choose the best between them as the ranked alternative in the iteration one. Although, if they gained similar qualifications again, they can be considered as alternatives with similar ranks.

Another similar method can be also used for describing the qualification values in each iteration (t). The following indicators can be used to show the number of alternatives that are outranked by A_k (($p_A^{\lambda_t}(A_k)$), the number of alternatives that outrank A_k(($f_A^{\lambda_t}(A_k)$), and the qualification of A_k ($q_A^{\lambda_t}(A_k) = p_A^{\lambda_t}$); respectively:

$$p_A^{\lambda_t}(A_k) = card(\left\{A_l \in A \middle| A_k S_A^{\lambda_t} A_l\right\}) \quad (25)$$

$$f_A^{\lambda_t}(A_k) = card(\left\{A_l \in A \middle| A_l S_A^{\lambda_t} A_k\right\}) \quad (26)$$

$$q_A^{\lambda_t}(A_k) = p_A^{\lambda_t}(A_k) - f_A^{\lambda_t}(A_k) \quad (27)$$

- For the second iteration, eliminate the ranked alternative/alternatives from the credibility matrix. Similar to the previous step, calculate $\lambda_1 = \max_{k,l \in A} S(k,l)$, and then gain the cutoff level of outranking (λ_2) (apply Equation (23) for λ_1 and λ_2). Then, compare the pairs of alternatives using the conditions presented in Equation (24) similar to the previous step. Gain the second ranked alternative/s.
- Repeat the process until all alternatives are ranked, and gain the list of alternatives' ranking considering in the descending distillation process the alternative/s ranked in the first iteration is/are the best.

Ascending distillation process

This process is similar to the descending distillation, but the difference is that in each iteration the alternative with the minimum qualification is chosen, and eliminated in the next iteration. Therefore, alternatives are ranked from the worst to the best.

Step 6. Final Preorder

In the final step, the ranking results of two distillation processes must be combined to gain a unit ranking list (similar to the ELECTRE II method) [7,12].

6. Conclusions

In conclusion, the ELECTRE method is a versatile and widely-used multi-criteria decision-making method with various applications across different fields. The advantages of this method include its ability to handle imprecise and uncertain data, its flexibility in accommodating various decision-making scenarios, and its robustness in dealing with complex and conflicting criteria. However, like any other MCDM method, the ELECTRE method also has its limitations, such as the need for a considerable amount of input data, the subjectivity of the decision-maker's preferences, and the potential for inconsistent results.

The process steps of the ELECTRE method involve careful consideration and analysis, including defining the problem, identifying the criteria and alternatives, assessing the criteria's importance, evaluating the alternatives' performance, and generating the ranking of alternatives based on the outranking principle. There are different versions of the ELECTRE method specifically designed for different purposes, such as selection and ranking problems, but they all share the same core strategy and process steps.

This paper provides a comprehensive overview of the ELECTRE method, its applications, and its main characteristics. Additionally, it aims to provide step-by-step processes to describe the ELECTRE I, II, and III methods in a simple and easy-to-understand manner. By understanding the fundamental concepts, applications, advantages, and limitations of the ELECTRE method, decision-makers can make informed and effective decisions in various contexts. While the review provides a general overview of its applications, the absence of detailed real-world examples limits the ability to assess the method's effectiveness and identify potential challenges or areas for improvement in specific contexts. Including more case studies or empirical evidence could provide valuable insights and enhance the manuscript's practical relevance. Future research can focus on improving the ELECTRE method by addressing its limitations and developing more efficient and accurate approaches for decision-making.

Author Contributions

Conceptualization, H.T.; methodology, H.T.; validation, H.T.; formal analysis, H.T. and M.M.; resources, H.T. and M.M.; data curation, H.T.; writing—original draft preparation, M.M. and H.T.; writing—review and editing, M.M.; visualization, H.T. and M.M.; supervision, H.T. All authors have read and agreed to the published version of the manuscript.

Conflict of Interest

There is no conflict of interest.

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ARTICLE

Understanding Applications and Best Practices of DEMATEL: A Method for Prioritizing Key Factors in Multi-Criteria Decision-Making

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ABSTRACT

Decision Making Trial and Evaluation Laboratory (DEMATEL) method is a powerful tool for understanding and visualizing the causal relationships among factors in complex decision-making problems. The method uses diagrams and matrixes to map out the causal relationships and interdependencies among factors, allowing decision-makers to identify key drivers and potential solutions to the problem. DEMATEL has a wide range of application areas, including supply chain management, environmental planning, healthcare, finance, and engineering, among others. The DEMATEL method is a valuable tool for decision-makers who need to understand the complex causal relationships among factors in order to make informed decisions. The method provides a structured approach for analyzing and prioritizing factors and for identifying potential solutions to complex problems. This paper describes the main features of this method, its application areas as well as the main process steps in the DEMATEL method.

Keywords: Decision making; Multi criteria decision making; Multi attribute decision making; DEMATEL; Decision making trial and evaluation laboratory

1. Introduction

Decision making trial and evaluation laboratory (DEMATEL) technique is one of the main multi-criteria decision-making (MCDM) methods that is used to visualize complex causal relationships' structures through its diagrams or matrixes. This MCDM method was developed in the "Geneva Research Centre of the Battelle Memorial Institute" at the end of 1971 by Gabus and Fontela [1] initially. This method has

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received promising attention from many researchers for solving complex decision-making problems in various fields in the past decades [2].

The DEMATEL method works based on structural modeling that is beneficial to analyze cause and effect relationships of the systems' components. In this method, the interdependence among factors can be confirmed, and intertwined and complicated problems can be investigated and addressed. Furthermore, in these problems, the DEMATEL method develops specific maps (charts or diagrams) in order to reflect relative relationships within factors. In this technique, an impact relation diagram is used to find the factors that possess a critical role in a system with a complex structure, and then the priorities of the clarified key factors are determined. In addition, the interdependency relationships are converted into cause and effect groups by using the matrixes. In this process, the end product is called an IRM (the Impact-Relations Map) which is a visual demonstration. The relationship between the criteria's causes and effects is converted into the system's structural and understandable model.

The DEMATEL method can be used to verify interdependence among unpredictable attributes and features and can help to gain a better understanding of practical solutions for problems and complex clusters. It quantifies the relevant degrees/relationships between different elements resulting in understanding the relational structures that help to solve a decision problem. The DEMATEL is based on the vision of using scientific research approaches to enhance the understanding of a particular problem.

The application of feedback is one of the merits of this method compared with others, and all of the factors (instead of just some specific ones) are considered in the structure of this MCDM method [3]. Its objective is to investigate, compare, and enhance the factors of the system by dividing them into the groups of cause-effect. The factors' influences on the other ones are examined numerically to find the most effective ones. That is to say, the improvement of cause-groups results to easily improve the effect-group's criteria, and the features of the cause-group can impact the effect group's aspects simply. Therefore, it is a suitable method for managers who aim to gain high-performance based on the criteria of the effect group in different businesses [2,4].

2. Application

The DEMATEL can be applied to a vast range of MCDM problems from computer science to energy and economics [3]. The distribution of research articles using the DEMATEL method based on subject area is shown in **Figure 1**. This distribution is gained from the search results for "DEMATEL" in the "ScienceDirect" database based on the articles that include "DEMATEL" in their "title, abstract, or keywords". The results show the application of the DEMATEL method in different subject areas.

Si et al. [2] reviewed the application areas of the DEMATEL in their study. They classified the studies based on classical (traditional) DEMATEL into three categories including:

- Type 1: Based on the interrelationships between factors or criteria;
- Type 2: Based on determining the key factors considering the causal relationships and interrelationship degree between the factors;
- Type 3: Gaining the weights of criteria by considering the interrelationships and impact levels of criteria.

Some examples of the reviewed articles are provided in **Table 1** to gain a better overview of the details of the studies. They also provided the results of DEMATEL application areas as the distribution of the studies in different application areas. Their results identified the main top three areas as computer science (40.6%), engineering (35.7%), and business and management based on the search methodology that they used to identify the articles (26.4%) [2].

3. Advantages and disadvantages

Like all developed methods, the DEMATEL method possesses both advantages and disadvantages. The main ones are listed in **Table 2**. Due to the listed disadvantages of DEMATEL, many authors

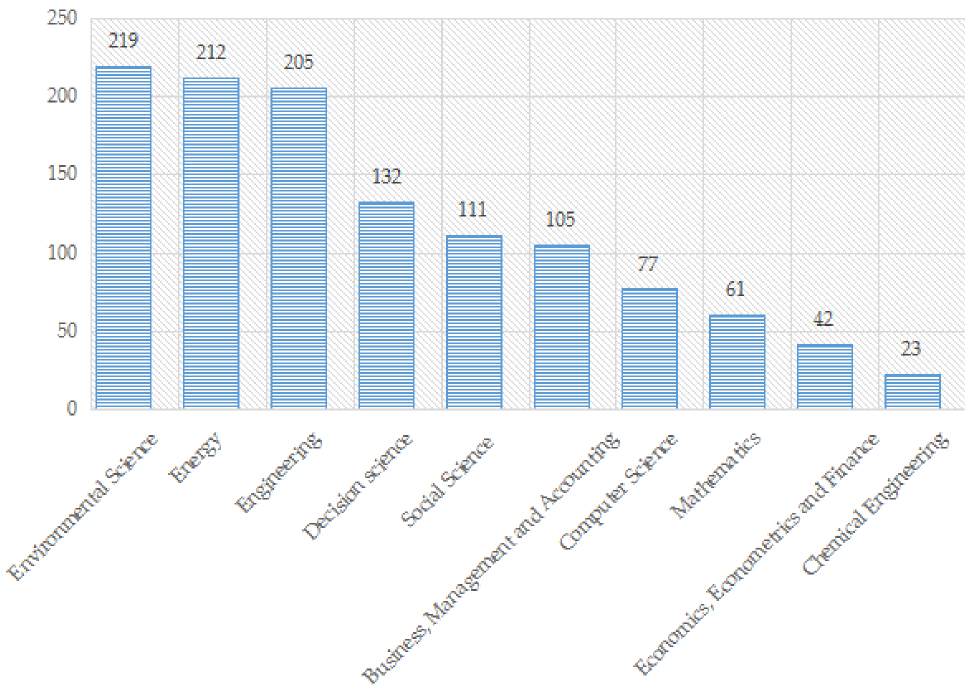

Figure 1. Distribution of DEMATEL application areas.

Table 1. Examples of DEMATEL applications.

Type	**Purposes of studies**
Type-1: Interrelationships	● Determining the degree of the perceived values for patients for healthcare management; ● Analyzing the components and dimensions of intelligence in universities based on the cause-effect relations; ● Recognizing the interrelationships between different evaluation criteria in specific zones of the railways; ● Determining the relationships between the factors of customer buying, and providing marketing strategies in a specific market; ● Proposing a model for job satisfaction for a specific industry by considering interactive influences of criteria and the causal relationship of them.
Type-2: Interrelationships and key factors	● Identifying and prioritizing the factors (both affected by and affecting) the enterprises' performances; ● Analyzing the relationships of cause and effect for barriers of a specific industry; ● Determining the causal relationships between main evaluation indicators, and gaining the most strategic ones for the industries' (such as banking's) performances; ● Identifying the causal relationships of factors, and prioritizing them to gain the significant factors for allocation of the resources in organizations.
Type-3: Interrelationships and criteria weights	● Recognizing the cause-effect relationship and evaluating the critical ones for specific processes in industries for example CO_2- capture and storage in the steel industry; ● Calculating the relative importance weights for compensatory objective functions; ● Recognizing the importance degree of design parameters in a process for example for website design; ● Computing global weights for the evaluation indicators to select investing strategies in a specific sector.

Table 2. Merits and demerits of DEMATEL.

Advantages	Disadvantages
● Analyzing direct and indirect mutual influences among factors; ● Understanding complex and complicated cause-and-effect relationships; ● visualizing the interrelationships between different factors by utilizing an IRM; ● Perceiving the factors that possess mutual impacts (influences) on others; ● Utilizing to find out the critical criteria for evaluation; ● Being able to measure the evaluation criteria's weights; ● Assuming the criteria dependent; ● Rational weighting for practical problems considers different weights for each cluster in the weighted super-matrix instead of using equal weights in some other methods.	● Although this method considers the interdependent relationships among alternatives, does not incorporate other criteria among them; ● Does not consider the alternatives' aspiration level; ● Does not reach the alternatives' partial ranking orders; ● Does not consider the experts' relative weights to aggregate their personal judgments into group assessments.

recommend using integrated methods based on DEMATEL and other techniques to address its demerits and benefit from their combined properties [2].

4. DEMATEL process steps

The DEMATEL method can be applied in six main steps. These steps are shown in **Figure 2** and are described as follows.

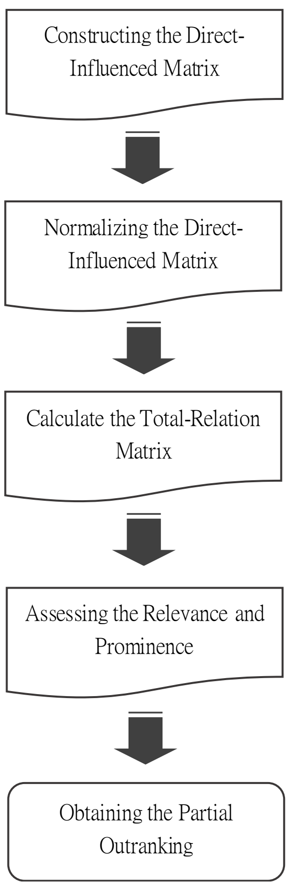

Figure 2. DEMATEL process steps.

Step 1. Average (Direct-relation) Matrix Generation.

In a problem with n criteria (factors), an n×n matrix (A_k) can be gained from the K^{th} expert's questionnaire/opinion. In this matrix $a_{ij}(k)$ is the influence degree of criterion E_i on criterion E_j determined by the K^{th} experts. For this decision-makers use a five-level pairwise comparison scale. In this score:

- 0 is for no influence.
- 1 is for low influence.
- 2 is for middle influence.
- 3 is for high influence.
- 4 is for very high influence.

Therefore, these elements create the A_k matrix as Equation (1):

$$A_k = \begin{bmatrix} 0 & \cdots & a_{1n}(k) \\ \vdots & \ddots & \vdots \\ a_{n1}(k) & \cdots & 0 \end{bmatrix} \tag{1}$$

If we consider the number of experts as m, then the average matrix Z can be obtained by averaging the scores of the experts. For this:

$$z_{ij} = (a_{ij}(1) + a_{ij}(2) + \ldots + a_{ij}(k) + \ldots + a_{ij}(m))/m \tag{2}$$

and the average matrix Z is gained as Equation (3):

$$Z = \begin{bmatrix} 0\ldots & z_{1j}\ldots & z_{1n} \\ \vdots & \vdots & \vdots \\ z_{i1}\cdots & z_{ij}\cdots & z_{in} \\ \vdots & \vdots & \vdots \\ z_{n1}\cdots & z_{nj}\cdots & 0 \end{bmatrix} \tag{3}$$

Step 2. Normalization of the Direct-Relation Matrix.

In this step, Equation (4) is used first:

$$\mathrm{S} = \max\left(\sum_{j=1}^{n} z_{ij}, \sum_{i=1}^{n} z_{ij}\right) \tag{4}$$

and then the normalized matrix X is:

$$X = Z/S \tag{5}$$

Step 3. Creation of Total Relation Matrix.

In this step matrix X that can just indicate the direct-relations should be turned into a total-direction or an aggregate relation matrix. For this, a continuous decrease of the problem's indirect effects besides the power of matrix X can make convergent solutions to the matrix inversion possible. This is similar to the absorbing Markov chain matrix. For this, Matrix Total ($T_{n\times n}$) is obtained as:

$$\begin{aligned} \mathrm{T} &= \sum_{q=1}^{\infty} X^i = X + X^2 + \ldots + X^q = X(I + X + X^2 + \ldots + X^{q-1}) \\ &= X(1-X)(1-X)^{-1}(I + X + X^2 + \ldots + X^{q-1}) \\ &= X(1-X)^{-1}(1-X^q) = X(1-X)^{-1}(1-X^{\infty}) \\ &= \frac{X}{(1-X)} \end{aligned} \tag{6}$$

In Equation (6), $\lim_{q\to\infty} X^q$ is considered the null matrix ($[0]_{n\times n}$), and the identity matrix is shown as I. Therefore $T_{n\times n}$ is:

$$T_{n\times n} = \begin{bmatrix} t_{11}\cdots & t_{1j}\cdots & t_{1n} \\ \vdots & \vdots & \vdots \\ t_{i1}\cdots & t_{ij}\cdots & t_{in} \\ \vdots & \vdots & \vdots \\ t_{n1}\cdots & t_{nj}\cdots & t_{nn} \end{bmatrix} \; where\; i,j = 1,2,\ldots,n \tag{7}$$

Step 4. Assessing the Relevance and Prominence.

In Equation (7), t_{ij} is the total influence (including both direct and indirect-influences) from the criterion E_i to E_j. To determine the relevance, the summation of all rows and columns must be calculated by using the following equation:

$$D = [D_i]_{n\times 1} = [\textstyle\sum_{j=1}^{n} t_{ij}]_{n\times 1} \tag{8}$$

$$R = [R_j]_{1\times n} = [\textstyle\sum_{i=1}^{n} t_{ij}]_{1\times n} \tag{9}$$

In Equations (8) and (9), considering $i = j = k$ the influence of criteria as well as the total extent of being influenced called "prominence" can be calculated by $D_k + R_k$ (which is the X-axis). In other words, the prominence shows the degree of being influenced by other elements and influences them as well. $D + R$ also is the central role degree that the elements play in the system. On the other hand, $D - R$ (called "relation") is the vertical axis vector demonstrating the net effect that the factor contributes to the system. The relation can be positive or negative. When $D_k - R_k$ is:

- Negative, the criterion has the tendency toward falling under the causal category (cause-group);
- Positive, the criterion has the tendency toward falling under the result category (effect-group).

Step 5. Setting a Threshold, and Drawing the Diagrams.

In this step, an IRM is created. The creation of IRM is based on the mapping of ($D_k + R_k$, $D_k - R_k$) database that adds beneficial insights to the decision-makers. In some situations, however, the IRM can be so complicated and complex that if all of the relations are added, it makes showing the valuable information to the decision-makers hard. In this situation, a threshold value must be set to describe the structural relationship among the criteria and manage complex and complicated problems better. This is used to filter the negligible effects in the T matrix. Therefore, only the values (t_{ij}) in the total relation matrix that are greater than the threshold are considered to show the influences in the cause-effect diagram. For example, t_{ij} is greater than threshold value then criterion E_j affects criterion E_i, and t_{ij}. If it is less than it, then this value is not selected and not converted in the IRM. This threshold value can be determined by using different methods such as experts' discussions, brainstorming, the results of literature, averaging the values in T matrix, and also a method called the maximum mean deentropy (MMDE) (MMDE steps and a numerical example are described in Chen's work [5]). In low threshold values, the vital information cannot be shown as the diagram can be very complex. In high values, on the other hand, many criteria can be considered independent, and their relationships with other criteria cannot be shown. Therefore, it is important to choose an appropriate value to gain a suitable diagram for cause and effect.

After recognizing the criteria relations (by using the threshold value), a network diagram can be drawn to show the relationships between the criteria simply. Furthermore, in the cause-effect diagram, ($D + R$) is set for the X-axis, and ($D - R$) for the Y-axis. The cause-effect diagram can demonstrate the complicated causal relation. The examples of the important diagrams gained from the DEMATEL are shown in **Figures 3 and 4**. **Figure 3** is an example of a network diagram that shows the relationship between the criteria in the situation that t_{12}, t_{13}, t_{31}, t_{34}, t_{43}, t_{54}, t_{15}, > *thresholdvalue*. In the IRM (**Figure 4**), generally calculating $(D + R)$ divides the diagram into four parts that give valuable visions to the decision-makers:

- Quadrant 1 includes factors with high relation and prominence that are core factors or intertwined givers;
- Quadrant 2 includes factors with high relation and low prominence that are called driving factors or autonomous givers;
- Quadrant 3 includes factors with both low relation and prominence that are called independent factors or autonomous receivers as they are relatively disconnected from the system;
- Quadrant 4 includes low relation but high prominence that are known as impact factors or intertwined receivers. These factors cannot be enhanced directly and must be influenced by other ones.

Also, the causality diagram of criteria can be drawn with $(D_k + R_k, D_k - R_k)$ values and by using the relationships shown in **Figure 3** (see an example provided in Chen's work [5]).

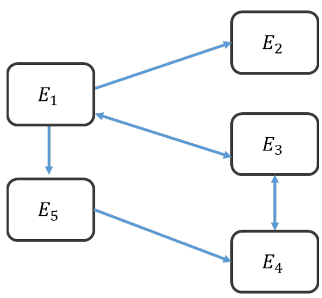

Figure 3. An example of a network diagram.

In addition, the weights of the criteria (W) can be obtained by Equations (10) and (11) [2,5,6].

$$W_{ia} = \sqrt{(D_i + R_j)^2 + (D_i - R_j)^2} \tag{10}$$

$$W_i = \frac{W_{ia}}{\sum_{i=1}^{n} W_{ia}} \tag{11}$$

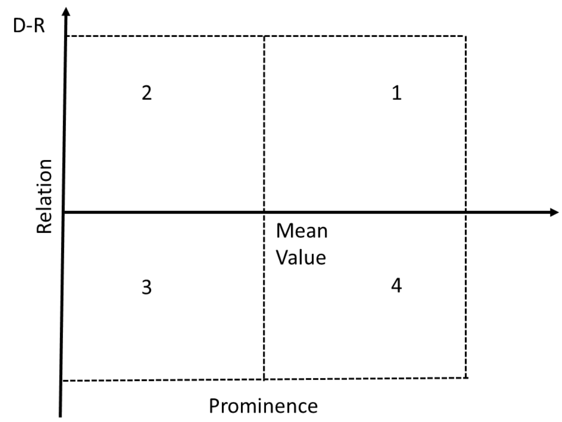

Figure 4. IRM with four quadrants.

Source: Adapted from a work by Si et al. [2].

5. Conclusions

DEMATEL is one of the main MCDM methods working based on structural modeling that is beneficial for analyzing cause and effect relationships of the systems' components [3]. This paper provided a survey on the DEMATEL application areas, advantages, and disadvantages, as well as the process steps. This method is beneficial in a vast range of application areas such as engineering, computer science, mathematics, social and decision science, business and management, etc. This method obtained an IRM as the result that provides very helpful information to the decision-makers. The DEMATEL method can be particularly useful in addressing complex and intertwined problems where the interdependency among factors is not straightforward. The method's ability to develop specific maps or diagrams to reflect the relative relationships within factors makes it a powerful tool for decision-making. Additionally, the method's feedback feature and consideration of all factors in the system's structure make it a suitable option for managers aiming to improve their business's performance. While the DEMATEL method has some limitations, such as the need for expert knowledge and the time required for data collection and analysis, its benefits make it a valuable tool in addressing complex decision-making problems. Overall, the DEMATEL method is a powerful and versatile tool for decision-making in various fields and can contribute to improving the understanding of complex systems' structures.

Author Contributions

Conceptualization, Hamed Taherdoost; methodology, Hamed Taherdoost, & Mitra Madanchian; formal analysis, Hamed Taherdoost; resources, Mitra Madanchian; writing—original draft preparation, Mitra Madanchian; writing—review and editing, Hamed Taherdoost; visualization, Mitra Madanchian; supervision, Hamed Taherdoost.

Conflict of Interest

There is no conflict of interest.

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ARTICLE

The Impact of Information Technology on Service Quality, Satisfaction, and Customer Relationship Management (Case Study: IT Organization Individuals)

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ABSTRACT

Recent research and studies have shown that Information Technology (IT) has a significant impact on service quality, customer satisfaction, and customer relationship development. With the proliferation and penetration of technology in all aspects of life, organizations are responding to the implications and opportunities that IT creates in relation to customer services. The main objective of using information technology in organizations is to increase customer satisfaction, service quality, and customer relationship management, which the authors will focus on here. Enhancing service quality, improving customer satisfaction, and establishing close and sustainable customer relationships are key advantages of leveraging information technology in this field. This article examines the impact of information technology on service quality, customer satisfaction, and customer relationship development and provides strategies and models for organizations to improve customer satisfaction and establish closer connections with them through the use of information technology. Seventy individuals from the IT field were used to evaluate the proposed model. The proposed model was compared with three models: SEM, regression, and decision tree, and the results demonstrated better performance of this approach.

Keywords: Information technology; Service quality; Customer relationship; Customer satisfaction; Improvement and development

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1. Introduction

In today's competitive business environment, organizations increasingly recognize the significant impact of Information Technology on customer services. Advances in information technology have transformed the way organizations interact with customers, leading to improved service quality, increased customer satisfaction, and the development of stronger customer relationships. The use of IT tools and systems provides organizations with new opportunities to understand customer needs, deliver personalized services, and create a seamless customer experience. Customer service quality has become a critical factor for the success and sustainability of businesses in various industries. Businesses strive to leverage IT capabilities to improve service delivery, optimize customer interactions, and establish customer loyalty. By integrating information technology into customer service processes, organizations can optimize operations, leverage real-time insights into customer preferences, and customize their offerings to meet individual needs [1]. Furthermore, customer satisfaction is a key performance indicator for organizations. Satisfied customers are more likely to become loyal customers, spread a positive reputation, and contribute to overall business growth. Information technology plays a vital role in empowering organizations to exceed customer expectations by providing quick access to information, personalized recommendations, and efficient problem-solving. **Figure 1** illustrates the varying potential impact of IT on customer service, depending on the extent of transformation (automation) of marketing and/or operations activities within firms. This distinction is depicted through two dimensions: customer focus and operations focus. Firms with a customer focus possess the capability to utilize IT to transform marketing and customer service activities, directly catering to customers' expectations in product marketing and offering additional services.

Establishing and maintaining strong customer relationships is also a critical aspect that organizations seek to achieve. Effective communication, timely responsiveness, and personal engagement are crucial in developing long-term relationships with customers. Information technology tools such as Customer Relationship Management (CRM) systems, social media platforms, and online customer portals enable organizations to facilitate continuous and meaningful interactions with customers, enhancing trust, loyalty, and long-term partnerships [2]. The objective of this article is to examine the impact of information technology on service quality, customer satisfaction, and customer relationship development. By analyzing existing research, practical case studies, and industry trends, this article provides a comprehensive view of strategies, frameworks, and models that organizations can leverage to effectively utilize information technology in improving their customer services. Through the analysis of existing research, practical case studies, and industry trends, this article offers valuable insights for organizations seeking to optimize their IT investments and implement customer-centric approaches [3]. **Figure 2** illustrates the main functions of information technology in addressing customer needs.

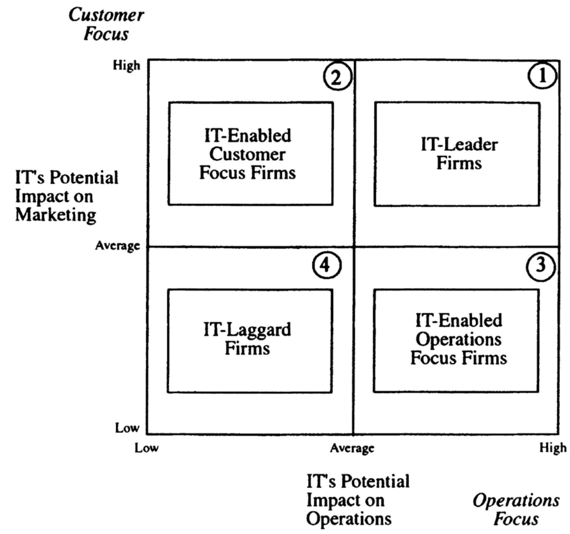

Figure 1. Customer service technology.

2. Analytical model for the impact of information technology on customer services

In this section, we present a comprehensive analytical model for examining the impact of informa-

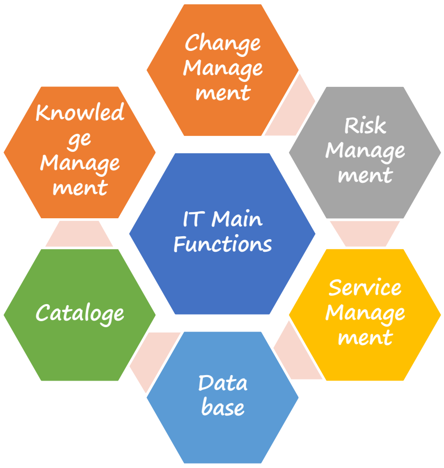

Figure 2. Key functions of information technology in customer needs.

tion technology on customer services. This model encompasses key factors that can enhance and improve customer services under the influence of information technology. An appropriate analytical model should consider various factors that, in interaction with each other, determine the impact of information technology on customer services. **Table 1** provides a summary of the factors and their descriptions in the analytical model of information technology [4].

Information Technology Factors: In this section, we identify factors related to information technology. This includes IT infrastructure, software, information systems, and emerging technologies such as artificial intelligence and the Internet of Things (IoT).

Organizational Factors: In this section, we identify organizational factors that can impact IT activities and customer services. These include organizational strategies and goals, organizational structure, organizational culture, and leadership.

Customer Factors: In this section, we identify customer factors that influence the use and satisfaction of IT services. This includes customer needs and expectations, user experience, customer behavior, and customer feedback.

Operational Factors: In this section, we identify factors related to organizational operations that can impact the delivery of IT services to customers. This includes processes, systems, technologies, and operational performance.

Environmental Factors: In this section, we identify external environmental factors that can influence the use of information technology and customer services. This includes economic factors, laws and regulations, competition, and industry trends [5,6].

3. Customer focus with the use of information technology

In this section, we examine the impact of using information technology on improving customer focus. This includes utilizing customer data and information to better understand their needs and expectations, providing customized services and personalization, and enhancing communication and customer interactions. The use of information technology in organizations can have a significant impact

Table 1. Description of analytical model dimensions.

Factor	Description	Example
IT agents	IT infrastructure, software, information systems, emerging technologies	Using CRM software to manage relationships with customers
Organizational factors	Organizational strategies and goals, organizational structure, organizational culture, organizational leadership	Creating a customer service culture in the organization
Customer agents	Customer needs and expectations, user experience, customer behavior, customer feedback	Designing a user-friendly website and providing online support options for customers
Operational factors	Processes, systems, technologies, operational functions	Using barcode readers in stores to speed up the process of serving customers
Environmental factors	Economic factors, laws and regulations, competitions, industrial developments	Changes in customer information protection laws and their impact on the use of information technology in the field of customer service

on improving customer focus. By creating appropriate management systems and tools, organizations can experience continuous improvement in customer focus. With information technology, organizations will be able to gather and analyze comprehensive and accurate information about their customers. This information includes preferences, needs, behaviors, and customer responses, which help the organization make necessary improvements in its services and products. Furthermore, information technology enables solutions such as online platforms, mobile applications, and modern communication methods, allowing organizations to directly and effectively engage with their customers [7]. These direct communications between the organization and customers can facilitate dynamic and two-way interactions, helping the organization precisely address customer needs and desires. Additionally, information technology can assist organizations in providing personalized services to customers, as accessing comprehensive information about customers enables the organization to identify their precise needs and preferences and customize their services accordingly. As a result, using information technology as a powerful tool can support organizations in improving customer focus and delivering better services to them [8]. **Table 2** provides a summary of the relationship between the organization's IT level and the level of customer focus.

4. Focus on operations with the use of information technology

In this section, we examine the impact of using information technology on improving organizational operations and customer services. This section includes utilizing IT processes and systems to enhance efficiency, reduce costs, increase the speed and quality of operations, and deliver services to customers [9].

Information technologies can assist companies in improving and effectively managing their operational processes. The following examples and table provide a comprehensive explanation of these impacts. For instance, a manufacturing company utilizes information technology to improve its production operations. By employing Enterprise Resource Planning (ERP) systems, self-diagnostic systems, and automated production systems, the company can enhance its production processes and manage them more intelligently. These technologies enable the company to reduce production time, decrease costs, improve product quality, and enhance overall performance. Therefore, the focus on operations with the use of information technology in this company has resulted in improved efficiency and performance. **Table 3** illustrates different levels of progress and maturity in IT management based on the utilization of various systems. Additionally, using an example, the impact

Table 2. The relationship between the organization's IT level and the level of customer focus.

The level of development of information technology management	Effect on improving customer focus	Example
Low level	Unstable customer relations and inability to provide personalized services and improve customer needs and preferences	An organization that manages information technology in a limited way using traditional tools. For example, limited use of separate systems and decentralized customer information
Middle level	The power to improve access to customer information, better identify their needs and preferences, and provide personalized services based on them	An organization that has improved some advanced IT processes and systems. For example, using CRM software to manage customer relationships and analyze customer data
High level	Access to comprehensive data and advanced customer analysis, identifying customer patterns and behaviors and providing personalized services and targeted offers	An organization that comprehensively and strategically uses information technology and considers it as a key factor in its business strategy. For example, artificial intelligence systems for advanced data analysis and customer behavior prediction

Table 3. The effect of using information technology on improving focus on operations.

The level of development of information technology management	Impact on improving focus on operations	Example
Low level	Reducing efficiency, increasing costs and errors in operations	An organization that uses manual and traditional methods in its operations
Middle level	Improving operation efficiency, reducing costs and errors, improving quality	An organization that uses information management systems and automation systems
High level	Improving general performance, improving efficiency, reducing costs and errors, improving quality	An organization that uses production automation systems and intelligent systems

of each level on improving the focus on operations is explained.

5. Mathematical models

In this section, mathematical models, assumptions, and analytical methods are utilized to quantitatively measure the various effects of information technology on the examined variables. Mathematical models can include regression equations, structural models, or decision models. Through appropriate analytical methods, the relationships and impacts between different variables are quantitatively examined and analyzed to provide evaluative results and inferences for enhancing customer services [10].

5.1 Regression model

This model examines the impact of information technology on service quality and customer satisfaction using dependent and independent variables. By analyzing regression coefficients, the effectiveness and significance of different variables on the dependent variables under investigation are determined. Regression analysis is a statistical method used to examine the relationship between a dependent variable and one or more independent variables. In this case, focusing on the impact of information technology on service quality and customer satisfaction, we will explore the regression model. The general formula for the regression model is as follows [9]:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_k X_k + \varepsilon \quad (1)$$

In this formula:

Y represents the dependent variable (e.g., service quality) that we want to examine its impact.

X_1 to X_k are the independent variables (e.g., information technology) whose effects on Y are being investigated.

β_0 is the intercept or the constant term that determines the starting point of the regression line.

β_1 to β_k are the regression coefficients, indicating the direct impact of each independent variable on the dependent variable.

ε represents the error term or uncontrolled factors that may affect the dependent variable. By analyzing the coefficients β_1 to β_k and evaluating their significance (using statistical tests such as t-test or F-test), we can conclude whether information technology has a significant impact on service quality and customer satisfaction. Additionally, by interpreting the sign and magnitude of the regression coefficients, we can infer the direction and strength of the influence of each independent variable on the dependent variable [5].

5.2 Structural equation model

This model investigates complex relationships and interactions among variables. By employing structural equation models, direct and indirect relationships between information technology, service quality, customer satisfaction, and customer relationship development can be modeled and analyzed. Structural Equation Modeling (SEM) is a complex statistical method used to examine the relationships between variables and investigate the interrelationships among variables in a predictive model. In this case, focusing on the impact of information technology on service quality and customer satisfaction, we will explore the structural equation model. The general formula for a structural equation model is as follows [2,10]:

$$X = \Gamma X + \Lambda\xi + \delta \tag{2}$$

$$Y = BX + \Psi\xi + \varepsilon \tag{3}$$

In this formula:

X represents the independent variables (e.g., information technology).

Y represents the dependent variable (e.g., service quality or customer satisfaction).

Γ represents the path coefficients, indicating the extent to which the variations in the independent variables are explained by the dependent variables.

Λ represents the factor loadings, indicating the extent to which the measurable variations in the latent variables are explained by the observed variables.

ξ represents the latent variables that cannot be directly measured.

δ and *ε* represent the errors or uncontrolled factors that may influence the independent and dependent variables.

By analyzing the coefficients *Γ* and *Λ* and evaluating their significance (using statistical tests such as t-test or F-test), we can determine whether information technology has a significant impact on service quality. Similarly, by analyzing the coefficients *B* and *Ψ* and evaluating their significance, we can conclude whether information technology has a significant impact on customer satisfaction. Ultimately, using a structural equation model allows us to analyze causal relationships between variables, examine the direct and indirect effects of variables, and provide a more comprehensive interpretation of the relationships among variables [3,4].

5.3 Decision model

This model is used for optimal decision-making regarding the utilization of information technology to improve customer services. By using decision models such as artificial neural networks, decision trees, and optimization algorithms, the impact of different variables and their optimal combination on enhancing customer services is evaluated. Decision-making models are mathematical frameworks used to analyze and evaluate the decision-making process under different conditions. These models utilize variables, parameters, constraints, and objective functions to arrive at the optimal decision in various situations and constraints. A general decision-making model is formulated as follows [5,6]:

max/min $f(X)$

subject to: $g(X) \leq 0 \quad h(X) = 0$

In this formulation:

f(X) represents the objective function, which is defined for either maximization or minimization and serves as a criterion for evaluating the quality of the decision-making.

X is a vector of decision variables, including independent and dependent variables, parameters, and observed values.

g(X) denotes the set of constraint conditions that specify the bounds under which the decision-making should be performed.

h(X) represents the set of equality constraints that determine the equality constraints in the decision-making process.

By solving the decision-making model, one can determine the values of the decision variables that optimize the objective function while satisfying the specified constraints. The objective function can be customized based on the specific problem, and the constraints can reflect the limitations and conditions imposed on the decision-making process. Overall, decision-making models provide a structured approach to analyze and making decisions by considering multiple variables, constraints, and objectives, ultimately guiding the decision-maker towards the best possible decision given the circumstances [1,11].

6. Discussion and results

In this section, we test the proposed model on real-world data. The proposed method is compared to three methods: decision tree, regression, and SEM.

To ensure a fair comparison, we use data from 70 IT organization individuals. These individuals are selected from a university environment, and the dataset is created with 12 independent features and 3 dependent features. A questionnaire is used to obtain the dataset, and coding is done using MATLAB software. All simulations and experiments were performed on a system with an Intel 2.7 GHz 7-core processor, 12 GB RAM, and Windows 10 operating system. The algorithms and methods were implemented using MATLAB software version 2018. The aim is to accurately assess customer satisfaction and service quality. **Table 4** presents the results of the proposed analysis. As evident, the proposed model has performed better in most parameters.

Table 4. The effect of using information technology on improving focus on operations.

Model	Service quality	Satisfaction	Costumer relationship
Decision tree	%87	%81	**%90**
Regression	%83	%77	%86
SEM	%72	%85	%81
Proposed	**%92**	**%90**	%88

As observed, the proposed method has performed better in two main parameters: service quality and customer satisfaction, compared to all three mathematical models. Only in the customer relationship parameter, our method has a very slight difference and ranks second. It is essential to note that due to data collection limitations from IT managers, the performance difference may not be fully demonstrated. With the suggestions made in this model, undoubtedly, the performance of the proposed model will be even better with larger datasets.

7. Conclusions

This article has examined and analyzed the impact of information technology on customer services in the financial services industry. The results have shown that optimal and intelligent utilization of information technology can have a significant impact on customer focus and improvement of company operations. Companies that lead in information technology and have a high level of IT management maturity are capable of delivering superior customer services and have a strong competitive position in the financial services industry. Additionally, the use of information technology in company operations can lead to performance improvement, cost reduction, increased speed, and enhanced customer experience. As observed, three criteria were used to evaluate the impact of IT on organizations: service quality, customer satisfaction, and customer relationship management. Information from 70 IT personnel was collected in raw form, and it was observed that the proposed method performed on average 10% better than the other three models. Furthermore, managers and implementers should prioritize investment in the development and improvement of information technology and formulate appropriate strategies to create customer focus and improve operations using information technology.

Author Contributions

Conceptualization, Hojjat Talebi; proposed methodology, Hojjat Talebi; design and analysis, Hojjat Talebi & Amid Khatibi Bardisir; resources, Hojjat Talebi; writing and editing, Amid Khatibi Bardsiri; Simulation, Amid Khatibi Bardsiri; supervision, Hojjat Talebi.

Conflict of Interest

There is no conflict of interest.

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ARTICLE

Sectoral Advanced Planning Systems (APS) Based on Utility Functions

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ABSTRACT

This paper contains the example of sectoral APS systems, for which the problem algorithmic space coincides with the relevant operational environment with great accuracy. The method of scheduling for technological processes with looping is described, based on the simultaneous application of two criteria: the value of relative direct costs and the average utility of order fulfillment. The influence of buffers on the work of shops is considered. The proposed method provides an automatic grouping of the same type of jobs on all machines involved while taking into account the required duration of jobs. A package of application programs has been developed that allows planning for an average number of orders. The result of the program is a set of non-dominant (not improved) options that are offered to the user for making a final decision.

Keywords: Scheduling; Production intensity; Buffer; Job shop

1. Introduction

In the author's view, the APS definition that best corresponds with its destination is done by Chen, W.L., etc. [1]: "APS systems are considered as an effective approach for generating an optimized production plan considering a wide range of constraints, including raw materials availability, machines, and operators' capability, service level, secure stock level, costs, sales, and demand".

Effective planning has to chime mid-term planning with short-term (daily) scheduling. For this purpose, the schedule of operations on the shop work centers during a fixed planning horizon must be the basis of shop manufacturing. Here, shop work centers include not only the process equipment of

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the shop, but also buffers for various operations, the transport devices inside the shop, and even (though not always) the means of transport for delivering raw materials or picking up finished products.

Recommendations for the application of specific APS systems are usually limited to one or more industries. Some authors, Wiers, V. and de Kok, T. [2] or Kilger, C. [3] list such possible branches, the number of which varies from 8 to 12 accordingly. In spite of the publication of these recommendations, some more modern APS systems, (e.g. Preactor) are used in various fields but with varying degrees of success.

In the author's opinion, there are 2 key requirements for the APS system application for planning in a production system. The first one certainly is to comply as much as possible with all functional restrictions for a specific processing stage. The second requirement consists of the right choice for the criteria for planning optimization.

Almost all of the papers dedicated to production planning include a criterion (or several criteria) to evaluate the quality of such planning. The selection of either criterion is very often determined by reasons of convenience of mathematical methods rather than real features of the considered production system [4].

Many authors, such as Setia, P. etc. [5] or Günter, H.P. [6] point out the need for careful compliance of functional limitations associated with the operating environment and algorithmic capabilities. To identify such connections, Jonsson, P. and Mattsson, S.A. [7] consider 4 possible variants of operating environments: complex products specially manufactured by order (type 1); configuration of products by order (type 2); production of batches of standard products (type 3); mass production (type 4). As a result of a survey of enterprises on the applications of existing APS systems, in the study of Ivert, L., K. [8], the conclusion is that the functionality of these systems often does not match the numerous operational features of these enterprises.

According to Lupeikiene, A. etc. [9], each individual APS system, according to the general theory of algorithms, has its own problem space and, obviously, this space should generally coincide with the space of the operational production environment.

It should be noted that the actual purposes of real production cannot always be formalized to the degree sufficient for mathematical optimization. The reason for this situation usually is that there are several purposes, rather than one, which often contradict each other. As stated in Fleischmann, B. etc. [10]: "There are often several criteria which imply conflicting objectives and ambiguous preferences between alternatives. In this case, no 'optimal' solution (accomplishing both objectives to the highest possible degree) exists."

APS system for a real operational situation must use a multi-criteria approach to simultaneously consider the timely completion of orders (i.e. customer service level) and other criteria that reduce expenses. However, these criteria contradict each other, and the need for their simultaneous implementation is named as "Dilemma of Operation Planning" [11]. The solution to this problem lies in finding the expedient point of "logistic positioning", i.e. a reasonable tradeoff for conflicting objectives. In some works [12,13], positioning and grouping are also used for production lines.

Here the criteria of scheduling quality are two time-current functions: the utility function of total orders set on the planning horizon and the function of relative costs for the same horizon [14].

As an example of a sectoral APS, this paper considers a case that is quite common in machine-building production when the sequence of the technological process includes the transfer of batches of parts from one workshop to another and back. An example is the processing of a batch in a machine shop, the transfer of a batch to a heat treatment or electroplating workshop and the return of this batch to the original workshop to complete the manufacture.

For such a technology, the concept of "loop" shop-to-shop routing is often used, denoting the possibility of circulation between workshops. It is obvious that the APS system for the case under consideration should cover both interacting workshops. Moreover, expanding on the above example, it can be assumed that the heat treatment workshop can serve several mechanical workshops and the schedule of work for each workshop may depend to some extent on the situation in other workshops.

Usually, the job performed in the theory of schedules is understood as a specific position (part) with the corresponding designation in the design specification, which must be manufactured to fulfill the current order for finished products. At the same time, the number of objects in one job should ensure the completion of this order, and the job completion period should be set in accordance with the duration of assembly operations with different levels of input into the finished product.

Obviously, with several levels of input for objects of the same job, the total number of these objects can be produced in several batches. In addition, with a significant complexity of the operation performed, the job can be divided into batches that can be performed in parallel at different work centers in order to speed up the job. During thermal or galvanic processing, the number of simultaneously processed parts is limited by the physical volume of the furnace or bath, which also leads to the need to divide the job into batches.

In some cases (equipment breakdown, urgent job, lack of material, etc.), the job has to be interrupted and then resumed in the next batch. Thus, each job mentioned in the scheduling assignment often passes through a network of work centers and buffers not as a whole, but as a collection of several batches, moreover, at each technological operation, the number of such batches, in principle, may be different.

The rest of the article is organized as follows: Section 2 describes the model of the production system. Section 3 establishes the interaction of work centers. Section 4 describes the algorithm for solving the problem. A numerical example is given in Section 5. Section 6 contains the short result. Section 7 describes the main conclusions.

2. Calculation model of the production system

Figure 1 shows a diagram of a network of work centers and buffers, simplistically describing one of the variants of machine-building production. Let's assume that the processing time of delivering blanks of parts or raw materials entering the system in **Figure 1** is small, although this is not always the case—for example, when delivering sheet materials [15]. Batches of parts and assembly units are moving along the production system in accordance with the technological route with a given flow rate. In some cases, the packaging involves the transfer of batches of parts from the machine shop for heat treatment to the thermal shop, and then return to the machine shop for refinement and subsequent assembly with other parts. We will call this variant of shop-to-shop routing as a "loop".

Any transfer of processing objects between workshops is carried out through the appropriate buffers. In **Figure 1**, the arrows show the possible directions of transferring batches from Workshops 1 and 2 to Workshop 3 and vice versa. The finished products arrive at a special warehouse, from which they are shipped to customers. In this example, it is assumed that the shipping process is not directly related to the production schedule, although in some cases, due to the great complexity of packaging and transportation, the shipment should be taken into account [15].

Table 1 shows the task for scheduling production on some selected horizons. Each of the 32 jobs of this task is described by a code, which in the first position contains the number of the workshop that produces batches for this job. The subsequent positions contain the serial number of a job; three possible types of objects are considered: parts, assembly units for sub-assembly and assembly units as finished products. The job in a line is intended to complete a job in another line or is a finished product. In the latter case, zero is written as the entry object.

In other columns in **Table 1**, the code of the part or assembly unit, the order code for the finished product, and the required quantity for the order completion are recorded. If at the time of planning, there are no necessary blanks or materials, you must specify the expected time of receipt in calendar hours after the start of planning. The required moment of

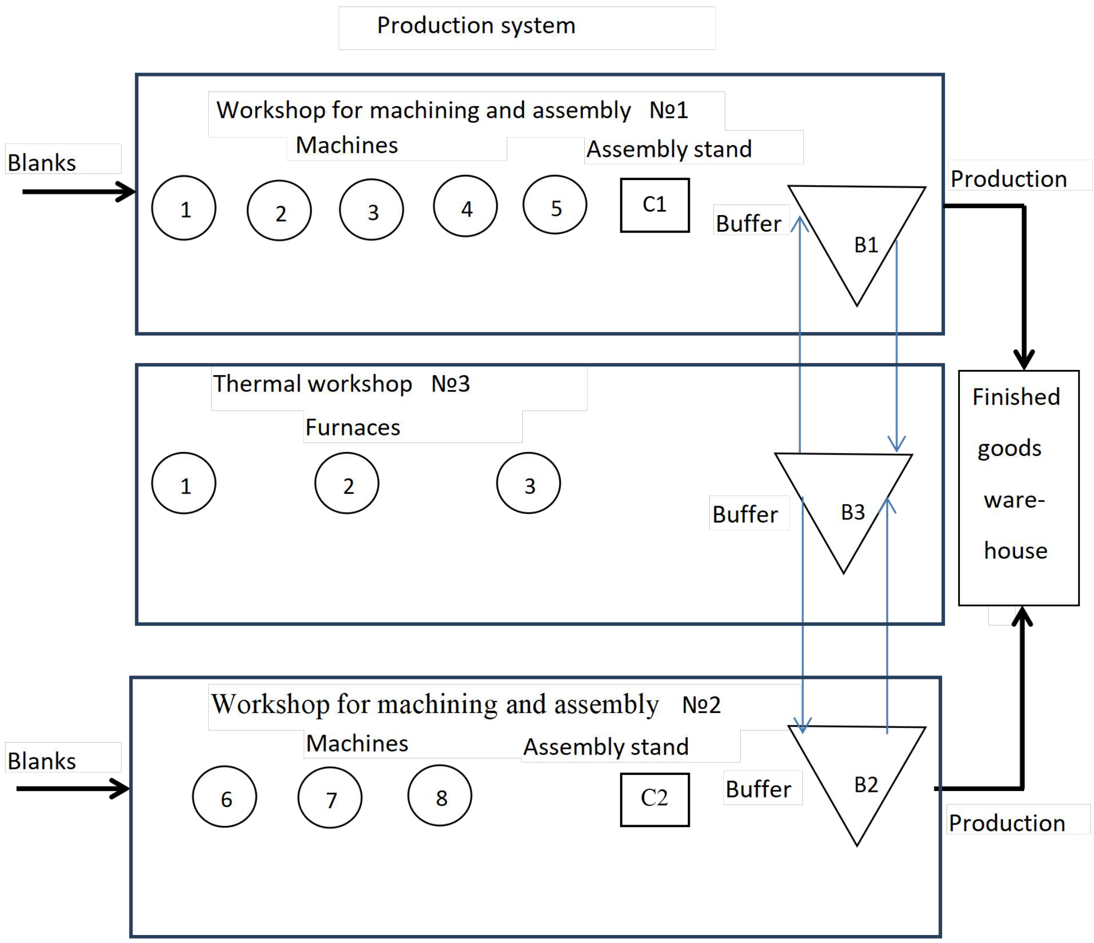

Figure 1. Scheme of processing and assembly in machine-building manufacturing.

job completion is set according to the first moment of need for objects of the corresponding type for the current order, which is determined by the process of explosion.

A certain percentage of the total number of objects for a particular job may have been previously shipped to the customer and some items may be in stock awaiting shipment. In particular, for job 108 representing finished products, 20% were sent earlier. Accordingly, for all jobs sequentially included in job 108, the number should be reduced by 20%.

Table 2 lists the types of possible parts and specifies the minimum production lot size. Since the parts can be processed in an oven or in a bath, it is necessary to set the estimated volume of one part, determined by its dimensions. At the time of planning, both in the buffers of the respective workshops and in the warehouse of finished products, there may be free remains of parts of these types. A similar table is compiled for assembly units.

A fragment of the list of detailed operations for parts of each type is shown in **Table 3**. For each operation with the current serial number, the type of machine or oven used, the type of fixture used, the possible heat treatment code, and the processing time of the operation in minutes are indicated.

In some work centers (buffers, furnaces, baths), it is possible to have several jobs together, as well as their simultaneous execution. The free balances physically located in buffers and warehouses are not indicated in **Table 4**, and their values are shown above in **Table 2**. In addition to **Tables 1-4**, a table of the complexity of setting heat treatment modes, a table of the applicability of devices and a working calendar are used as initial data. In this article, it is proposed to use the method of branches and boundaries for scheduling. To do this, you need to build a multi-level tree of operations, consistently consider-

Table 1. Jobs on the selected horizon.

Job code	The shop number	Object type code (1—parts, 2—assemblies, 3—products)	Part code or assembly code	Where does it enter (job number, warehouse-0)	Order code for finished product	Expected receipt of the workpiece at the beginning	Required calendar day of readiness after start	Quantity based on order for finished products	Weight coefficient	Sent as a percentage of the order	It is a part of assemblies in warehouses as a percentage of the order
101	1	1	1	0	1	0	0	200	2	0	0
102	1	1	2	105	2	0	1	30	1	20	0
103	1	1	4	105	2	0	1	60	2	20	0
104	1	1	3	105	2	0	2	30	3	20	0
105	1	2	1	108	2	0	2	30	1	20	0
106	1	1	5	108	2	0	3	40	1	20	0
107	1	1	3	108	2	0	3	20	1	20	0
108	1	3	5	0	2	0	4	20	1	20	0
109	1	1	2	114	3	1	3	40	1	0	50
110	1	1	6	114	3	1	2	40	1	0	50
…	..	..	..	..	..	…	…	…	…	…	…
205	2	1	9	208	4	0	2	20	1	0	0
206	2	1	5	208	4	0	2	40	1	0	0
207	2	1	7	212	4	0	4	20	1	0	0
208	2	2	9	212	4	0	4	20	1	0	0
209	2	1	8	212	4	1	4	20	1	0	0
210	2	1	6	212	4	1	5	20	1	0	0
211	2	1	7	212	4	1	5	20	1	0	0
212	2	3	9	0	4	1	7	10	1	0	0

Table 2. Types of manufactured parts.

Part code	**Minimum lot**	**Estimated volume of the part (by dimensions) in liter**	**Free remains of parts in the buffers of workshops, pcs.**	**Free remains of parts in the warehouse of finished products, pcs.**
1	50	2.0	0	0
2	20	1.5	0	0
3	20	1.0	10	0
4	50	2.2	0	0
5	30	0.7	40	10
6	20	2.4	0	0
7	40	1.4	0	0
8	30	3.5	0	0
9	30	2.5	0	0

Table 3. Fragment of the operation details.

Part code	**The operation number**	**Number of the type of machines or furnace**	**Device type number or heat treatment code**	**Processing time, min.**
1	1	1	0	8
1	2	1	3	12
1	3	102	1	120
1	4	4	7	4
2	1	1	1	8
2	2	102	1	120
2	3	4	7	10
3	1	1	3	12
3	2	2	3	6
3	3	101	3	130
3	4	3	4	12
3	5	4	7	12
4	1	1	1	8
4	2	3	0	12
4	3	101	3	60
4	4	2	6	6

Table 4. Initial state of work centers.

Name of the work center	Work center code	The number of the type of machine or oven or buffer	Work-shop number	Mark of inclusion	Working volume in liters	Fixture code or heat treatment code	Job code in the current planning	The number of the operation being performed (or performed in the buffer)	Batch number for the current operation	The percentage of job performed on the operation by the batch	Expected release time in hours or the last downloads in the buffer
Machine	1	1	1	1	0	0	0;	0;	0;	0;	0;
Machine	2	1	1	1	0	1	101;	2;	1;	33;	10;
Machine	3	2	1	1	0	8	104;	2;	1;	17;	9;
Machine	4	3	1	1	0	0	103;	4;	1;	30;	12;
Processing center	5	4	1	1	0	10	102;	3;	1;	30;	10;
Machine	6	5	2	1	0	6	206;	5;	1;	50;	0;
Machine	7	1	2	1	0	7	201;	1;	1;	100;	8;
Processing center	8	4	2	2	0	9	203;	4;	1;	100;	9;
Furnace	9	102	3	1	100	2	103;	3;	1;	50;	8;
Furnace	10	102	3	1	100	1	102;	2;	1;	50;	8;
Furnace	11	101	3	1	120	1	0;	1;	0;	0;	12;
Assembly stand	12	201	1	1	0	0	0;	1;	0;	0;	0;
Assembly stand	13	202	2	1	0	0	0;	1;	0;	0;	10;
Buffer	21	301	1	1	1000	0	101;104;110;114;	1;5;1;1;	1;1;1;1;	20;20;50;20;	8;8;10;8;
Buffer	22	302	2	1	1000	0	205;206;	2;4;	1;1;	100;50;	0;8;
Buffer	23	303	3	1	1000	0	202;107;	2;2;	1;1;	50;100;	0;8;
Finished goods warehouse	24	304	0	1	2000	0	101;120;	4;1;	1;1;	20;30;	8;8;

ing the feasibility of building new tree nodes. To determine the boundaries at each level of construction, we will apply the criteria for the order utility function and the cost of operations described in Mauergauz Y. [14]. The calculation algorithm is given below.

3. Interaction of work centers in the production system

Figure 2 shows possible options for the interaction of work centers. In any case, the main component of such interaction is some (active) work center in which the current operation is carried out.

In this example, there are three types of active work centers: a) machines in workshops 1 and 2 for machining, b) assembly stands in the same workshops, and c) furnaces in shop 3. **Figures 2a and 2b** show possible operations for shop 1, and **Figure 2c**—for shop 3. To carry out an operation, sources of materials, parts from previous operations or assembly units are always needed to continue the assembly. As follows from **Figure 2**, such sources for the operation in the shop can be a warehouse of materials from outside the shop, other machines in the same shop, as well as the buffer of the shop.

The recipients of the results of the operation can be both in the same workshop and outside it. For example, **Figure 2a** shows that the recipients can be machines for performing a subsequent operation located in the same workshop, which stands for assembly, as well as a buffer of this workshop. In addition, if it is necessary to perform heat treatment as the next operation, the finished batch should be transferred to the buffer of the thermal shop 3.

If the operation is the last one, and the manufactured parts are finished products, then batches of these parts are transported to the finished product warehouse. If it is absolutely necessary to use the equipment of another machine shop for further processing, then the recipient is its buffer. During the assembly operation (**Figure 2b**), the recipients are either the buffer of the current workshop or the finished product warehouse. After the heat treatment (**Figure 2c**), the batches of parts are transferred to the buffers of the machine shops.

It follows from **Figure 2** that during any processing or assembly operation, it is necessary to consider possible changes in the contents in the buffers of workshops and in the finished product warehouse.

Changes are possible both at the beginning of the current operation and at the end of it. Moreover, if the processing time of the batch is long enough, it is possible to transfer part of it to the buffer. Below are the variants of these changes.

a) At the beginning of the operation on the machine or the assembly stand of the machine shop, the system must ensure the availability of the vacated work center. If the previous operation on this center is completed, but the processed objects are still in the center itself or in a storage location near the center, these objects must be moved to the buffer of the corresponding workshop.

b) A batch of workpieces or parts awaiting the continuation of machining must be transported to the vacated machine for a new operation. If the source is the work center – the machine (**Figure 2a**), then it is also completely released. If the source is a workshop buffer, then the contents of the buffer are reduced by the amount of the batch being moved.

c) The operation of assembling a batch of some job begins only if there is a certain amount for all parts and assembly units included in this assembly. The specified quantity for different positions may be different, and the timing of the batches may also vary. Obviously, the size of the assembly batch is determined by the minimum available batch for the item included in the package, and the start time of the assembly batch is set at the moment when the last of the required positions appear.

At the start of the assembly batch (**Figure 2b**), the parts and assembly units involved in the assembly from the machines and from the buffer of the workshop must be moved to the assembly stand. At the same time, the remaining number of parts and assembly units for all participating positions should be in the buffer of the workshop.

d) For heat treatment (**Figure 2b**), batches of parts must be transferred to the buffer of the thermal workshop. During the operation, joint heat treatment

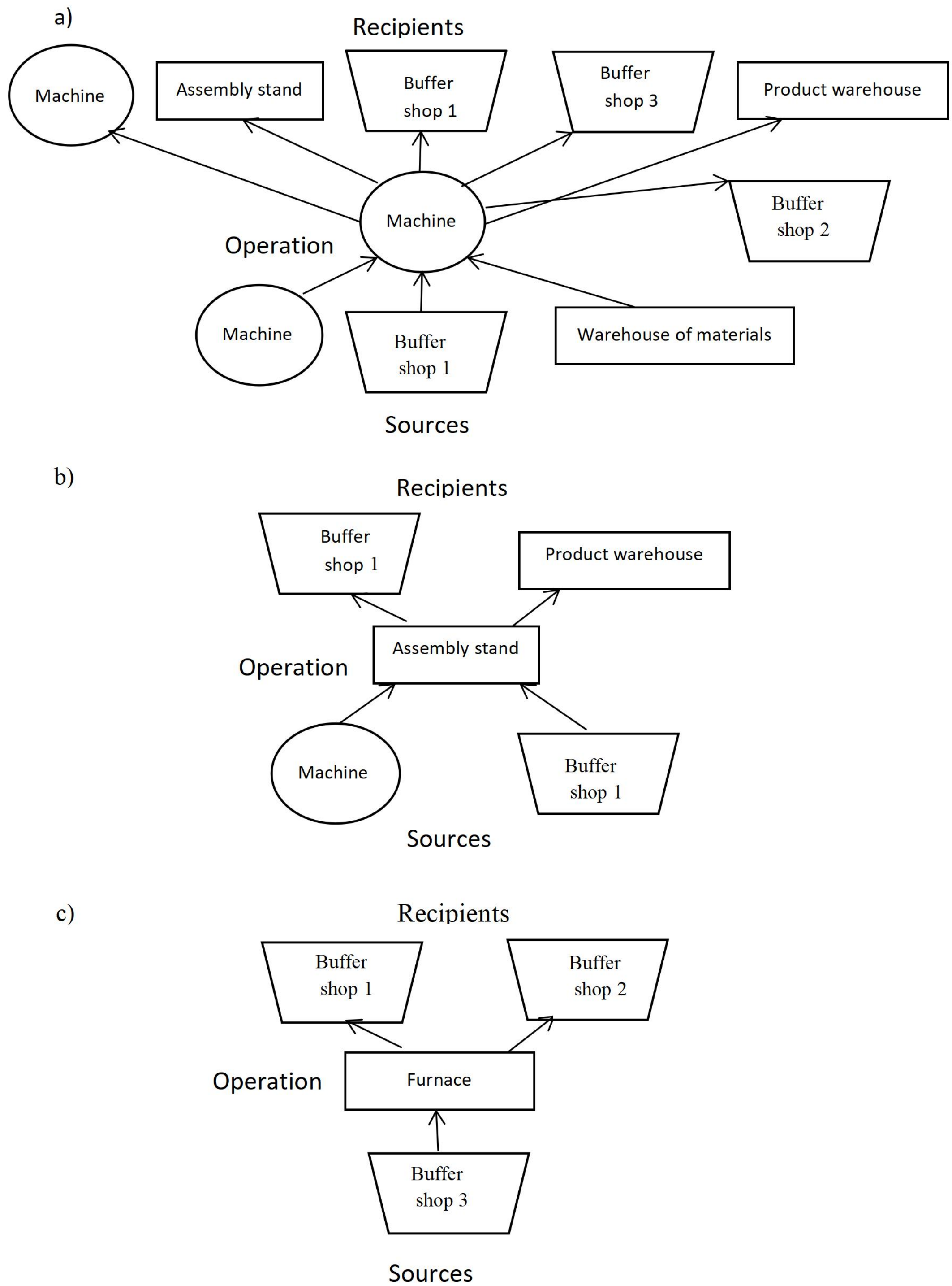

Figure 2. Options for interaction of work centers. a) machines in workshops 1 and 2 for machining, b) assembly stands in the same workshops, c) furnaces in shop 3.

is possible for different batches coming from different workshops. The number of parts in one batch of heat treatment may be less than the quantity received due to the limited working space of the furnace. Therefore, at the beginning of the operation, the contents of the thermal buffer are reduced in accordance with the loading of the furnace. After processing, batches of parts must be immediately transferred to the buffers of the corresponding workshops.

e) The batch of the job that are finished products must be transferred to the appropriate warehouse after assembly on the stand (**Figure 2b**) or the last operation on the machine (**Figure 2a**). The rules of changes in buffers described above are taken into account in the algorithm below and the corresponding computer program.

4. Solution algorithm

The structural formula of the present problem in accordance with the known three-element method of classification of schedules has the form:

$$FJ \,\middle|\, pmtn,\ prec, d_i, s_{mx}, b_x \,\middle|\, U, \bar{V}. \tag{1}$$

The parameter of the first field FJ describes flexible job shop. In the second field, the parameter *pmtn* shows that processing at work centers is carried out in batches, in general, not equal to the size of orders; the parameter *prec* defines multi-stage processing; d_i is the specified moment of completion of the job; s_{mx} is labor intensity for the preparation of the operation at the work center m for the operation x; b_x is available capacity of the work center (or the required buffer) for the operation x. The third field contains the target functions $U, \bar{V}$.

Recall that the production intensity [14], in the case of multi-stage production, has the form:

$$H_i = \frac{w_i p_i}{G} \frac{1}{(d_i - t)/(\alpha G) + 1} \text{ if } d_i - t \geq 0$$

$$\text{and} \tag{2}$$

$$H_i = \frac{w_i p_i}{G}((t - d_i)/(\alpha G) + 1) \text{ if } d_i - t \leq 0,$$

where w_i is weight coefficient; p_i is remaining processing time in hours until the end of the job; G is duration of the planned period in calendar hours; t is current time; d_i is the specified time of task completion in calendar hours; α is psychological coefficient.

If job execution is multistage, the process time of job i that remains until completion consists of process time on N_i of certain j operations.

$$p_i = \sum_{x=1}^{N_i} p_{ix}. \tag{3}$$

Necessary release date of operation g_i in hours is as:

$$g_i = d_i - p_i + 1. \tag{4}$$

The current utility for an order i is:

$$V_i = w_i p_i / G - H_i. \tag{5}$$

The nature of dependencies (2) and (5) is described in detail in Mauergauz Y. [15]. If the number of orders on the planning horizon is n, their total current utility is equal to the sum of the utilities of each, because orders are usually independent.

Then the total value of the function of the current utility of orders:

$$V = \sum_{i=1}^{n} V_i = \frac{1}{G}\sum_{i=1}^{n} w_i p_i - \sum_{i=1}^{n} H_i. \tag{6}$$

The average utility $\overline{V_l}$ of the entire volume of planned jobs at level l is calculated for the time from the initial moment t = 0 to the end of the last already planned operation [15] at each step of the algorithm.

The calculation of the value of direct costs at the l level for job k should be carried out according to the recurrent formula [15].

$$U_{l+1,k} = \frac{c_s}{c}\left(\sum_{j=1}^{l} s_j + s_{km}\right) \tag{7}$$

where c is the cost of a work shift; c_s is the cost of an hour of changeover; s_j is the complexity of setting up for each job j in the chain for a tree node that includes a level l; s_{km} is the complexity of job k transportation to machine m.

For solving the problem (1) it makes sense to apply the method, based on the MO-Greedy approach [16]. In this case, the algorithm for calculating production schedules can represent a tree of sequential decisions about conducting a new operation. At each level of tree construction, from all possible such solutions, those are selected for which the criteria for the average utility of orders $\bar{V}$ and costs U on the planning horizon are "non-dominant". This means that possible solutions with the worst values for both criteria are discarded. In a greedy algorithm, at each step, a choice is made that seems to be the best.

Let's describe the algorithm step by step.

Step 1. *(Distribution of free balances between the jobs of the new task)*

Step 2. *(Determination of percentages of operations at the initial moment)*

Step 3. *(Determination of the remaining process-*

ing time for all jobs)

Step 4. *(Calculation of utility functions at the initial moment of planning)*

Let's put the level number $l = 0$; initial cost function $U_0 = 0$; initial orders function V_0 is determined by the formula (5); number of nodes $Z_0 = 1$.

External cycle

Step 5 *(Identification of possible operations at the following levels)*

For each node z of the constructed tree at level l the loading of each machine is restored, the possible operations are determined and values g_i are calculated using formulas (3) and (4).

Middle cycle

Step 6. *(Determination of the required machine at the following levels)*

For each operation k that is possible and not previously performed, the necessary family f of machines and devices is determined.

Internal cycle

Step 7 *(Calculation of utility functions at the following levels)*

For each machine m belonging to the type f, taking into account the moment of its possible release, values are calculated $U_{l+1,z,k,m}$ и $\overline{V}_{l+1,z,k,m}$ by formulas (7) and (6).

Step 8 *(Defining content in buffers)*

End of the internal cycle

End of the middle cycle

Step 9. *(Definition of non-dominant tree nodes)*

If the l + 1 level is not the last, then to dominate the l + 1 level a possible tree node y above a possible node x must be observed inequalities.

$$U_{l+1,y} \leq U_{l+1,x}, \ \overline{V}_{l+1,y} \geq \overline{V}_{l+1,x} \text{ and } g_{l+1,y} < g_{l+1,x}.$$

Otherwise: in order to dominate at the last l + 1 level, it is necessary that:

$$U_{l+1,y} \leq U_{l+1,x}, \quad \overline{V}_{l+1,y} \geq \overline{V}_{l+1,x}.$$

Step 10. *(Transition to a new level or termination of the program)*

If the level is higher than the last one (all operations are performed), then the end of the program.

Otherwise: Memorizing non-dominant nodes at the l level. Increase the level number $l = l + 1$ and go to step 5.

End of the external cycle

A distinctive feature of this algorithm in comparison with the similar algorithm given in Mauergauz Y. [17] is the presence of step 8 to determine the contents of buffers. The corresponding procedure is carried out according to rules a)-e) of the previous paragraph.

5. Example of schedule calculation

Let's assume that in accordance with the existing orders, the master plan is formed at the enterprise, on the basis of which tasks are given to workshops for a certain horizon (**Table 1**). Since the previous plan is not always fulfilled, the new plan may consist of both new jobs and jobs that transfer from the previous plan. At the same time, the time reserved for performing such jobs may be negative.

Figure 3 shows a Gantt diagram for several machines and assembly stands in workshops 1 and 2, as well as for furnaces in workshop 3. Each rectangle of the diagram, as usual, corresponds to the job in the task in **Table 1**. For machines, the code of the device used is written inside the rectangle, for furnaces—the code of heat treatment. Since the job is carried out in batches, the job numbers on the diagram can be repeated.

The system automatically groups the jobs on one machine by the codes of devices, and in furnaces—by the code of heat treatment. For example, machine 5 is used only with fixture 10, on machine 3 the jobs are grouped for fixtures 8, 3 and 4. Furnace 9 is used only for heat treatment with code 1, and in furnace 11 the jobs are grouped by heat treatment codes 3 and 2.

Figure 4 shows a diagram of batches of jobs on specific processing and assembly operations.

The batch number is recorded above the rectangle of the job, and inside the rectangle is the inventory number of the work center with the operation being

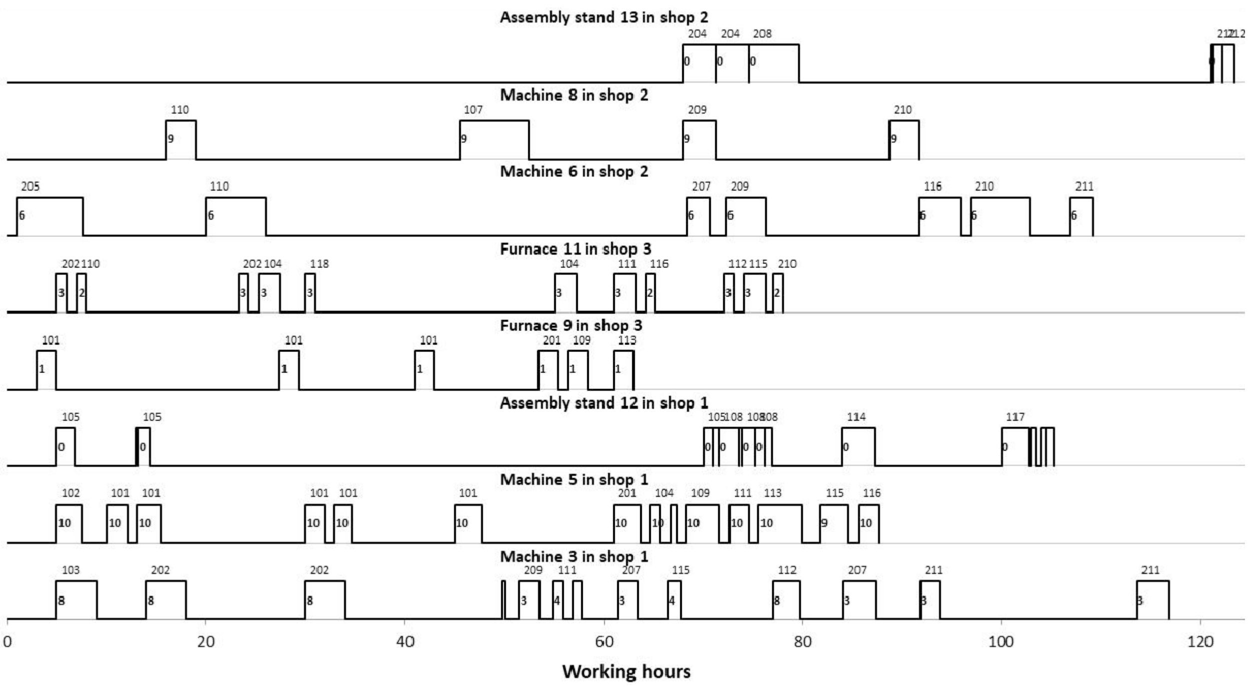

Figure 3. Gantt chart.

performed. For example, during the execution of job 101 (**Table 1**), type 1 parts are manufactured, which requires 4 operations.

At the same time, 20% of the job has already been fully completed and is in the finished product warehouse, and some operations on batches of this job have also been partially completed by the beginning of planning (**Table 4**). The buffer of shop 1 already contains batch 1 of job 101, containing 20% of this job on operation 1. In addition, on machine 2, the batch of the same job ends in the amount of 33% for operation 2. Therefore, the remainder of the job on operation 1 in the amount of 27% should be performed in the form of batch 2.

Because the number of parts for job 101 is 200 (**Table 1**), and the complexity of the second operation of the part type 1 is 12 minutes (**Table 3**), then it is advisable to perform the entire remainder of the job 101 on the second operation, equal to 47%, in several batches. The program automatically splits this volume into 2 batches, shown in **Figure 4**.

Operation 3 (heat treatment) for job 101 is carried out in 5 batches, the sizes are determined by the available volume of furnaces. At the same time, furnaces 9 and 10 are used in parallel, as shown in **Figure 4**. Since the first batch on operation 4 for job 101 is already in stock (**Table 4**), the next 5 batches for operation 4 are executed starting from number 2 (**Figure 4**). Similarly, batches are performed on operations for other jobs.

Figure 5 shows the schedules of receipt of batches of finished products to the warehouse. As follows from **Figure 5**, the schedule for job 101 (blue) at the beginning of planning (8 hours) contains batch 1 in 20% of the total size of the job. Then, gradually, 5 new batches arrive at the warehouse, eventually amounting to 100%. A similar situation occurs with other jobs describing finished products. The exception is job 108 (brown), 20% of which was shipped earlier (**Table 1**).

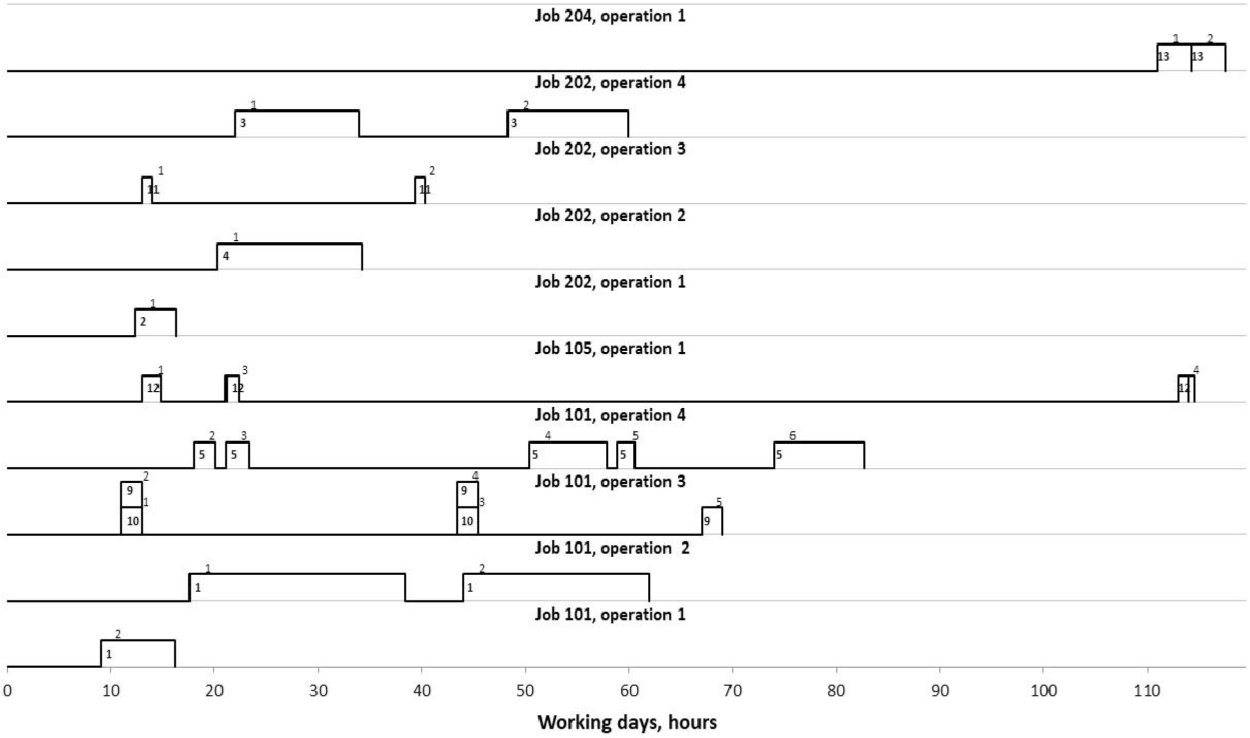

Figure 4. Batches of jobs on operations.

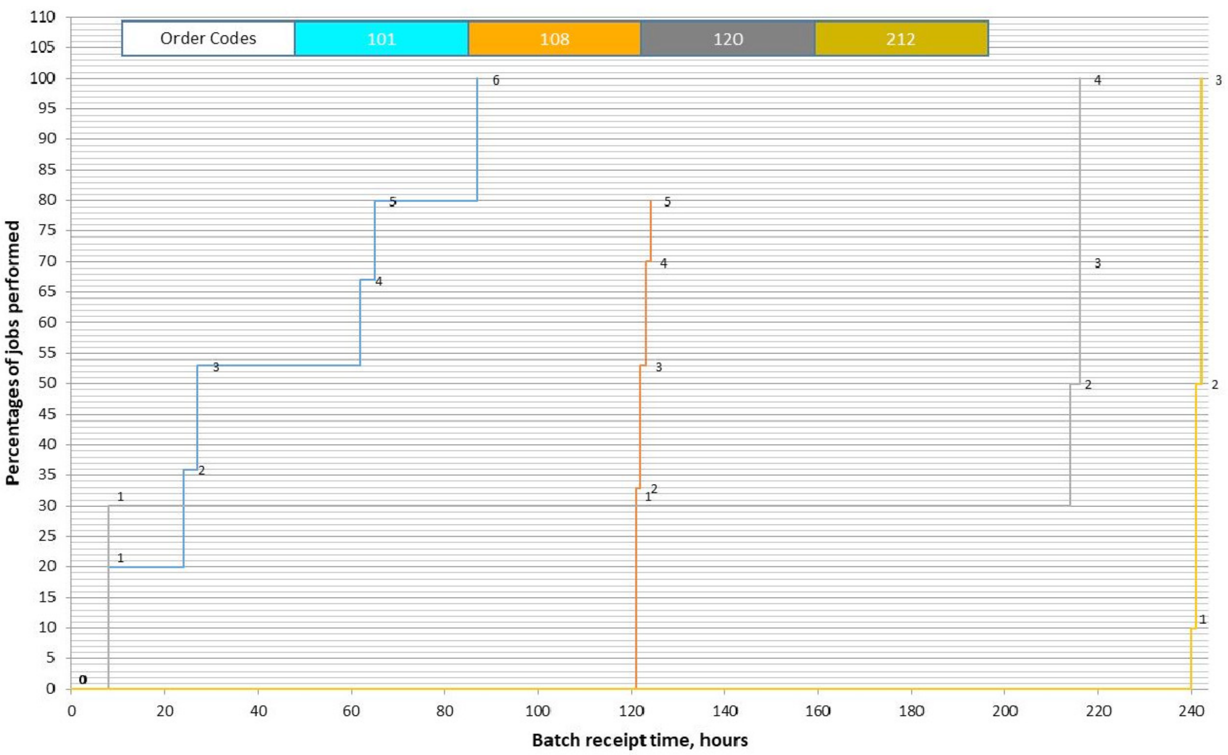

Figure 5. Receipt of batches of finished products to the warehouse.

6. Results

Using the example of a sectoral APS of a machine-building enterprise, the calculation of the equipment charge plan and the execution of operations for several interacting workshops at once is shown. At the same time, the initial state of the work centers, the possible division of jobs into batches and the movement of material objects in buffers are taken into account. As a result, this solution closely reflects the operating activities of the machine-building enterprise.

7. Conclusions

The solutions obtained by the described method are not 100% optimal and, generally speaking, can be improved. The reason is the use of a "greedy" algorithm that does not provide "global" optimization. But the solution turns out to be quite satisfactory, fast and reliable—the duration of the program in the examples given is about 1 min. The main advantage of the utility function method is the possibility of a fairly simple adaptation of the program structure to the specific operating environment of the task under consideration.

Indeed, the differences between various tasks consist in the mechanism for calculating the utility function, as well as in taking into account various restrictions (for example, related to buffers). At the same time, most of the algorithm for building a schedule tree is preserved without significant changes.

The proposed method provides automatic grouping of the same type of jobs on all machines involved, while taking into account the required duration of jobs. To build schedules, a set of decisions is built on the planning horizon, on the basis of which the user makes the final decision. When the horizon increases, the system automatically offers options with increasing grouping of jobs into groups.

The appearance of deviations from the planned course of production should be adjusted in the schedule and taken into account during the next planned cycle. Since the quality criterion of the schedule is a function of the average utility of all jobs within the planned horizon, changes in the value of this criterion with individual schedule adjustments are usually not very large and, accordingly, have little effect on the structure of the schedule as a whole.

Author Contributions

Conceptualization, methodology, formal analysis, computer programming, resources, writing, visualization, all these are done by the author.

Conflict of Interest

There is no conflict of interest.

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ARTICLE

Strategies for Adoption of Circular Economy in the Nigeria Construction Industry

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ABSTRACT

The concept of circular economy has gained recognition as a way to manage waste and conserve resources sustainably, and has the potential to transform the construction industry. This is particularly relevant in the construction industry due to the significant amounts of waste generated during the construction and demolition process. This study examines the perceived importance and effectiveness of strategies related to the circular economy in the construction industry. The data were collected through a survey administered to professionals in the construction sector, capturing their perceptions of various strategies. The results reveal that most strategies received high mean ratings, indicating their perceived significance. Strategies such as waste management and recycling facilities, design for disassembly, and prioritising the use of renewable and sustainable materials were highly valued by the respondents. Additionally, statistical analyses confirmed the significance of these strategies. However, some strategies received comparatively lower ratings, suggesting the need for further attention and improvement. The findings have important implications for policymakers, industry professionals, and stakeholders, guiding decision-making and resource allocation. By prioritising and implementing the identified strategies, stakeholders can drive the adoption of circular economy principles, enhance resource efficiency, and reduce waste in construction practices. Furthermore, this study lays the foundation for future research, highlighting the importance of exploring barriers to implementation, understanding synergies and trade-offs among strategies, conducting longitudinal studies to assess long-term impact, and broadening the participant pool for a more comprehensive understanding. Overall, this study contributes to the growing body of knowledge on the circular economy in the construction industry and provides valuable insights for promoting sustainability and circularity within the sector.

Keywords: Circular economy; Construction industry; Strategies; Resource efficiency; Sustainability

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1. Introduction

Like other industries around the world, the construction industry is experiencing a paradigm shift due to demographic, digital, and economic factors, which has prompted the building industry to implement initiatives to reduce its environmental impact [1]. Buildings and construction consume the most energy (36%) and emit the most carbon (37%) globally [2], posing a significant challenge to the Architecture, Engineering, and Construction (AEC) industry in terms of sustainability and resource efficiency [3]. Furthermore, in 2020, the average daily construction waste generated was 3,418 tonnes, accounting for 23% of all waste deposited in landfills [4]. If correctly managed, construction and demolition waste (CDW) can be a significant source of cash [5]. Implementing the circular economy (CE) is a modern and practical strategy to achieve sustainability in the construction industry through waste management and resource conservation [6].

As defined by the Ellen MacArthur Foundation [7], CE is intended to retain the highest level of utility and value for goods, components, and materials at all times, distinguishing between technical and biological cycles. The Ellen MacArthur Foundation embraced the notion of CE in 2015, and this definition has been used as a basis for further definitions by other scholars. CE is still growing in terms of development and impact [8], and there is no standard definition for CE due to its interdisciplinary nature [9]. CE is seen as a sustainable growth approach since it allows for separating resource usage and economic growth, promoting long-term development [10]. Implementing CE is considered a critical option for fulfilling the world's resource, energy, and climate mitigation goals, particularly the SDGs for 2030 [11].

Since the introduction of CE, studies have demonstrated that CE techniques are ecologically beneficial and have resulted in reduced waste, particularly in the manufacturing sector, where it was first advocated [12-15]. Ensuring that the construction industry reaps the benefits of implementing CE policies [16]. Adopting CE methods can benefit the construction industry by increasing productivity and addressing the drawbacks of the traditional linear construction methodology [7]. In contrast to the linear construction method, primarily concerned with project completion, the CE idea considers the End of Life (EOL) phase of all building activities [17]. As pioneering work by Geissdoerfer et al. [18] demonstrated, CE is a "cradle to cradle" strategy as opposed to the "cradle to grave" linear approach usually applied in the worldwide construction business.

Despite the compelling need for the construction industry to implement CE to reduce waste and save resources, it confronts several problems, including industry fragmentation, a lack of collaboration, and industry opposition to change. The slow adoption of CE in the construction industry, according to Charef et al. [19] can be linked to the sector's complexity. To overcome the barriers to the CE, a wide range of stakeholders across the value chain must adapt their practises [20]. According to Munaro et al. [21], there is a pressing need and demand in the construction industry to transition from the existing linear paradigm to a more sustainable one, with an emphasis on implementing the CE strategy to ensure a more ecologically responsible construction industry.

In recent years, a plethora of CE measures have been proposed in the literature at all levels of the CE system [22]. However, most of these metrics lack standard theoretical or methodological foundations and exhibit variations in content and form Svarc et al. [23]. As a result, there are no standard measurements for CE, making comparison difficult and leading to confusion about the level of circularity performance [23]. Despite this, studies are scarce focusing on indicator-based frameworks (integrated systems of indicators) capable of capturing numerous aspects of the CE transition [24].

Although the policy has several implicit notions about the future of CE, there has been little research into what a circular lot would look like Pinyol et al. [25]. Bauwens et al. [26] provide a framework of four hypothetical circular future scenarios. However, research on how these scenarios can form in practice is lacking [25]. CE initiatives at universities are scattered and unintegrated, and there is no framework to bring them together for a more significant impact [27]. Furthermore, there is no link between higher education performance and societal sustainability [28]. More study is needed to test the suggested theoretical policy framework against the techniques used by policymakers from different regions to reduce the gap between policy development and implementation [29].

A comprehensive strategy has the potential to effectively surmount the limitations encountered in Circular Economy (CE) implementation within the construction industry. By integrating various elements such as innovative design principles, advanced material selection, streamlined waste management processes, and stakeholder collaboration, this strategy can holistically address the multifaceted challenges of CE adoption. Through careful consideration of product life cycles, from procurement to end-of-life, and the incorporation of circular practices like modular construction, materials reuse, and recycling, the strategy fosters a more sustainable and resource-efficient construction ecosystem.

According to the literature, CE implementation in the construction industry is still in its early phases, necessitating a more effective and comprehensive approach to improving waste and resource conservation. Based on the problems and limitations in CE implementation in the construction industry, this research intends to develop a comprehensive strategy for adopting CE in the Nigerian construction industry. The study set the following objectives to; develop effective strategies for the adoption of CE in the Nigerian construction industry, and determine the impacts of the identified strategies.

2. Literature review

2.1 Overview of linear economy

The most crucial part of creating a zero-waste city is transitioning from a linear economic model to a CE [30]. According to World Economic Forum research published in 2019, only 9% of the global economy runs in a circular method, which means that only 9% of waste is reused or recycled into new ones [31]. The remaining 91% of the economy operates linearly, with waste produced due to production and consumption [32]. There is an urgent need to lessen the environmental impact of the existing linear production and consumption system [33], which uses a lot of materials and generates a lot of waste and emissions. As the global economy expands, worldwide waste generation is expected to rise by up to 70% by 2050 [34]. Because the current consumption and production systems are unsustainable, a new economic model is required [20], and the CE has been advocated as a solution by entrepreneurs, policymakers, and researchers [33].

In the construction sector, the linear economy is a production and consumption model that follows a "take, make, use, and dispose of" method. This model involves extracting and processing raw materials into products, which are subsequently utilised and eventually discarded as waste. This linear paradigm, typified by non-collaborative work practises, has traditionally been followed by the construction industry, resulting in a lack of linkages across industrial sectors, supply chain members, and partners in implementing sustainable practices.

2.2 Concept of circular economy in the construction industry

The origins of the CE can be traced back to various intellectual schools, such as Industrial Ecology and Cradle to Cradle [35]. The CE aims to build a sustainable economic system by minimising waste, energy losses, and resource consumption by narrowing, delaying, and closing the resource cycle [18,36]. The CE is viewed as a solution to problems such as waste generation, resource scarcity, and the need for economic rewards [37].

The CE is seen as a broad concept that incorporates several measures targeted at reducing, reusing, recycling, and recovering economic resources [10,36,38,39]. The phrase "circular economy" was coined by Pearce et al. [40], who promoted sustainable economic development (SED) and emphasised the relationship between the economy and the environment. This contrasted with the linear economic paradigm founded on cost-benefit concepts [41].

The CE's fundamental premise is to shift away from linear "take-make-dispose" economic paradigms and focus on completing the materials and energy loops to keep the value of resources in the economy [40]. However, it was not until 2015 that the CE gained popularity because the Ellen MacArthur Foundation promoted its use. Ghisellini et al. [42] defined the CE principles as decreasing waste, lowering pollution, prolonging the life of products and materials, and renewing natural systems. Similarly, CE is defined by Geissdoerfer et al. [18] as a system in which resource inputs and waste, emissions, and energy loss are minimised by slowing, closing, and shrinking material and energy cycles.

The CE concepts are summarised in the 10 Rs, which are as follows: R0 Refuse, R1 Rethink, R2 Reduce, R3 Reuse, R4 Repair, R5 Refurbish, R6 Remanufacture, R7 Repurpose, R8 Recover, and R9 Recycle [43-45]. It has been proposed that applying these concepts to the construction industry might aid in developing a CE [46]. According to Mendoza et al. [47], CE attempts to shorten resource cycles by implementing eco-efficient solutions that lower the number of resources utilised and the environmental effect per unit of product or service. Slowing down resource cycles entails increasing the usage of items to increase their worth over time, whereas closing resource cycles allows upcycling to restore or produce new value from spent resources [36]. Implementing the circular economy in the construction industry can reduce waste, conserve resources, and create a more sustainable future.

2.3 Application of circular economy in the construction industry

Most European Union countries have met the Waste Framework Directive's 2020 target of 70% recovery of construction and demolition waste (CDW). Still, these high recovery rates are primarily achieved through backfilling, in which valuable materials are crushed and used for road construction. Suppose there is an increase in reuse and enhanced recycling. In that case, there is an excellent opportunity for the environment and resources, resulting in a higher economic value from CDW. On the other hand, the circularity gap in the construction and demolition industry is compounded by the extended lifespan of structures and infrastructure, resulting in a delay between input and output.

Although there is significant potential for the development of a CE in the construction and demolition industry, technological, regulatory, and behavioural constraints must be addressed before this potential can be fulfilled. According to Mahpour's [48] literature analysis, the most significant technical hurdle to implementing the CE in the construction industry is a lack of experience, which leads to a lack of effective processes, making circular activities more complicated and time-consuming. Aguilar-Hernandez et al. [49] assessed the circularity gap in 43 countries. They discovered a low level of circularity, proposing interventions to close the material loop of nations, such as improved waste management systems, closed supply chains, increased resource efficiency, and extended product lifetimes.

Hopff et al. [50] developed a framework to understand the various aspects and scales of campus operations and how to implement circular principles in campus development, another study discussed the benefits and challenges of implementing the circular economy framework in a national cross-sectoral policy programme. Despite its narrow focus on the campus, the paradigm [50] developed went beyond simply examining R-strategies implementation.

Guzzo et al. [51] detailed techniques for R-strategies implementation and emphasised the significance of examining many viewpoints (conceptual, strategic, and practical) to reconcile circular innovation's theoretical and practical components. A CE implementation plan based on legislation and policy, enabling infrastructure, public awareness, collaborative business models, product design, supply chain, and information and communication technologies was proposed by Lieder & Rashid [37]. Prendeville et al. [52] developed a matrix connecting circular city concepts (such as "regenerate", "share", and "optimise") with various solutions based on the ReSOLVE framework [53]. Superti et al. [54] stressed the importance of numerous actors in the CE, such as the government, start-up incubators, and researchers, in addition to those directly involved in producing, using, or recycling products. Pinheiro et al. [55] provided a similar integrative approach. They emphasised the critical role of various stakeholders (customers, government, and legislation) in advancing CE. According to Bacova et al. [56], regional administrations play a critical role in boosting CE implementation by setting framework conditions or by helping local and regional actors. The concept of policy dispersion is inadequate, and the impact of location and cultural context on the adoption of global policies could be investigated using the domestication framework's procedures [57]. It has also been shown that transformative learning is essential in Education for Sustainable Development (ESD) [58]. For example, the Ellen MacArthur Foundation's CE100 Annual Summit brings together commercial enterprises, students, and universities [59]. The UK Government and the European Union provide financing programmes to assist universities and businesses in collaborating to create circular economy technologies [60].

3. Methodology

In research, numerous approaches are utilised, including quantitative, qualitative, and mixed methods (which integrate quantitative and qualitative methodologies). This approach is supported by the evidence of Saunders et al. [61] and Cresswell [62]. According to Kothari [63] and Saunders et al. [61], the quantitative research method is distinguished by a deductive-objective-generalising approach. In contrast, an inductive-subjective-contextual viewpoint indicates the qualitative method. Furthermore, the quantitative method is concerned with numerical data.

In contrast, the qualitative methodology concerns interpreting observation or interview data. This study adopts the quantitative approach using a survey (questionnaire) to collect responses from the respondents. This approach allows respondents to provide answers based on their level of agreement or disagreement. Further, due to the geographical difference between the professionals, a survey approach is best suited, easy to reach and cost-effective. The population consists of Architects, Builders, Engineers, and Quantity surveyors. These professionals are best suited to provide adequate responses due to their contribution and essentiality in the construction industry. The professionals were asked to select from amongst the developed strategies. These strategies were developed through an adequate review of the literature and preliminary findings by the authors.

The developed questionnaire is designed based on a 5-Likert scale to assess the respondents' views on the developed strategies. The data were distributed randomly and virtually using Google Forms. This approach is considered adequate and easy to reach. The population includes construction workers such as architects, builders, engineers, and quantity surveyors. A total number of 164 responses were received and considered for analysis. Using Microsoft Excel and SPSS V26, the data were analysed using descriptive and inference statistics. Results were presented in a table for clear and meaningful presentation and discussion. The analysis included Cronbach alpha, mean ranking, one sample t-test, and one-way ANOVA (Kruskal Wallis).

4. Presentation and discussion of the result

4.1 Characteristics of respondents

Table 1 shows the highest academic qualification; most participants (64.63%) held a bachelor's degree, 22.56% with a master's degree, and 12.80% with a doctorate. This demonstrates a diverse educational background among the respondents. When examining their professions, the study attracted professionals from various fields within the construction industry. Engineers represented the largest group, accounting for 41.46% of the respondents, followed by builders (32.32%), architects (15.85%), and quantity surveyors (10.37%). This diverse professional representation suggests a well-rounded perspective on the subject matter. The years of experience among the participants were also varied, with the largest group (43.90%) having 6-10 years of experience, followed by 25.00% with 11-15 years of experience. The distribution of experience across the different categories indicates a balanced representation of participants at different career stages.

Table 1. Respondent's characteristics.

Respondent's characteristics		Frequency	Percentage
Highest academic qualification	Bachelor degree	106	64.63
	Master's degree	37	22.56
	Doctorate Degree	21	12.80
	Total	**164**	**100.00**
Profession	Architect	26	15.85
	Builder	53	32.32
	Engineer	68	41.46
	Quantity Surveyor	17	10.37
	Total	**164**	**100.00**
Years of experience	0-5	19	11.59
	6-10 years	72	43.90
	11-15 years	41	25.00
	16-20 years	23	14.02
	20 years above	9	5.49
	Total	**164**	**100.00**
Knowledge of circular economy	Yes	42	25.61
	No	99	60.37
	Maybe	23	14.02
	Total	**164**	**100.00**

Interestingly, regarding knowledge of the circular economy, only 25.61% of the respondents indicated knowing this concept. In comparison, the majority (60.37%) did not possess this knowledge, and 14.02% were unsure. These findings suggest that there may be a need for further education and awareness-building regarding the circular economy within the construction industry. Overall, these characteristics of the respondents provide valuable context for interpreting the study's findings and highlight the need for targeted efforts to promote awareness and understanding of the circular economy principles among professionals in the field.

4.2 Reliability

The reliability statistics for the study indicate a high level of internal consistency among the items measured, as shown in **Table 2**. Cronbach's alpha coefficient, a commonly used measure of internal consistency, was calculated to be 0.906. This coefficient ranges from 0 to 1, with higher values indicating greater internal consistency. In this case, the coefficient of 0.906 suggests a strong level of reliability within the data set. The study consists of 23 items that were included in the analysis. These items collectively contribute to the overall measurement of the construct under investigation. With a large number of items and a high Cronbach's alpha coefficient, it can be inferred that the items are highly correlated and measure the intended construct consistently.

Table 2. Reliability test.

Cronbach's alpha	N of items
0.906	23

4.3 Mean ranking of the developed strategies

Table 3 presents a comprehensive overview of the mean ratings and significance levels for various strategies related to the circular economy in the construction industry. Analysing the top 8 strategies with the highest mean ratings, it is evident that the respondents highly valued these strategies. Strategies such as developing waste management and recycling facilities (Mean: 4.34), designing for disassembly (Mean: 4.32), and prioritise the use of renewable and sustainable materials (Mean: 4.30) received exceptionally high mean ratings, indicating their perceived importance and effectiveness in promoting circular economy practices. The low significance levels for these strategies further confirm their statistical significance, solidifying their significance in the respondents' perception. On the other hand, the last five strategies with relatively lower mean ratings were still considered somewhat important, albeit to a lesser extent. Encouraging the development of new business models (Mean: 3.26) received the lowest mean rating among all the strategies while still sur-

Table 3. Mean ranking of the strategies.

Strategies	Mean	SD	S-K	K-S	Test value = 3.5			R
					t	df	Sig	
Develop waste management and recycling facilities	4.34	0.771	–1.000	0.453	13.978	163	0.000	1
Design for disassembly	4.32	0.734	–1.063	1.230	14.358	163	0.000	2
Prioritise the use of renewable and sustainable materials	4.30	0.657	–0.404	–0.732	15.570	163	0.000	3
Implement systems to recover and recycle construction materials	4.29	0.758	–0.876	0.386	13.298	163	0.000	4
Redesign products to be more durable	4.26	0.835	–1.038	0.546	11.686	163	0.000	5
Develop financial instruments and incentives that support circular economy	4.26	0.723	–0.825	0.696	13.389	163	0.000	6
Proper demolition and deconstruction planning	4.22	0.727	–0.751	0.537	12.678	163	0.000	7
Adopts off-site construction techniques	4.21	0.581	–0.052	–0.318	15.601	163	0.000	8
Design buildings to maximise resources and minimising waste	4.14	0.782	–0.563	–0.278	10.480	163	0.000	9
Optimise resource use through efficient processes	4.13	0.684	–0.517	0.461	11.755	163	0.000	10
Introduce reverse logistics	4.12	0.569	0.013	0.010	13.857	163	0.000	11
Develop processes for remanufacturing products	4.10	0.841	–0.700	–0.085	9.194	163	0.000	12
Invest in technologies and infrastructure	4.09	0.713	–1.360	4.922	10.518	163	0.000	13
Encourage collaboration and partnerships	4.08	0.709	–0.741	1.107	10.461	163	0.000	14
Integrate eco-design principles into product development	4.07	0.705	–0.741	1.149	10.405	163	0.000	15
Increase education and awareness	4.06	0.707	–0.087	–0.978	10.167	163	0.000	16
Develop and promote circular design guidelines	3.90	0.838	–0.130	–0.930	6.151	163	0.000	17
Encourage product longevity through maintenance	3.90	0.764	0.178	–1.263	6.640	163	0.000	18
Encourage product and material traceability	3.87	0.693	–0.719	1.066	6.872	163	0.000	19
Provision of financial incentives and regulations	3.74	0.788	0.184	–0.840	3.963	163	0.000	20
Incorporate circular economy criteria into procurement processes	3.62	1.132	–0.664	–0.130	1.311	163	0.192	21
Establish efficient systems for the collection, sorting, and reprocessing	3.39	1.048	–0.450	–0.403	–1.341	163	0.182	22
Encourage the development of new business models	3.26	1.025	–0.152	–0.514	–3.047	163	0.003	23

passing the benchmark. These lower-rated strategies still demonstrated statistical significance, suggesting they are perceived as significant to a certain degree. Overall, these findings provide valuable insights into the highly valued and considered essential strategies for advancing circular economy principles in the construction sector, as well as the areas that could benefit from further attention and improvement.

4.4 Chi-square and Kruskal Wallis (one way ANOVA)

Table 4 presents the results of chi-square tests and Kruskal-Wallis tests conducted for the construction industry's different strategies related to the circular economy. The chi-square test evaluates the association between the strategies and the variables. In

Table 4. Chi-Square and Kruskal Wallis.

Strategies	Chi-square	df	Asymp. Sig.	Kruskal-Wallis H	df	Asymp. sig.
Design for disassembly	106.683[a]	3	0.000	2.593	4	0.628
Implement systems to recover and recycle construction materials	90.390[a]	3	0.000	2.732	4	0.604
Prioritise the use of renewable and sustainable materials	38.207[b]	2	0.000	2.781	4	0.595
Design buildings to maximise resources and minimising waste	70.390[a]	3	0.000	2.926	4	0.570
Adopts off-site construction techniques	72.049[b]	2	0.000	6.775	4	0.148
Proper demolition and deconstruction planning	98.195[a]	3	0.000	6.143	4	0.189
Encourage collaboration and partnerships	126.000[a]	3	0.000	3.441	4	0.487
Encourage product and material traceability	146.390[a]	3	0.000	8.775	4	0.067
Increase education and awareness	21.415[b]	2	0.000	3.323	4	0.505
Develop waste management and recycling facilities	96.098[a]	3	0.000	6.731	4	0.151
Introduce reverse logistics	84.305[b]	2	0.000	1.699	4	0.791
Provision of Financial incentives and regulations	62.780[a]	3	0.000	4.968	4	0.291
Develop and promote circular design guidelines	46.244[a]	3	0.000	2.440	4	0.655
Redesign products to be more durable	82.293[a]	3	0.000	5.084	4	0.279
Optimise resource use through efficient processes	115.366[a]	3	0.000	2.557	4	0.634
Encourage product longevity through maintenance	6.817[b]	2	0.033	4.002	4	0.406
Invest in technologies and infrastructure	146.098[a]	3	0.000	3.611	4	0.461
Develop financial instruments and incentives that support circular economy	101.024[a]	3	0.000	7.275	4	0.122
Integrate eco-design principles into product development	128.829[a]	3	0.000	3.376	4	0.497
Develop processes for remanufacturing products	61.902[a]	3	0.000	8.080	4	0.089
Incorporate circular economy criteria into procurement processes	50.146[c]	4	0.000	31.703	4	0.528
Establish efficient systems for the collection, sorting, and reprocessing	62.585[c]	4	0.000	77.744	4	0.172
Encourage the development of new business models	55.024[c]	4	0.000	163.000	4	0.361

contrast, the Kruskal-Wallis test compares the mean ranks of the strategies across different groups. The results show the test statistics, degrees of freedom (df), and the associated significance levels.

Analysing the chi-square test results, several strategies demonstrate a statistically significant association with the variables. For instance, strategies such as "Design for disassembly" (Chi-Square = 106.683, df = 3, p = 0.000), "Implement systems to recover and recycle construction materials" (Chi-Square = 90.390, df = 3, p = 0.000), and "Proper demolition and deconstruction planning" (Chi-Square = 98.195, df = 3, p = 0.000) show significant associations. This suggests that the perception of these strategies differs significantly across different groups.

Similarly, the Kruskal-Wallis test results indicate significant differences in mean ranks for various strategies. Strategies such as "Adopts off-site construction techniques" (H = 6.775, df = 4, p = 0.148), "Encourage product and material traceability" (H = 8.775, df = 4, p = 0.067), and "Develop and promote circular design guidelines" (H = 8.080, df = 4, p = 0.089) exhibit relatively higher p-values, indicating a lack of statistically significant differences in mean ranks across different groups.

On the other hand, the strategies "Encourage the development of new business models" (H = 163.000, df = 4, p = 0.361) and "Establish efficient systems for the collection, sorting, and reprocessing" (H = 77.744, df = 4, p = 0.172) show higher test statistics and p-values, suggesting no significant differences in mean ranks among the strategies across different groups.

In summary, the results of the chi-square and

Kruskal-Wallis tests indicate significant associations and differences in mean ranks for several strategies related to the circular economy in the construction industry. These findings highlight the variations in perceptions and rankings of strategies among different groups, providing valuable insights for understanding the significance and effectiveness of these strategies in promoting circular economy practices within the industry. Since the respondents have similar opinions on the developed strategies, this could make the process of developing policies on CE easy and effective.

5. Conclusions

In conclusion, this study has examined the perceived importance and effectiveness of various strategies related to the circular economy in the construction industry. The findings indicate that most strategies were perceived as essential and effective, with high mean ratings and statistical significance. The respondents particularly valued strategies such as waste management and recycling facilities, design for disassembly, and prioritising the use of renewable and sustainable materials. However, some strategies received comparatively lower ratings, indicating the need for further attention and improvement in their implementation.

The theoretical implication of this study lies in the concept of CE, emphasizing the shift from a linear "take-make-dispose" model to one that prioritizes resource efficiency, reduced waste, and sustainable practices. This study acknowledges the potential benefits of adopting circular economy principles in the construction industry, such as minimizing material waste, extending product lifecycles, and lowering environmental impacts. The practical implications of this research encompass the identification of context-specific strategies, policy recommendations, and stakeholder engagement methods that can facilitate the implementation of circular economy practices in Nigeria's construction sector. These insights can guide industry stakeholders, policymakers, and businesses towards fostering sustainable growth, reducing environmental burdens, and enhancing resource management within the construction industry. Further, the outcome of this study can further be implemented in other developing countries with similar characteristics as Nigeria.

The implications of this study are significant for policymakers, industry professionals, and stakeholders involved in the construction industry. The identified strategies can guide decision-making and resource allocation, enabling stakeholders to focus on the strategies highly valued and recognised by industry professionals. By prioritising these strategies, stakeholders can drive the adoption of circular economy principles, enhance resource efficiency, and reduce waste in construction practices. Furthermore, this study provides a foundation for future research in the field of circular economy in the construction industry. First, further investigation is needed to understand the barriers and challenges associated with implementing the identified strategies. Identifying and addressing these barriers will be crucial in facilitating the successful adoption and implementation of circular economy practices.

Future studies could explore the potential synergies and trade-offs between different strategies. Understanding the interdependencies and interactions among the strategies can provide valuable insights into the holistic implementation of circular economy principles in the construction industry. This will allow stakeholders to optimise their efforts and resources, ensuring a more integrated and practical approach to circularity. Longitudinal studies are warranted to assess the long-term impact of these strategies on key performance indicators, such as waste reduction, resource efficiency, and overall sustainability in the construction sector. By monitoring and evaluating the outcomes of the implemented strategies over time, stakeholders can gain a deeper understanding of their effectiveness and make informed decisions for continuous improvement. Lastly, future research could expand the scope of the study by including a broader range of participants from different regions and backgrounds. This would enhance the generalizability of the findings and provide a more comprehensive understanding of the perceptions and priorities related to the circular economy in the construction industry.

Authors Contribution

Abdullahi Idris—*Conceptualisation and Writing.*

Abdulkabir Opeyemi Bello—*Writing and Analysis.*

Conflict of Interest

There is no conflict of interest.

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ARTICLE

Companies' E-waste Estimation Based on General Equilibrium Theory Context and Random Forest Regression Algorithm in Cameroon: Case Study of SMEs Implementing ISO 14001:2015

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ABSTRACT

Given the challenge of estimating or calculating quantities of waste electrical and electronic equipment (WEEE) in developing countries, this article focuses on predicting the WEEE generated by Cameroonian small and medium enterprises (SMEs) that are engaged in ISO 14001:2015 initiatives and consume electrical and electronic equipment (EEE) to enhance their performance and profitability. The methodology employed an exploratory approach involving the application of general equilibrium theory (GET) to contextualize the study and generate relevant parameters for deploying the random forest regression learning algorithm for predictions. Machine learning was applied to 80% of the samples for training, while simulation was conducted on the remaining 20% of samples based on quantities of EEE utilized over a specific period, utilization rates, repair rates, and average lifespans. The results demonstrate that the model's predicted values are significantly close to the actual quantities of generated WEEE, and the model's performance was evaluated using the mean squared error (MSE) and yielding satisfactory results. Based on this model, both companies and stakeholders can set realistic objectives for managing companies' WEEE, fostering sustainable socio-environmental practices.

Keywords: Electrical and electronic equipment (EEE); Waste from electrical and electronic equipment (WEEE); General equilibrium theory; Random forest regression algorithm; Decision-making; Cameroon

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1. Introduction

The best living conditions and guaranteed survival depend on a healthy environment. International policies are becoming increasingly responsible and protective of this environment. However, even if good living conditions are supported by the consumption of electrical and electronic equipment (EEE), WEEE creates a retarding effect to these efforts through its exponential growth, estimated at more than 1,400,000 Mega tons by 2023 [1], and its poorly controlled management in most developing countries.

African developing countries, in their race towards a numerical balance [2], are becoming WEEE dumping grounds as a result of cross-border movements combated by the Basel Convention [3]. The fight against WEEE is thus becoming an uphill battle, as second-hand or end-of-life EEE is easier to access. As the lifespan of these EEEs is almost over, they very quickly become WEEE and are abandoned in the environment to the benefit of informal recyclers. Through their dismantling and open-air incineration activities, informal recyclers become catalysts for environmental pollution [4].

The hazardous nature of WEEE no longer needs to be demonstrated, either for the environment or for health. The incineration of WEEE also causes air pollution and greenhouse gas emissions [5]. Incineration ash has a high concentration of metals such as Cu > Pb > Zn > Mn > Ni > Sb > Cr > Cd and contaminates between 10 and 30 cm of the earth's crust [6]. Rahul Rautela [7] emphasizes the polluting properties of informal recycling activities on soil, air, and water.

On the human side, some of the substances resulting from incineration such as PBDD/Fs (polybrominated dibenzo-p-dioxins) are lipophilic and can bioaccumulate through the food web in the human body [8]. Many studies also found connections with elevated rates of spontaneous abortions, premature births, and reduced birth weights due to backyard WEEE recycling [7].

On the economic and social front, there has been a strong expansion of informal recycling trades employing mainly young people; this means the creation of between 4,000 and 6,000 direct jobs [9] in sub-Saharan Africa with rudimentary remuneration [10]. Conversely, the treatment of e-waste allows for entrepreneurship, job creation, reuse, and refurbishment for the sale of cheap electronics, less waste, and the recovery of metals [9].

In Cameroon, like everywhere else, companies consume common EEE to support their core business, and for reasons of social responsibility and contribution to sustainable development are called upon to play their part in the production of WEEE. An EEE is defined as equipment operating using electric currents or electromagnetic fields, as well as the production, transfer, and measurement of these currents and fields, designed to be used at a voltage not exceeding 1000 volts in alternating current and 1500 volts in direct current [11], A waste is economically conceptualized as a product whose physical and financial flow have the same direction [12], it is defined as any residue from a production, transformation or use process; any substance or material produced; or, more generally, any movable or immovable property abandoned or intended for abandonment [13]. A joint order in Article 2 distinguishes waste electrical and household electronic appliances (WEHEA) from professional waste electrical and electronic equipment (PWEEE) [11]. National waste management policy is oriented towards municipal solid waste collection, transport, and landfill [14].

Several research studies interested in understanding the growth of WEEE have proposed methods for estimating and calculating the amount of WEEE generated at national, regional, and international levels. However, it is difficult to approve calculation methods and Vanessa Froti and all [15] think that determining the quantities of global WEEE is difficult due to a lack of harmonization on the definition of WEEE, the difficulty of measuring the flows of legal or illegal cross-border movements; elimination of WEEE in ordinary garbage cans and informal collection and recycling practices. Research studies attempting to estimate the quantities of WEEE in developing countries, especially in Africa, have always deplored the lack of a historical database. This is due to the lack of control over EEE imports, which is a legacy of cross-border movements [16,3], and the limited data available held by agencies and organizations [17].

As WEEE production is the result of EEE consumption, it would be interesting to start estimating or calculating the quantities of WEEE generated by these economic agents. Companies in developing countries are not insignificant when it comes to WEEE production. They use EEE to provide saleable products and services for profit. The question arises regarding how to estimate or calculate the WEEE companies produce.

Trying to answer this question, we're going to analyze the use made of EEE in companies, to understand the path it takes. This step is important if we are to understand the stages undergone by an item of EEE before it becomes WEEE. Since we're talking about companies, the consumption of EEE is objectified, i.e., their consumption patterns are not necessarily similar to those of households. With this in mind, we propose a set of contextual hypotheses based on general equilibrium theory (GET). This theory is widely used in economics to analyze the behavior of economic agents and to understand and anticipate certain economic phenomena and interactions at both macro and micro levels. Adapting this economic theory to our phenomenon will enable us to propose a model for calculating WEEE quantities that is close to the realities of business.

This paper proposes a model for calculating the amount of WEEE produced by companies, taking into account the economic context of the company and its performance objectives. Assumptions derived from Walrasian equilibrium by adaptation simplify the calculation context of WEEE and the random forest regression learning algorithm will be deployed for prediction. The method we use will be both qualitative and quantitative. Qualitative in order to determine the stages in the EEE's journey until it becomes WEEE, and quantitative for reasons of manipulation of the numerical data collected to quantify the WEEE produced.

This article will be structured as follows: Section 2 will present the state of the art in WEEE estimation and calculation, the applications of GET to WEEE management, and the random forest regression algorithm; Section 3 will present the methodology used in this research, which is a mixture of qualitative and quantitative approaches; Section 4 will present the results of applying the model; Section 5 will be devoted to discussions and recommendations; and Section 6 will provide a conclusion to this research.

2. Literature work

The existence of WEEE and its inordinate growth rate is a fact. Given the harmful nature of this type of waste, we're seeing a great deal of progress in WEEE research. Many researchers have focused on the hazardous components of WEEE, such as PVC in wire coatings and cables, di (2-ethylhexyl) phthalate (DEHP), diisononyl phthalate (DINP), butylbenzyl phthalate (BBP), diisodecyl phthalate (DIDP) and dibutyl phthalate (DBP) [18]. Informal recycling activities expose nature and life to substances such as PCBs and chlorinated materials [19]; chlorobenzenes [20], triphenyl phosphates (TPPs), cadmium sulphide [21]; mercury, chromium, beryllium [22].

Other research has highlighted environmental impacts such as high concentrations of heavy metals in soils [23] and vegetation [24]. Concentrations of manganese, nickel, and bismuth were respectively up to 4, 11, and 53 times higher in e-waste soils than in reference soils [25]; high concentrations of Cu, Pb, Zn, and Cr in some soil samples in Yaoundé, exceeding recommended thresholds [26].

Research has focused on human and socio-economic impacts. Toxins released into the environment accumulate in human tissues [27]; they have been found in e-waste workers [28], surrounding populations [29] and represent environmental risks [10]. Informal e-waste recycling is a major source of income for many poor urban communities [30]. E-waste management has economic benefits such as financial stability, job creation, and community cohesion [31]. These impacts, requiring an effective response, have led to the application of concepts such as reverse logistics and the circular economy.

More recent articles look at reverse logistics and the circular economy as tools for sustainable WEEE management. The concept of circular economy and its link with trade and highlighting their different interactions are presented [32]. 110,000 tons of e-waste were collected, of which 80% were recycled into useful materials and 17% were recovered energetically through the circular economy in Holland in 2016 [33]. The circular economy deployment model adopted by China and the challenges facing the country are highlighted [34]. A mathematical model for managing end-of-life electronics, considering multiple manufacturers and retailers for reverse logistics [35]. A focus on approaches such as recycling, the adoption of circular economy concepts, the formulation of appropriate policies, and the use of advanced computational techniques are discussed as effective ways of managing e-waste, with the possibility of recovering valuable and critical materials, as well as the use of machine learning for monitoring and processing such waste [36]. These techniques for clean, sustainable management of WEEE contribute to the SDGs, but will only be fully appreciated once the quantities of WEEE produced have been brought under control.

With regard to estimating or calculating WEEE, a number of research projects have been carried out at both national and regional levels, using different methods depending on data availability and the type of EEE. The table below summarizes the state of the art in this field.

This state-of-the-art estimation or calculation of WEEE (**Table 1**) indicates that calculation methods differ based on the approaches and available data for certain EEE. These methods possess the distinct feature of being grounded in mathematical techniques and tools of varying complexity, which might not be readily understandable for common readers or users. Furthermore, these studies are focused on the quantities of WEEE at national or regional scales. Engaging with scales of this nature might appear relevant due to the requirements and achieved outcomes. However, discrepancies between the predicted results and actual reality can be notable.

This article adopts a "reverse" approach as it focuses on the consumption of EEE to propose a calculation method. The main producers of WEEE are economic agents such as households and businesses. SMEs use EEE to improve their activities and ultimately generate WEEE. In order to remain profitable and address environmental challenges, businesses need to manage EEE in a particular way, leading to potentially unique approaches to managing WEEE. Considering its economic specificity, we propose a calculation model for WEEE specific to the business context, drawing inspiration from general equilibrium theory (GET).

General equilibrium is an economic concept introduced by Léon Walras in his 1874 work, "Elements of Pure Economics or the Theory of Social Wealth". It aims to explain how prices are formed in markets by reducing the economic system to a model.

GET relies on three main characteristics [56]. Firstly, it is based on a system of interdependent variables representing quantities supplied and demanded in markets under certain price conditions. Secondly, it refers to the individual behaviors of economic agents. Rational individual choices are taken into account in the analysis, considering the constraints perceived by agents. The third characteristic of general equilibrium is that it relies on coordination through prices. Economic agents primarily coordinate through a system of prices that can be flexible, fixed, or partially fixed.

Any general equilibrium analysis explicitly or implicitly refers to these characteristics and takes a stance on each of them. Some research may emphasize certain characteristics, neglect them, or reserve them for other studies. The formalisms used to study general equilibrium are generally not directly transferable to other disciplines. However, the general idea of general equilibrium can be adapted to other fields of study by translating the characteristics according to the specific needs of each object of study in accordance with its extension principle.

The extension of GET to various research domains has allowed its application to the environment,

Table 1. Overview of existing methods for estimating or calculating WEEE.

Authors	**Methods**																		**Country/region**
	DRA	**TSA**	**FM**	**EA**	**IOA**	**Methods**										**GM**	**SD**	**MM**	
					TS	**MSM**					**SBM**		**MFA**	**PBM**	**SSLM**				
						SD	**DD**	**SM**	**CM**	**A2**	**SLM**	**C&U**							
Zeng et al. [37]													x						China
Duman et al. [38]																x			Washington
Islam and Huda [39]							x												Australia
Ravindra and Mor [40]												x							Chandigarh e India
Awasthi et al. [41]				x															European Countries
Tran et al. [42]											x								Vietnam
Pengwei et al. [43]							x												China
Babayemi et al. [44]													x						Nigeria
Guo and Yan [45]														X					China
Gomes et al. [46]	x																		Brazil
Kumar et al. [47]				x															Global
Kusch and Hills [48]				x															European Countries
Parajuly et al. [49]							x												Denmark
Dasgupta et al. [50]																	x		India
Hamouda et al. [51]											x								Algeria
Ikhlayel [52]					x	x	x			x		x							Jordan
Petridis et al. [53]							x		x										Global
Cao et al. [54]						x		x				x							China
Neto et al. [55]		x					x												Brazil

Note: Method (group): DRA—Disposal Related Analysis; TSA—Time Series Analysis; FM—Factor Model; EA—Econometric Analysis; IOA—Input-Output Analysis; IOA methods: TS—Time Step method; MSM—Market supply method; SM—Simple Delay; DD—Distribution Delay; SM—Stanford Method; CM—Carnegie Mellon Method; A2—Approximation 2 method; SBM—Stock-Based Model; SLM—Stock Lifespan Model; C & U—Consumption and Use method; MFA—Material Flow Analysis; PBM—Population Balance model; SSLM—Sales stocks and lifetime model; GM—Grey Model; SD—System Dynamics; MM—Mathematical Model.

specifically in the management of WEEE. Plambeck and Wang [57] highlight the importance of striking a balance between WEEE reduction and promoting sustainability in the electronics industry through regulations based on "purchase tax" and "disposal tax" and their impacts. Wakolbinger et al. [58] examine the influence of technical, commercial, and legislative factors on WEEE management and demonstrate the importance of the interaction between the supply and demand of precious materials in policy decisions.

Authors have focused on the WEEE supply chain and recycling, leading to the formulation of a variational inequality model used to obtain material flows and prices in a multi-level electric bicycle network, along with an algorithm for analyzing qualitative properties of the equilibrium model [59]. Another model analyzes a Cournot pricing game between manufacturers and consumer markets, offering interesting perspectives [60].

Research has examined the impact of government subsidies on recycled material flows in a decentralized reverse supply chain through an equilibrium model, revealing that the optimal allocation of subsidies to laptop collectors significantly increases the total quantity of recycled materials collected [61]. The allocation to transformers has a significant impact on equilibrium quantities and subsidy efficiency [62].

One study proposes an advanced computable general equilibrium analysis at the country level to assess the impacts and adaptations related to climate change. It focuses on Egypt and simulates the effects of climate change on consumption, investment, and income until 2050. The results indicate that, in the absence of adaptation investments, Egypt's real GDP could decrease by 6.5% by 2050, but adaptation measures could reduce this loss to around 2.6% [63].

GET is widely used to analyze the impacts of parameter variations on certain phenomena. However, few authors have drawn inspiration from General Equilibrium Theory to estimate the quantities of waste generated. Yuzuru Miyata [64] is one such author who constructed a computable general equilibrium (CGE) model to analyze the interaction between waste disposal/treatment and the economy in the city of Hokkaido in 1985. The model incorporates waste production and treatment for both businesses and households. The effects of waste pricing, promotion of recycling, and other factors on the economy, including income, prices, and well-being, are examined by applying the model [64].

Given that our study focuses on a specific economic agent, namely the enterprise, it is highly appropriate to provide context for this research. The challenges faced by businesses are certainly different from those of other EEE consumers. They need to optimize their investment returns and exhibit rational behavior. Thus, GET serves as the theoretical foundation that aligns with our research objectives.

The main objective of this article is to estimate or predict the quantities of WEEE. After simplifying our study context using GET, we will apply our data to a learning process. Our approach involves using a machine learning algorithm to estimate WEEE production.

Machine learning and its ability to solve problems in various domains have made it increasingly popular through its algorithmic solutions [65]. There are several learning algorithms available, including linear regression, support vector machines, decision tree classifiers, random forest regression, and neural networks [66]. In line with our need to quantify WEEE, the random forest regression algorithm will be our estimation algorithm.

Indeed, there are several regression methods such as linear regression, decision tree regression, gradient boosting regression, and random forest regression. Our choice is oriented toward Random Forest Regression due to its effectiveness in ensemble learning, where multiple decision trees are combined to make predictions [67]. This method has gained popularity owing to its ability to handle both categorical and numerical features, effectively capturing complex patterns and interactions. The algorithm offers the following key advantages:

1) Versatility: Random forest regression can accommodate various types of data, making it suitable for datasets with a mixture of feature types. And doesn't mean that the more trees, the better the pre-

diction.

2) Non-linear relationships: It has the capability to capture non-linear relationships between variables, allowing it to model complex data patterns effectively.

3) Robustness: Random forest regression addresses the issue of overfitting by aggregating predictions from multiple decision trees, thereby reducing individual tree biases.

These characteristics make random forest regression a suitable choice for estimating the amount of electronic waste generated by SMEs in developing countries. By considering the diverse nature of the data and capturing complex relationships, this method can provide reliable and accurate estimates for waste management planning and policy-making.

What makes this article innovative is its approach of moving from the specific to the general. In other words, it proposes a calculation model that is applicable to individual economic agents and can be generalized to multiple enterprises. From another perspective, this study takes into account the realities of the economic agents under investigation, in the truest sense of the term, and closely relates to the life cycle of EEE within enterprises. Lastly, the main innovation lies in the fact that the random forest regression algorithm is deployed for the calculation of the quantities of generated WEEE will be based on relevant parameters of EEE usage.

3. Research methodology

3.1 Area of study

In this study, the city of Douala in Cameroon was chosen as the place of study. It is located on the edge of the Atlantic Ocean, at the bottom of the Gulf of Guinea, and at the mouth of the Wouri River [68]. Given its openness to sea lanes for both Cameroon and countries of the Central African sub-region, it constitutes a geographically strategic location for the establishment of businesses. According to the National Institute of Statistics of Cameroon [69], this justifies the presence of 41.4% of modern enterprises (in the formal sector and producing a DSF) installed in the city of Douala in 2018. Our study was carried out in Cameroon, by its recognized status as a developing country and, more specifically, with ISO 14001: 2015-certified small and medium-sized companies in the economic capital Douala.

3.2 Data collection tools

In the first part of our structured interview guide, we were only able to obtain limited data, such as those necessary for calculating the rates related to the maintenance of EEE. The most significant rates included their repair rate, utilization rate, and average lifespan of the EEE.

The main input data for the model, specifically the quantities of available EEE within the company, were obtained through the review of the financial statements for the year 2021. The EEE selected for our analysis is based on their significance as support for the company's core activities and their representation across various industry sectors. These include "Phones", "Laptops", "Desktops" and "Air conditioners".

3.3 Sampling

For the sake of representativeness, our sample consisted of specific organizations based in the city of Douala. This choice was made due to Douala being Cameroon's economic pool. Companies are more diverse there than in other cities in the country. Our sampling technique was theoretical, as it selects participants according to a rationale based on the concepts that emerge during a study. The relevance of our sample stems from the fact that the people with whom we spoke were authorized managers and responsible for strategic or operational IT maintenance. Given that our study was carried out during the COVID-19 period, the accessibility and administration of an interview guide to collect qualitative and quantitative data proved to be more complicated in companies; hence, we eventually obtained a reduced number of samples.

The guide was drawn up in a detailed manner, in order to not deviate from the orientations that we have given ourselves around the following themes: general information about the company, general information on EEE and WEEE, company culture in WEEE material, and their EA (Environmental Aspects), regulatory and normative knowledge in terms of WEEEM (WEEE Management), controls and measures to prevent and fight against WEEE, and potential difficulties related to WEEEM.

3.4 Contextual hypothesis

1) The market for Electrical and Electronic Equipment (EEE) remains unsaturated, allowing for continued access to new EEE. The EEE available in the market is in excellent condition without any defects.

2) Equilibrium is achieved when the total quantity of EEE within the company is equal to the quantity of WEEE generated by the company. Factors such as utilization rate, lifespan, and repair rate contribute to the transformation of EEE into WEEE.

3) The company adopts a rational approach and optimizes the performance of its EEE. The decision to purchase EEE is based on forecasts of the generated WEEE. Emphasis is placed on the utilization rate, maintenance, and lifespan of the equipment to maximize efficiency.

- Utilization rate represents the actual usage of the devices relative to the predicted usage, indicating how the devices are used in practice.

- Lifespan refers to the average operational lifetime of the EEE, with average values considered for each type of equipment.

- Maintenance encompasses the maintainability of the EEE, focusing on actions such as repair, leading to the repair rate.

4) The company is environmentally conscious and aligns with the sustainable development goals (SDGs). It adheres to environmental laws and regulations by implementing appropriate practices for the management of its WEEE. The company actively contributes to sustainable development and environmental preservation.

3.5 Data analysis tools

Our analysis of the data for this initial survey category was conducted in two stages. The data were categorized into two groups based on their nature. Qualitative data was identified as relevant parameters impacting the life of Electrical and Electronic Equipment (EEE) in a business context. Quantitative data was utilized to construct data tables for each company.

The development of a machine learning algorithm using the Python programming language, based on the random forest regression method, enabled us to estimate the quantities of Waste Electrical and Electronic Equipment (WEEE) that could be generated over a one-year period.

3.6 Preliminary data processing

To begin with, we needed to simplify the expressions of relevant parameters influencing the life cycle of EEE in the business context.

The first parameter is the lifespan of the EEE. In this research, we have adopted the average lifespan of EEE based on existing studies, as in reality, these values are relatively consistent.

The second parameter is the utilization rate of the EEE. This is a performance indicator used by our sample companies. It is calculated by dividing the total duration of EEE usage by its maximum intended usage duration.

The third parameter is the repair rate of the EEE. All the companies in our sample prioritize the repair of EEE experiencing failures, which is also a performance indicator. It is highly regarded by our sample companies and is calculated as the ratio of the total duration of EEE interruption due to failures to the total number of interruptions for failure-related reasons (see **Table 2**).

3.7 WEEE estimation algorithm

To estimate the quantities of WEEE that can be generated over a one-year period, we developed an estimation algorithm based on the random forest

Table 2. Formula of parameters calculation.

Parameters	Mathematical expression	Observations
Lifespan (L)	L = Literature review average lifespan for each device	/
Using rate (U)	$U = (\sum u_i / u_{max}) \times 100$ UI = using time, u_{max} = maximum using time,	Rates are determined annually for each type of EEE by the company
Repair rate (R)	$R = (\sum r_i / N_i) \times 100$ r_i = interruption duration, N_i = number of failures	

regression method implemented in the Python programming language.

Here is an overview of the steps involved in the algorithm:

Step 1. Data collection: We gathered relevant data, including qualitative parameters impacting the life of EEE in the company and quantitative data used to construct data tables for each company.

Step 2. Data preprocessing: We simplified the expressions of the relevant parameters influencing the EEE lifecycle in the business context, such as the lifespan of EEE, utilization rate, and repair rate. This involved normalizing and transforming the data to ensure compatibility.

Step 3. Setting program: 1-Input Data

Let Dn = ((Ei, Xi), ..., (En, Xn)) be the training set, where Ei is an input vector representing parameters such as the quantity ofWEEE, utilization rate (U), repair rate (R), mean lifespan (L), and Xi is the corresponding amount of generated WEEE over a given period (see **Table 3**).

2-Random forest training: To train the random forest regression model, we follow the following steps:

- Tree construction: We create a set of M random regression trees, where M is the number of trees in the forest (we can let M approach infinity for better performance).

- Resampling: Before constructing each tree, we resample the training set D_n using a random variable Θ to obtain a new data sample D_n^(Θj) for each tree Θj.

- Node splitting: At each node of the tree, we randomly select m_tree directions from the input parameters E to perform a split according to the CART (Classification and Regression Trees) criterion.

- Tree Construction: We build the tree by performing successive splits until each cell (node) contains fewer data points than node size (see **Figure 1**).

Step 4. Model Training: Using the random forest regression method, we trained the algorithm on the preprocessed data. Random forest regression is a machine learning technique that constructs an ensemble of decision trees and combines their predictions to generate accurate estimates.

Step 5. Feature importance analysis: We performed a feature importance analysis to identify the parameters that have the most significant impact on the quantities of generated WEEE. This analysis helps in understanding the key factors driving WEEE

Table 3. Tabular representation of data organization.

	Company ($C_{1,\dots,8}$)			
	Phones	Desktops	Laptops	Air conditioners
EEE quantity (E^n)	$E_{1,1}^n ; \dots ; E_{1,8}^n$	$E_{2,1}^n ; \dots ; E_{2,8}^n$	$E_{3,1}^n ; \dots ; E_{3,8}^n$	$E_{4,1}^n ; \dots ; E_{4,8}^n$
Using rate (U)	$U_{1,1}^n ; \dots ; U_{1,8}^n$	$U_{2,1}^n ; \dots ; U_{2,8}^n$	$U_{3,1}^n ; \dots ; U_{3,8}^n$	$U_{4,1}^n ; \dots ; U_{4,8}^n$
Repair rate (R)	$R_{1,1}^n ; \dots ; R_{1,8}^n$	$R_{2,1}^n ; \dots ; R_{2,8}^n$	$R_{3,1}^n ; \dots ; R_{3,8}^n$	$R_{4,1}^n ; \dots ; R_{4,8}^n$
Lifespan (L)	L_1	L_2	L_3	L_4
WEEE generated quantities $^{(n+1)}$	$X_{1,1}^{n+1} ; \dots ; X_{1,8}^{n+1}$	$X_{2,1}^{n+1} ; \dots ; X_{2,8}^{n+1}$	$X_{3,1}^{n+1} ; \dots ; X_{3,8}^{n+1}$	$X_{4,1}^{n+1} ; \dots ; X_{4,8}^{n+1}$

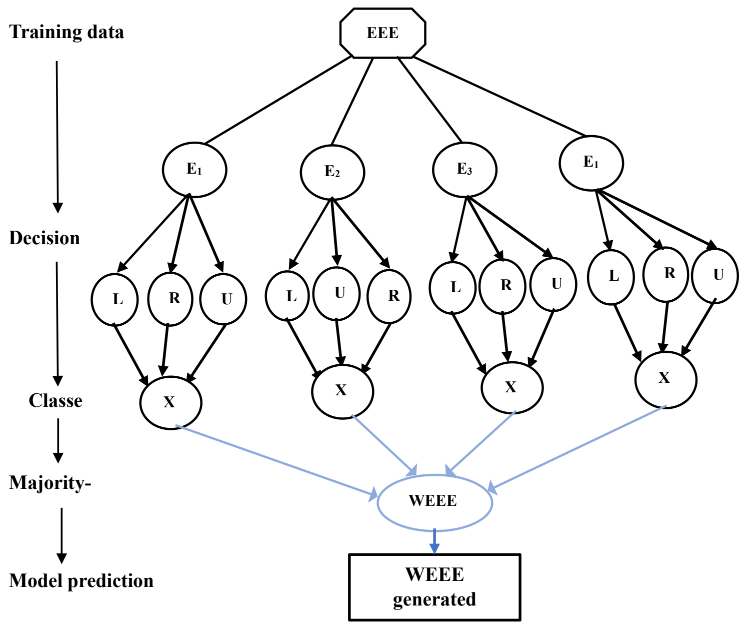

Figure 1. Random forest trees for an SME.

generation.

Step 6. Estimation of generated WEEE quantity: Once we have trained the ensemble of M trees, we can use the model to estimate the quantity of WEEE generated for new input data Xi, i.e., for new combinations of input parameters. The estimation of the generated WEEE quantity for an input vector Ei is given by:

m_(M,n) (Ei;Θ1,…,Θ_M,Dn) = 1/M ∑_(j=1)^M (1_(Ei∈An (Ei;Θj,Dn)) Xi)/(Nn (Ei;Θj,Dn)); where An (Ei; Θj, Dn) is the cell containing the input vector Ei in tree Θj, and Nn (Ei; Θj, Dn) is the number of data points (parameters) previously selected and falling into that cell.

-Final Prediction:

To predict the quantity of WEEE generated over a given period for a company, we take the average of the estimations for each input vector Ei:

m_ (∞,n) (Ei;Dn) = E_Θ [m_(M,n) (Ei;Θ, Dn)]; where E_Θ represents the expectation with respect to the random parameter Θ, conditioned on Dn. This represents the final prediction of the quantity of WEEE generated for a given company using the random forest regression model.

By using the trained algorithm, we applied it to the input data, which includes the quantities of EEE available in the company. The algorithm utilizes the identified parameters and their relationships to generate estimates of WEEE quantities for a one-year period. This was made possible by training on 80% of the data and using the remaining 20% for simulation purposes.

Step 7. Evaluation and validation: We assessed the accuracy and reliability of the generated estimates by comparing them to real data or conducting validation experiments. The mean squared error (MSE) was the most suitable scientific tool for this procedure as it is highly recommended for regression programs. This step ensured the effectiveness of the estimation algorithm.

4. Result analysis

This research follows a quantitative paradigm primarily because it utilizes quantitative data obtained from literature reviews, documentary research, and observations conducted on our samples. The definition of the study context using GET and the algorithmic programming of an estimation model through the Python programming language has led us to results that closely approximate reality.

The methodological result of our scientific approach is shown in **Figure 2** below.

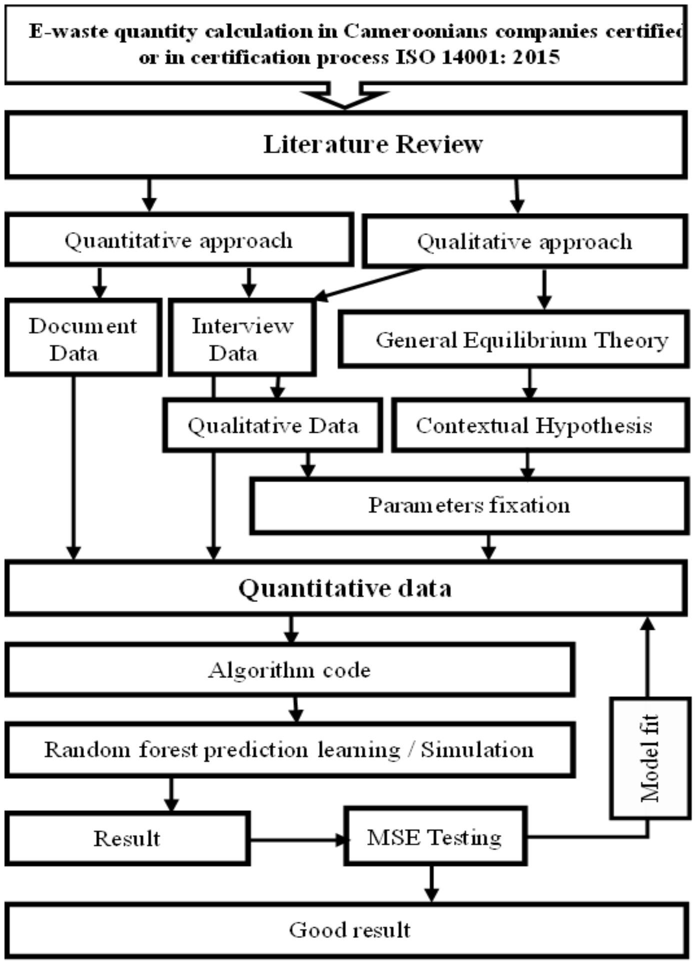

Figure 2. Research flowchart.

4.1 Qualitative results

The qualitative results of this approach allow us to identify the relevant parameters that describe the lifecycle of an EEE within companies. It emerges that, in the majority of cases, EEE devices have a certain average lifespan that is more or less known. The manner in which they are utilized significantly influences their fate, thus necessitating consideration of their utilization rate. Typically, before being permanently taken out of service, they undergo several repairs aimed at maintaining their operational status, which justifies the relevance of the repair rate. **Figure 3** represents the EEE using process. Furthermore, the relevance of the selected parameters is based on the fact that our sample SMEs have identified these three parameters as their main indicators for assessing and evaluating their EEE.

4.2 Quantitative results

As mentioned in our methodological approach, a crucial step was to develop and deploy the machine learning code that would correspond to our prediction problem, namely the random forest regression algorithm. The learning phase was conducted using 80% of the data, representing N = 8 companies from our sample. The remaining 20% served as a performance test for the regression model.

The training data used are summarized in **Table 4** below:

After machine learning by the algorithm, we proceeded to analyze the performance of our prediction. The performance of a regression model generally expresses the reliability of its application in terms of the quality of its prediction results. A good prediction should provide values close to reality. Our chosen performance indicator for this model was the mean

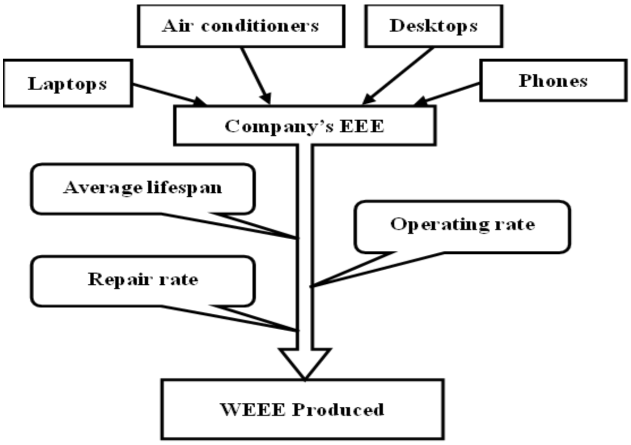

Figure 3. Flowchart of EEE using process.

Table 4. Tabular representation of data organization.

	Company ($C_{1, 2, 3, 4, 5, 6, 7,8}$)			
	Phones	**Desktops**	**Laptops**	**Air conditioners**
EEE quantity (E^{2020})	10, 15, 10, 21, 43, 12, 13, 4	13, 15, 8, 27, 11, 10, 10, 0	6, 8, 8, 12, 22, 2, 2, 4	8, 5, 4, 15, 9, 31, 32, 1
Using rate (U)	0.9, 0.9, 0.8, 0.7, 0.55, 0.7, 0.7, 0.6	0.9, 0.92, 0.9, 0.8, 0.7, 0.95, 0.95, 0.0	0.9, 0.89, 0.8, 0.75, 0.85, 0.7, 0.7, 0.7	0.8, 0.6, 0.7, 0.8, 0.9, 0.9, 0.6, 0.85
Repair rate (R)	0.0, 0.3, 0.35, 0.2, 0.2, 0.1, 0.15, 0.2	0.6, 0.7, 0.6, 0.6, 0.6, 0.15, 0.15, 0.0	0.7, 0.6, 0.4, 0.4, 0.5, 0.2, 0.25, 0.4	0.8, 0.8, 0.8, 0.8, 0.85, 0.1, 0.1, 0.23
Lifespan (L)	3	10.36	5.066	12.3
WEEE generated quantities $^{(2021)}$	4, 3, 2, 6, 8, 3, 1, 1	3, 2, 2, 3, 2, 1, 0, 0	1, 1, 1, 2, 3, 0, 0, 0	1, 1, 0, 3, 1, 0, 1, 0

squared error (MSE). Its application to our study yielded an MSE ranging from 0 to 0.9 for each of the studied EEE. **Figure 4** below provides a graphical representation of this performance evaluation.

This figure highlights the MSE as a measure of error evaluating the performance of our model. The values range from 0.3 to 0.8, indicating a discrepancy between the predictions and the actual data. This discrepancy, for us, is an area for improvement, but it remains close to the reality of our sample companies. Improving this performance would likely involve a much larger dataset, which would facilitate the algorithm's learning process and bring the predicted results even closer to reality.

The simulation of our model was conducted using data obtained from two explored companies. The results of the simulation are as follows:

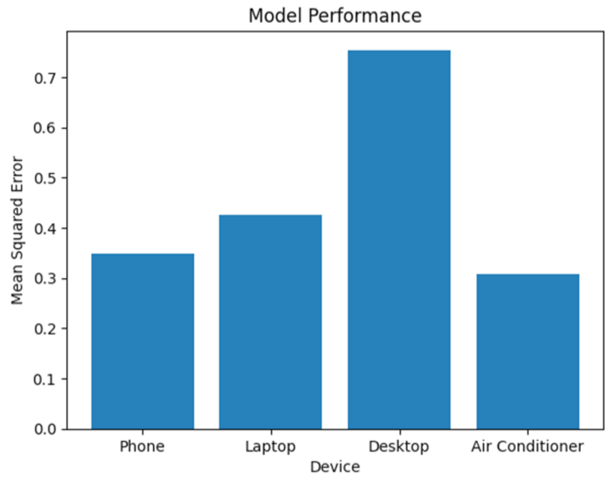

Figure 4. Graph of predicting performance.

Tables 5 and 6 allow us to formulate the following interpretation: For each of the companies, the deployed algorithmic model can predict the quantities of WEEE they are likely to generate. Based on the EEE used by these companies during the year 2020, along with their respective utilization rates, repair rates, and average lifespan of the studied EEE, the algorithm provided us with quantities of WEEE produced in 2021 that are very close to the actual values, with decimal differences. For example, in company 9, the algorithm estimated 3.59 waste phones, and the actual number was 4 waste phones. In companies 9 and 10, we observed 2 and 3 desktops, respectively, as waste produced in 2021, and the model predicted 3.59 and 3.55 desktops as waste for the same year.

A graphical representation of the prediction results (**Figure 5**) clearly reveals the proximity between the actual quantities of WEEE generated by types of EEE in 2021 and the predicted quantities of WEEE for the same year.

A graphical synthesis of both prediction results and reality provides a better understanding of the discrepancies between them.

Figure 6 clearly suggests some confusion between the units of predicted quantities of WEEE

Table 5. Predicted E-waste quantities from Company 9.

	Company (C_9)			
	Phones	Desktops	Laptops	Air conditioners
EEE quantity (E^{2020})	16	10	6	3
Using rate (U)	0,7	0,8	0,75	0,85
Repair rate (R)	0,22	0,6	0,4	0,8
Lifespan (L)	3	10,36	5,066	12,3
WEEE generated quantities $^{(2021)}$	4	2	1	1
WEEE predicted quantities $^{(2021)}$	3.59	2.21	0.92	0.74

Table 6. Predicted E-waste quantities from Company 10.

	Company (C_{10})			
	Phones	Desktops	Laptops	Air conditioners
EEE quantity (E^{2020})	22	17	5	7
Using rate (U)	0,8	0,9	0,8	0,75
Repair rate (R)	0,3	0,5	0,4	0,6
Lifespan (L)	3	10,36	5,066	12,3
WEEE generated quantities $^{(2021)}$	4	3	1	1
WEEE predicted quantities $^{(2021)}$	3.55	2.51	0.91	0.81

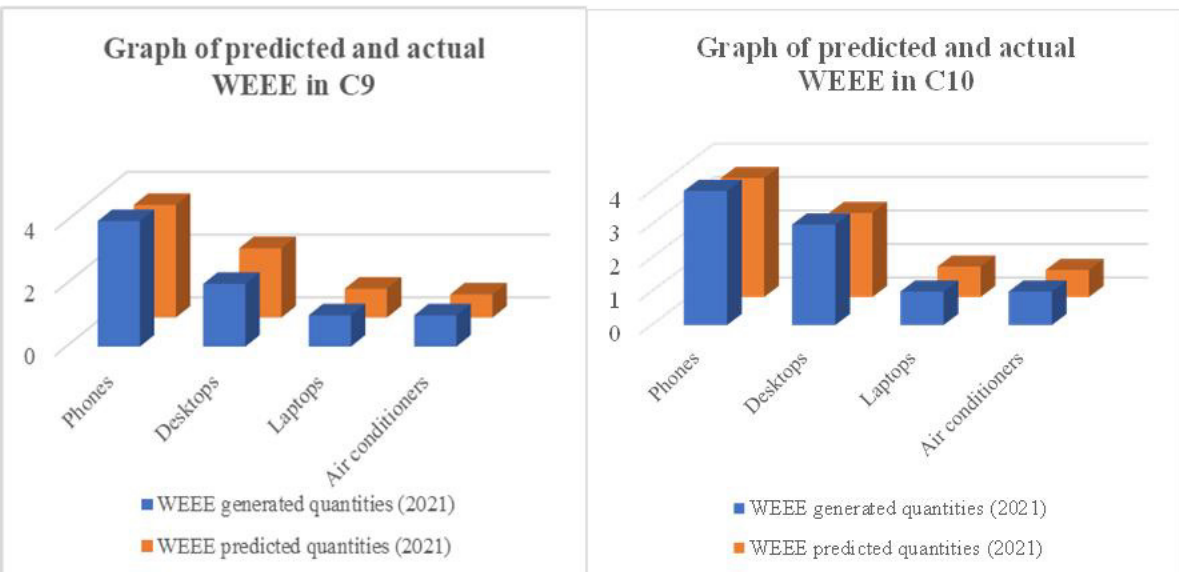

Figure 5. Graph of predicted and actual WEEE.

and the actual quantities produced for each of the studied EEE. This, in turn, confirms the performance of the prediction model. The visible prediction errors underscore the need for a larger dataset to refine the algorithm's learning process and, consequently, enhance its precision.

We can have an idea of the quantities of WEEE for the year 2022 if we obtain data regarding the quantities of EEE used by these organizations in 2021, as well as the parameter values related to factors such as lifespan, utilization rate, and repair rate for that specific year.

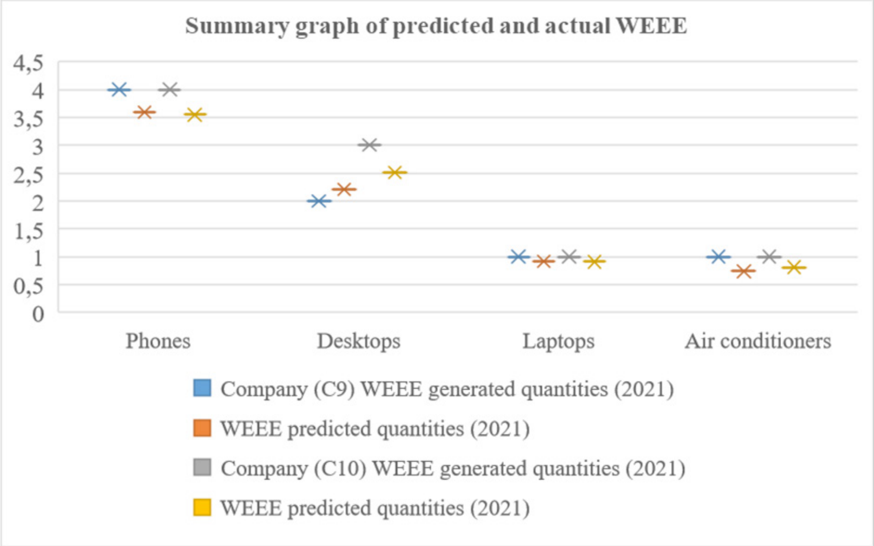

Figure 6. Synthetic graph of predicted and actual WEEE.

5. Discussion

This study allowed us to delve into the behavior of a specific type of economic agent, namely businesses, in Cameroon (a developing country). More specifically, we analyzed and highlighted the trajectory of EEE within the context of SMEs. The results led us to understand that the transformation of EEE into WEEE is influenced not only by its lifespan but also by its utilization rate and repair rate.

The method of calculating or estimating the quantities of generated WEEE appears better suited through the automated algorithmic learning technique based on random forest regression, provided accurate data is available. Given that businesses operate continuously, no organizational year goes by without the production of WEEE.

In comparison to existing works, conducting a direct comparative study is challenging due to the fact that the pre-existing works do not adhere to the same ideological approach as ours. Our approach quantifies WEEE among end consumers and aims to generalize it to find aggregated values over a specific period. The advantage of this approach lies in the fact that end consumers almost always have data on the EEE in use or consumed, and the main difficulty could be accessing this data. Conversely, other prediction approaches require considerable amounts of data, which might not always be available or need to be constructed.

Moreover, this study's strength lies in describing the journey of EEE in its context and considering the factors influencing their transformation into WEEE. This seems rare since existing works that share similar perspectives mainly consider the lifespan of EEE and/or planned obsolescence.

Regarding the calculation method, existing works propose statistical techniques and tools of varying complexity, which might not be easily reproducible for common users. In contrast, in our case, once the algorithm is available and well-trained, having input data is sufficient to generate results. The proposed prediction method is practical, accessible, and does not require statistical prerequisites from users.

One common aspect shared with other research might be that the method's performance is better demonstrated with larger datasets. However, considering the performance results of our method, having a large dataset might be necessary but not sufficient.

In conclusion, this discussion of the results highlights the practical, reproducible, and performance-driven nature of the proposed method.

5.1 Recommendations

It is no longer necessary to provide a historical overview of estimation methods used by researchers to calculate the quantities of WEEE. This research proposes a new approach to estimation methods that can be generalized to consumers of the same nature. Furthermore, the application of this method can be extended to any type of EEE consumer, provided that the specificity of parameters related to their transformation into WEEE is taken into account. In the past, calculation methods appeared complex, and data availability was limited. With this approach, the only remaining challenge lies in the availability of data.

5.2 Managerial implication

In practice, managing without measurement is merely blind action and management entails forecasting, organizing, directing, and controlling. This research proposes a tool for predicting the quantities of WEEE that will be produced by companies. It would serve the organization itself in assessing and revising its WEEE management strategy, setting reasonable targets to minimize its environmental footprint.

The potential benefits of this research for businesses are as follows:

- Informed decision-making: With a reliable model for estimating WEEE, businesses will be able to make more informed decisions regarding their electronic waste management policies. This may include waste reduction strategies, choices of recycling or revalorization options, and more relevant investments in sustainable WEEE management.

- Financial planning: By having a more accurate estimation of generated electronic waste, businesses can better plan for waste management costs and forecast future expenses. Considering that Cameroonian law on hazardous waste from businesses (referred to as PWEEE) places the responsibility for their evacuation, treatment, and disposal on the users and mandates that it must be done by approved service providers, this can lead to improved financial management and more efficient resource utilization in the near future.

- Compliance with regulations: Electronic waste management is subject to strict environmental laws in many countries. In the Cameroonian context, though the legislative framework for WEEE exists, its implementation suffers from infrastructure and rigorous monitoring insufficiencies. A reliable estimation model can help businesses comply with legal requirements regarding WEEE management.

- Social responsibility and brand image: Implementing responsible WEEE management can enhance a company's brand image by demonstrating its commitment to sustainability and the environment. This demonstration becomes more significant when backed by quantifiable forecasted objectives. A WEEE prediction model provides a forecast basis for the quantities of WEEE against which quantified and budgeted management practices and objectives can be aligned.

This research can bring significant advantages to businesses by improving their WEEE management. It can enable better financial planning, compliance with environmental regulations, and enhance their social responsibility and brand image. These improvements can contribute to the overall sustainability of businesses and their positive impact on the environment.

The potential benefits of this research at the governmental level are as follows:

- Waste management policies: By providing reliable estimates of the quantity of WEEE generated by businesses, this research can assist governments in developing more targeted and effective waste management policies. These policies may include incentives to encourage WEEE recycling and revalorization, as well as regulations to control and reduce electronic waste.

- Planning and resource allocation: Accurate estimates of WEEE produced by businesses will enable governments to better plan and allocate their resources for waste management. This may involve establishing collection infrastructures, recycling centers, and appropriate disposal sites.

- Monitoring environmental compliance: With a WEEE estimation model, governments can better monitor and assess businesses' compliance with environmental regulations regarding electronic waste management. This will allow corrective actions to be taken in case of non-compliance and ensure responsible WEEE management.

- Business and public awareness: The results of this research can be used to raise awareness among businesses and the public about issues related to electronic waste and the importance of proper management. Increased awareness can lead to more active participation by businesses and citizens in WEEE management.

- Collaboration with businesses: Accurate estimates of WEEE produced by businesses can facilitate collaboration between governments and companies to find effective and sustainable solutions for electronic waste management. Public-private partnerships can be encouraged to promote responsible WEEE management.

Overall, this research can have significant implications for governmental waste management strategies, resource planning, environmental compliance monitoring, awareness campaigns, and collaborative efforts with businesses to address the challenges posed by electronic waste.

By this research, governments would have a means to predict the quantities of WEEE generated by companies, contributing to the development of an effective national strategy for short, medium, and long-term WEEE management. It also serves as a control tool for monitoring the fate of WEEE.

The environmental, health, and social impacts of the rapid growth of WEEE in developing countries are undeniable. This research provides a quantified barometer for awareness programs emphasizing the importance of implementing responsible WEEE management practices to minimize their environmental impacts.

From the perspective of environmental regulations, this work offers targeted guidance on environmental objectives regarding WEEE production by companies. The choices and adoption of rules can be realistic and context-appropriate.

Additionally, a precise estimation of the quantities of generated WEEE serves as a data source for business opportunity analysis and can facilitate the commitment to invest in the eco-friendly treatment industry of WEEE.

5.3 Research limits

This study has certain limitations that should be taken into account. Firstly, the accurate estimation of WEEE produced by companies can be challenging due to the accessibility of reliable data. Companies have the particularity that all inputs are recorded in their financial documents, but they may not be readily available to the public.

This research may not have considered certain aspects related to EEE, such as their nature at the time of purchase, as companies may acquire second-hand EEE. An approach that incorporates cost-based estimation, such as the costs of purchasing EEE, maintenance costs, and/or EEE productivity, could have been included in the predictive analysis. The redefinition of WEEE, where declared WEEE may still be usable for another entity, could also influence the prediction results.

This work was conducted with a small sample size, totalling 10 companies, which may be considered less statistically significant for some researchers. Thus, there is room for further research that provides sufficient data to refine the trend of WEEE quantities produced.

Another limitation of this article is that the predictions are only feasible in the short term (1 year). It would be possible to make estimations for the medium and long term by aggregating predictions over multiple years. Additionally, it could be proposed for the algorithm to learn and make predictions for the medium and long term by incorporating parameter values corresponding to these time periods.

6. Conclusions

The field of management remains a complex area of study as it typically involves multiple disciplines. Our endeavor was to calculate or estimate the quantities of WEEE produced by companies. A review of the literature presented several studies with a similar objective. Each study distinguished itself by the chosen estimation method based on data availability and size. These studies primarily focused on larger scales of analysis. In contrast, our study concentrated on the sources of WEEE production and conducted research on the consumption of EEE by ISO 14001:2015 certified SMEs in the economic capital of Cameroon. It was found that the transformation of EEE into WEEE is influenced during consumption by parameters such as average lifespan, utilization rate, and maintenance, often expressed through repair rates. General Equilibrium Theory enabled us to contextualize and simplify this qualitative analysis while adhering to the paradigm of our population.

We needed to adopt an estimation method that was user-friendly, efficient, and up-to-date. Hence, our choice fell on the random forest regression machine learning algorithm. After developing the code using the Python programming language, data deployment was carried out through machine learning. 80% of our collected data was used for the algorithm to learn and generate predictive values of WEEE for one year. The remaining 20% of our collected data, representing data from two companies, served as a simulation, and the discrepancies were found to be insignificant. The performance test of our algorithmic model using the MSE method yielded values ranging from 0.3 to 0.8, indicating promising performance.

The significant contribution of this research lies in its hybrid methodology. Our study combined classical research methods with artificial intelligence through a learning algorithm to estimate the quantities of WEEE produced. Moreover, the application of GET established the foundation of this research and simplified the research context without losing sight of the fundamental objectives of our study population. The relevance of this research is that it provides the scientific community with an easy method for calculating or estimating WEEE, thereby resolving difficulties associated with calculation methods and shifting focus to data availability and accessibility issues.

This work represents a relevant management tool for organizations and institutions. By applying this method, organizations and companies have a kind of barometer that allows them to anticipate the quantities of WEEE they may produce in a given year and plan for their EEE needs accordingly. Given their environmental orientations, they have the opportunity to set realistic targets and define appropriate policies to reduce their environmental footprint and contribute to sustainable development goals. Institutions, on the other hand, have a concrete tool to anticipate the annual size of WEEE, which would enable them to develop a national policy and plan for managing business WEEE. It will now be possible to monitor the quantities of WEEE and their fate.

However, there are limitations to this research. The size of our sample could have been larger, but data collection was heavily disrupted by the COVID-19 pandemic. Health restrictions and the imposition of new habits significantly limited our contact with the study population. We do not claim to have considered all the aspects influencing the transformation of EEE into WEEE in companies. The prediction period in this research may seem short to some researchers, and future studies could explore medium or long-term predictions. Another limitation is that the model's performance evaluation could be questioned by employing an indicator other than MSE.

Future research should aim to improve the model by incorporating more real-world data collected in the field, enabling the algorithmic model to learn more and refine predictions, thus reducing the MSE values closer to zero. Consequently, the management of WEEE and the race toward contributing to sustainable development will also involve developing countries.

Author Contributions

Each author has made significant contributions to this manuscript, with roles as follows:

- Gilson Tekendo Djoukoue: Conception/design, Data collection, qualitative analysis and results interpretation.

- Idriss Djiofack Teledjieu: Development of a machine learning algorithm for prediction.

- Sijun Bai: Supervision, Review, and Validation of the final version for submission and publication.

Conflict of Interest

We declare that there are no conflicts of interest related to this research. None of the authors have any financial or professional relationships that could inappropriately influence the results or interpretations presented in this article.

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ARTICLE

Greening the Supply Chain: Drivers and Outcomes in the Korean Manufacturing Industry

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ABSTRACT

This research investigates the determinants of green supply chain management (GSCM) adoption and its impact on organizational performance, while considering the potential moderating factors influencing GSCM adoption. Despite the growing prevalence of GSCM practices among Korean firms, the factors driving their adoption have not received sufficient attention. To bridge this gap, the study uses structural equation modeling, integrating stakeholder theory and resource-based theory to explore how green entrepreneurial orientation (GEO), institutional pressure, and relational capital affect GSCM adoption. Additionally, the study explores the effects of GSCM implementation on competitiveness and economic performance. Drawing data from a sample of 213 Korean manufacturing firms, the PLS-SEM analysis highlights the significant influence of GEO, institutional pressure, and relational capital on GSCM adoption. Additionally, the study emphasizes the positive impact of GSCM implementation on firm competitiveness. These findings provide valuable insights for enhancing sustainability in supply chain management and are applicable to similar context countries such as Taiwan, China, Japan, and the Netherlands.

Keywords: Green supply chain management; Green entrepreneurial orientation; Institutional pressure; Relational capital; Competitiveness; Economic perform

1. Introduction

The 2015 Paris Agreement and the 2021 sixth special report by the Intergovernmental Panel on Climate Change (IPCC) have created increased pressure

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on firms worldwide to adopt strategies that reduce the negative impact of their products and services on the environment. With customers and regulatory authorities overwhelmingly supporting environmental protection, conservation is a top priority for firms worldwide [1,2]. In response, Korean firms are complying with strict operational standards to mitigate climate change and environmental damage. Accordingly, efforts are underway to strengthen organizational processes and behaviors to pursue green business strategies and practices [3,4]. These practices can help firms address key regulatory issues, such as competitive pressure, business performance, environmental protection, and operational excellence. Despite the growing interest of many Korean companies in environmentally friendly practices such as green supply chain management (GSCM), there is a lack of research on who actually adopts this approach and what its effects are. This study was conducted to address this curiosity and fill the research gap.

Primarily, the concept of GSCM integrates sustainable environmental practices into the traditional supply chain processes. This comprehensive business approach is designed to mitigate environmental degradation, focusing on green purchasing, manufacturing, logistics, and investment recovery [5]. Implementing GSCM practices helps firms improve their environmental, social, and operational performance, leading to a competitive advantage [6,7]. Waste reduction has emerged as a viable solution for reducing manufacturing costs, and GSCM is recognized as a key tool for achieving this goal [8,9]. Thus, firms must adopt innovative GSCM practices to enhance their operational efficiency, reduce costs, and improve existing value chains.

Several dimensions of GSCM have been examined in previous studies, including definition and scope, and the concept has been identified as the summation of green purchasing, integrated supply chains, and reverse logistics [10,11]. Researchers have also examined ecological supply chain management and its determinants and impact on various aspects of organizational performance (e.g., [11]). Firms are improving their supply chain management to maintain ecological standards through inter-organizational relationships, particularly with customers and suppliers [12]. For example, SONY has implemented a "green partner quality certification system", and encouraged its suppliers to follow environmental standards. Other global firms such as NIKE, IKEA, BOEING, and Ford are participating in sustainability projects with their customers and suppliers to restrict the use of chemicals and waste materials that endanger human and environmental health [13]. An increasing number of companies are incorporating sustainable practices in their supply chain management strategies to reduce their environmental impact and contribute to global efforts to save the planet.

Nevertheless, the existing literature lacks a comprehensive framework to explain the relationship between GSCM and operational performance. While some studies explore GSCM's antecedents, they often overlook the internal and external factors influencing this relationship [8]. Focusing on these factors is crucial as it provides a deeper understanding of how organizations can effectively implement GSCM practices and improve their operational performance [8,14,15]. To bridge this gap, our study analyzes real-world scenarios in the context of GSCM practices in South Korea, aiming to identify the antecedents, conduct, and performance while considering both internal and external influences. By unraveling these complexities, our research aims to provide valuable insights for researchers and practitioners and contribute to the advancement of sustainable supply chain management practices in the Korean industry.

This study explores various issues related to GSCM, leading to the following research questions:

Q1: To what extent do a firm's internal conditions impact GSCM adoption? Do a firm's green entrepreneurial orientation (GEO) and relational capital influence its GSCM adoption?

Q2: How do external conditions affect GSCM adoption? Specifically, to what degree do government institutional efforts influence firms' effective adoption of GSCM?

Q3: What is the impact of implementing GSCM practices on firm performance? This question is important, as it seeks to understand the extent to which the adoption of GSCM practices improves performance outcomes for firms.

This study addresses vital questions relevant to any firm considering or implementing GSCM. Drawing on stakeholder theory and resource-based theory, the research emphasizes the crucial role of GEO, relational capital, and institutional efforts in GSCM adoption within the Korean context. Investigating their interplay advances the understanding of their collective influence, offering valuable insights for academia and industry. Synthesizing relevant literature, the research constructs a comprehensive model based on key findings. Using 213 valid surveys from Korean manufacturing firms, the study examines how internal and external factors influence GSCM adoption. Despite the growing importance of GSCM, the existing literature lacks a comprehensive framework to elucidate its relationship with operational performance, especially regarding internal and external factors. This research fills the crucial gap in GSCM practices by examining antecedents, conduct, and performance in the Korean context, considering internal and external influences. The study's results provide valuable insights into academic literature and practical GSCM applications.

2. Literature review

2.1 Green supply chain management (GSCM)

A supply chain involves moving goods or services from their origin to end users, both internally and externally, within a firm [12]. However, traditional supply chain management results in energy wastage and environmental damage, leading to the emergence of GSCM as a solution [16]. In response to increasing societal and governmental pressure, GSCM has been implemented to reduce resource usage and pollution. As a result, academic research and literature have focused on areas such as institutional pressure, implementation, and evaluation of GSCM. Insights into these areas are essential for justifying the adoption of GSCM practices [8,17].

Described as a set of supply chain management (SCM) strategies, initiatives, and partnerships developed in response to environmental concerns, GSCM encompasses all stages of a product or service life cycle from design and procurement to production, distribution, utilization, reuse, and disposal [18,19]. Srivastava (2007) defined GSCM as "the integration of environmental considerations into SCM, including product design, material sourcing and selection, manufacturing processes, delivery of the final product to customers, and end-of-life management of the product after its useful life." [20]. Similarly, some scholars define GSCM as an environmentally friendly practice or eco-initiative that encompasses all stages of a product's lifecycle, including the design, production, and distribution phases [21,22].

2.2 Organizational performance

This study investigates the influence of GSCM techniques on organizational performance, encompassing both environmental and economic aspects. Existing research indicates that GSCM implementation positively impacts environmental performance but yields varying results for economic performance [23-25]. The heterogeneity of findings may stem from limited studies and the influence of internal and external factors on the GSCM-organizational performance link. This ambiguity poses a challenge for companies attempting to justify GSCM adoption, irrespective of their motives [26,27]. To accurately assess GSCM's impact, a comprehensive approach is essential [28]. Studies propose a multidimensional framework, combining financial and non-financial metrics, to gain a holistic understanding of GSCM's effects. By incorporating financial, environmental, and social dimensions, organizations can make informed decisions and align their strategies with sustainability goals, ultimately bolstering performance evaluations. This multidimensional perspective facilitates a more robust evaluation, leading to a deeper comprehension of GSCM's influence on organizational outcomes [29,30].

2.3 Theoretical background

This study is conducted in the context of two major theories. First, the stakeholder theory proposed by Freeman (1984) posits that organizations must maximize stakeholder value. These stakeholders comprise the organization, and the management must strive to fulfil their needs and interests while ensuring their rights and participation in the decision-making process [31]. The fundamental premise of stakeholder theory is the shift in accountability from beneficiaries to those affected or impacted by the firm's activities [32]. The normative, imperative, and strategic nature of the theory implies that stakeholders are intrinsically valuable and have a discernible effect on the organization's business performance [33]. Additionally, the theory contends that stakeholder pressure compels organizations to adopt strategies that promote environmental protection [34].

Freeman's (1984) seminal definition of stakeholders as "any group or individual who can affect or is affected by the achievement of the organization's objectives" encompasses shareholders, investors, employees, customers, suppliers, and public stakeholder groups, such as legislative governments and regulatory authorities that build infrastructure and markets, whose laws and regulations must be observed, and to whom taxes and other obligations are payable [35,36]. This definition establishes a connection between stakeholders and firm activities [37]. Regulatory stakeholders, such as the government and legislators, formulate and enforce environmental protection laws, whereas internal stakeholders wield relative power within the organization and influence firm performance. In contrast, market-oriented stakeholders affect firm performance through market relationships or trade [38]. As organizations generate externalities that cause negative and positive environmental outcomes, organizational and regulatory stakeholders exert increasing pressure on firms to mitigate the negative impact and promote positive environmental outcomes [39].

The resource-based theory contends that an organization's sustained competitive advantage is influenced by its heterogeneous resources that are valuable, rare, inimitable, and non-substitutable [40,41]. Resources refer to "stocks of available factors that are owned or controlled by the firm" [42]. The theory assumes that firms differ due to their unique resources, thereby establishing a connection between internal characteristics and competitive advantage [43]. Additionally, sustainable competitive advantage depends on the firm's ability to reintegrate its asset stocks and use them for new market opportunities, and to synchronize all resource management processes, including bundling and structuring the portfolio resources, while receiving feedback from the external environment, such as market forces [44]. According to Hitt et al. (2016), managers are responsible for selecting, developing and bundling resources to create, design and implement strategies [43]. These internal processes should also be linked to external suppliers in the supply chain because each activity along the chain requires resources and capabilities [43]. Thus, adopting GSCM enables firms to create valuable resources and capabilities, which are critical for competitiveness in the current eco-friendly business environment.

Informed by stakeholder and resource-based theories, this study proposes that green entrepreneurial orientation, institutional pressure, and relational capital, which are critical organizational resources and stakeholder pressures, influence a firm's decision-making concerning GSCM, and, subsequently, its outcomes. This approach is consistent with previous studies that accentuate the impact of internal and external stakeholder groups on a firm's adoption of GSCM practices [45]. **Figure 1** illustrates the study's conceptual model, and using this framework, hypotheses are developed to capture the relationships between the different constructs in the subsequent section.

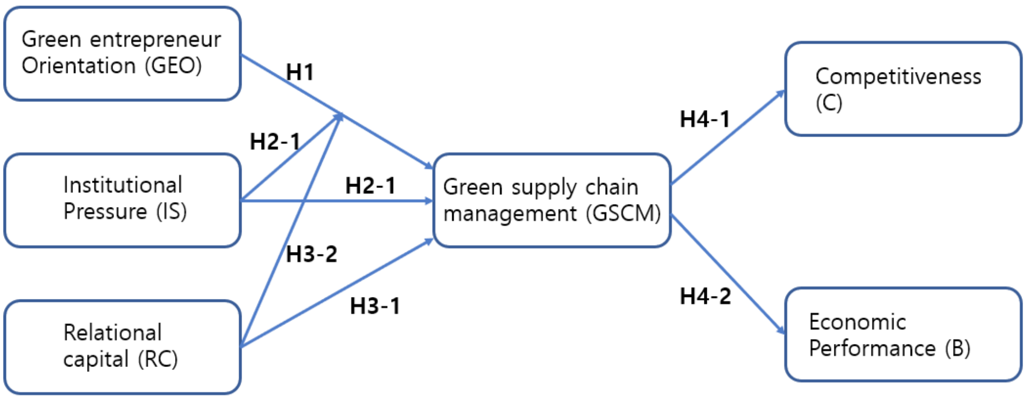

Figure 1. Conceptual model.

3. Model development and hypotheses

3.1 Green entrepreneurial orientation (GEO) and GSCM

A firm's GEO influences the adoption of GSCM practices significantly. Even though previous studies demonstrate a positive association between GEO and firm performance [46,14], the underlying mechanism remains largely unknown. Hughes et al. (2017) contend that the precise pathways through which GEO enhances organizational performance are not well understood beyond the direct effect [47]. To enhance comprehension, it is essential to employ a comprehensive measurement method to investigate how a firm's GEO serves as a critical antecedent to GSCM adoption [14].

The concept of GEO is defined as "the inclination of an entrepreneur to explore potential opportunities that reduce both economic and environmental costs by initiating green activities" [14]. The concept of GEO differs from environmental entrepreneurship and eco-entrepreneurship as it focuses on innovative behavior, proactive market participation, and commitment to take risks to promote green practices [14,48]. Three key factors explain the emergence of GEO: entrepreneurs' emotional attachment to green issues, regulatory and social pressure, and the desire to improve environmental and economic performance [49,50]. Entrepreneurs create value and drive business growth through their innovation, proactive behaviors, and risk-taking strategies. Similarly, green entrepreneurs create value beyond profit maximization by adopting green and sustainable business practices.

Entrepreneurial orientation (EO) encompasses a firm-level decision-making attitude that drives strategic processes and generates innovative ideas for organizational growth and rejuvenation [47]. In a similar vein, GEO seizes potential business opportunities through green activities, leading to both economic and ecological benefits [51]. This study firmly posits that GEO plays a pivotal role in motivating firms to adopt GSCM practices. The adoption and implementation of GSCM practices are recognized as inherently risky endeavors, primarily due to the increasing information asymmetry between firms and their suppliers [46,52]. Without a resolute commitment to green and sustainable growth, as well as a willingness to integrate GSCM principles into supplier relationships, firms may encounter considerable challenges in implementing these practices. However, when firm leadership demonstrates conscious engagement and a steadfast dedication to managing the supply chain, it can greatly facilitate the adoption of GSCM practices [53,54]. Consequently, this study hypothesizes that GEO exerts a positive influence on the adoption of GSCM practices.

H 1: GEO robustly and positively influences the adoption of GSCM practices.

3.2 Institutional pressure and GSCM

This study argues that while a strong leader's inclination towards GSCM is important, external factors contribute to the adoption of GSCM practices. Previous research has identified institutional pressure as a key facilitator in adopting GSCM [55,38,15,53,56]. This study proposes that institutional pressure, as an external factor, is a crucial determinant of GSCM adoption. Governments are increasingly demanding corporate action toward environmental sustainability by enforcing regulations, resulting in many firms developing green strategies to meet customer requirements and gain competitive advantage, such as obtaining ISO 14001 certification for environmental management [57].

Institutional pressure is a key area in sustainability research, and this study examines the mechanisms through which it affects the adoption of GSCM practices. Institutional pressure creates a sense of urgency to comply with regulations and societal expectations. For example, governments may penalize firms that do not adhere to environmental standards, urging them to adopt GSCM practices. Customers, investors, and other stakeholders can exert institutional pressure to demand sustainable products and services, forcing firms to meet these expectations and remain competitive. Moreover, institutional pressure legitimizes GSCM practices and can help firms overcome their internal resistance to change. Conforming to societal norms and expectations, firms are likely to gain support from employees and other internal stakeholders for implementing GSCM initiatives. Thus, institutional pressure plays a critical role in GSCM adoption by incentivizing and legitimizing sustainable business practices.

This study highlights the increasing demand for environmentally sustainable strategies from stakeholders and interest groups, such as customers, political and social entities, religious groups, local communities, and regulatory bodies [58,59]. Specifically, this study argues that green entrepreneurs who perceive the importance of legitimizing their operations in a sustainability-oriented environment are more responsive to institutional pressure and adopt green business approaches, such as GSCM, to survive [60,12].

The study suggests that green entrepreneurs, who view “green” as a new paradigm and “greening” as a sustainability-oriented business management approach, recognize the significance of legitimizing their operations within a sustainability-focused business environment [52].

Thus, this study hypothesizes that:

H 2: Institutional pressure affects GSCM adoption.

H 2-1: Institutional pressure positively influences the adoption of GSCM practices.

H 2-2: The outcome of GEO on GSCM practices is more substantial when institutional pressure increases.

3.3 Relational capital and GSCM

A firm’s internal conditions play a critical role in the adoption of GSCM practices. Relational capital is an essential aspect of green practices as it captures the value inherent in collaborative buyer-supplier relationships and the knowledge derived from such relationships [61]. Trust, obligation, respect, and friendship are integral components of relational capital that actors have formed with each other through a history of interactions [62]. Research shows that relational capital is the lubricant that stimulates environmental responsibility and the adoption of GSCM practices, including a wide range of inter-firm activities such as green innovation in co-procurement, co-production, reverse logistics, and distribution [52,63,64]. Relational capital supports green innovation activities in GSCM by engaging valuable members in the supply chain network [65].

Social network theory contends that promoting cooperation among supply chain members is a significant challenge in implementing GSCM [66]. Effective communication, reduced opportunism, cooperative response to unforeseen issues, and the ability to adapt are critical to GSCM practices [67,68]. Strong social capital improves GSCM engagement by building and maintaining relationships based on trust and loyalty and indicates a greater capacity for green innovation and better deployment of GSCM practices [69,61]. Thus, leaders with strong GEO are more likely to adopt GSCM practices when their firms possess strong social capital.

Thus, this study hypothesizes that:

H 3: Relational capital impacts the adoption of

GSCM practices.

H 3-1: Relational capital directly influences the adoption of GSCM initiatives.

H 3-2: The effect of GEO on GSCM practices is stronger when a firm possesses sufficient relational capital.

3.4 Impact of adopting GSCM practices on firm performance

Adopting GSCM practices can enhance a firm's performance across multiple dimensions, including environmental, economic, and social [67,56]. Environmental performance, the first dimension, involves reducing air and water pollution, solid waste, and hazardous materials, and minimizing environmental accidents during economic activities. The second dimension, economic performance, focuses on enhancing efficiency and cost savings through the adoption of GSCM practices such as waste reduction, improving resource productivity, and enhancing energy efficiency. Social performance measures the impact of GSCM practices on the well-being and satisfaction of employees, customers, suppliers, and other stakeholders in the community [30,67]. These multiple dimensions of organizational performance must be considered when implementing GSCM practices to realize optimal benefits.

Implementation of GSCM is expected to improve firm performance; however, empirical evidence shows mixed results. Specifically, in the context of the Chinese market, some studies have found that GSCM has a positive influence on economic performance by improving environmental and operational performance [70]. Additional research by Yu et al. (2017) demonstrated that collaboration with green initiative suppliers affects environmental and operational performance positively [71]. Feng and Choi (2017) reported that GSCM practices such as green purchasing and innovation can enhance environmental and economic performance [72]. Feng et al. (2018) also suggested that improved environmental and operational performance through GSCM adoption can enhance financial performance [73]. However, some studies have reported adverse performance outcomes with GSCM. For example, eco-design, reverse logistics, green purchasing, and customer cooperation have not significantly improved performance [74,67].

The impact of GSCM practices on firm performance is mixed, stemming from a multitude of factors such as varying industry contexts, complexity and variability of GSCM practices due to different approaches and implementation levels, and the lack of standardized performance measurement methods [75]. Previous research showed that using a combination of economic performance and competitiveness may yield a more comprehensive evaluation of the impact of GSCM practices on firm performance [76,54]. Economic performance and competitiveness are widely accepted as measures of business performance. They are easily quantifiable and comparable across firms, enabling a direct assessment of the impact of GSCM practices on performance [76]. Additionally, examining financial and non-financial factors by focusing on economic performance and competitiveness facilitates a more holistic evaluation of firm performance, eventually providing a more comprehensive understanding of the impact of GSCM practices on a firm's overall performance.

This study defines economic performance as financial performance, encompassing metrics such as revenue, profit, return on investment, and market share [76]. In contrast, competitiveness pertains to a firm's ability to compete effectively in the marketplace, considering factors such as cost efficiency, product quality, and innovation [54,28]. These measures offer a concrete and tangible means to evaluate the financial and operational advantages of GSCM practices, namely cost savings achieved through waste reduction and increased supply chain efficiency [18,76]. Economic performance and competitiveness are crucial for a company's long-term success, as they are interdependent. However, economic performance is a relevant short-term performance measure, given that financial metrics such as revenue and profit clearly indicate a firm's financial health in the short term [76]. In contrast, competitiveness measures may require more time to reflect a firm's performance changes.

This study posits that the adoption of GSCM practices yields positive outcomes on economic performance and competitiveness. First, such practices can help firms reduce their environmental impact by reducing waste, conserving resources, and mitigating negative environmental effects. These practices can have positive long-term implications for operational efficiency as they can lead to cost savings owing to improved energy efficiency, increased recycling, and reduced waste, ultimately resulting in lower operating costs. Additionally, firms can manage their supply chain risks better, improve product quality, and enhance customer satisfaction, leading to increased competitive advantage and customer loyalty. In fact, GSCM practices improve firms' financial performance by increasing their revenue and profits. For instance, by enhancing the sustainability and efficiency of their supply chain operations, firms can reduce costs, improve productivity and innovation, and respond better to market demand, thereby improving their overall competitiveness.

Thus, this study hypothesizes that:

H 4: Adopting GSCM practices impacts firm performance positively.

H 4-1: Adopting GSCM practices has a positive influence on firm competitiveness.

H 4-2: Adopting GSCM practices positively affects a firm's economic performance.

4. Research methods

4.1 Sampling and data collection

Drawing on prior research [9,77], firms that hold ISO 14000 series certification are defined as entities that implement GSCM practices. A sample of 926 manufacturers was selected from the Corporate Information Database (TS2000) using predetermined selection criteria, and e-mail surveys were conducted to collect the data. The Korea Chamber of Commerce and Industry provides information on companies through the TS2000. It includes databases of business and audit reports submitted to the Financial Supervisory Service by various corporations, such as technology-intensive small and medium enterprises (SMEs), young entrepreneurial firms, well-established firms, and strongly internationalized firms. The diverse backgrounds of target firms were relevant to this study.

The online survey collected a demographic profile and measurement items related to GEO, GSCM, competitiveness, economic performance, and internal/external conditions. To ensure the choice of suitable respondents, this study targeted founders and senior and mid-level managers of listed firms. Recruitment was conducted via email, social networking sites, and telephone. Of the 926 survey questionnaires, 213 effective responses were obtained between June 2022 and September 2022. The minimum sample size for reliable PLS-SEM analysis depends on model complexity, effect sizes, and desired power. Some recommend a minimum of 100 samples [78], but no fixed rule exists. The response rate exceeded the minimum standard of 20% [79], reaching 23%. **Table 1** provides an overview of the participating firms' characteristics.

4.2 Measurements

The items were assessed on a 7-point Likert scale ranging from "strongly disagree" (1) to "strongly agree" (7). Drawing on Li et al. [80] and Jian et al. [14], four items were employed to measure the GEO. GSCM practices were evaluated using five items based on the work of Zhu et al. [67], focusing on the green supplier and customer management practices of the value chain's upstream, internal, and downstream components. Drawing on prior research, two items were used to assess the extent of institutional pressure as an external condition. Relational capital was measured using three items as suggested in the literature [45,61]. Finally, four items were used to measure a firm's competitiveness and assess improvements in quality, efficiency, design, and patenting. Economic performance was evaluated based on respondents' views of their respective firm's performance over the past three years in terms of market share, customer satisfaction, and profitability using three items, as outlined in the previous literature [18,76]. **Table 2** summarizes all the constructs, measurement items, and their respective sources.

Table 1. Sample profile (n = 213).

Respondent composition		**Firm composition**	
Gender		Type of manufacturing	
Male	194	Information Technology	49
Female	19	Automobile	42
		Machine & equipment	41
Age		Transportation & logistics	35
31-40	53	Chemical	32
41-50	83	Others	14
51-60	77	No. of employees	
		< 50	17
Education		51-300	108
Post-graduate (Master, Ph.D.)	55	301-500	34
Graduate	153	501-1,000	32
High school	5	1,000 <	22
		Revenue ($1 = 1,240 won)	
		< $8mil	41
		$8mil-$40mil	53
		$40mil-$80mil	66
		$80mil-$400mil	28
		$400mil <	25

Table 2. Measurement of construct items.

Construct	**No.**	**Item**	**Sources**
Green entrepreneurial orientation (GEO)	GEO1	Our firm favors a strong emphasis on green practices, such as R & D, technological leadership, and innovation	[14]
	GEO2	When facing uncertainty, we adopt a proactive position to seize potential green opportunities	
	GEO3	In dealing with competitors, we initiate green actions that competitors respond to	
	GEO4	In dealing with competitors, we adopt a competitive “undo- the competitors” position	
Green supply chain management practices (GSCM)	GSM1	Providing design specifications to suppliers that include environmental requirements for purchased items	[67, 12]
	GSM2	Cooperation with suppliers for environmental objectives	
	GSM3	Suppliers’ ISO14001 certification	
	GSM4	Second-tier supplier environmentally friendly practice evaluation	
	GSM5	Cooperation with customers for cleaner production	
Competitiveness (C)	C1	Improvement in product and process quality	[76]
	C2	Improvement in efficiency and productivity	
	C3	Innovation in product and process design	
	C4	Patenting of products and processes	
Economic performance (B)	B1	Our market share and sales has increased during the last three years compared to competitors	[18]
	B2	Our customer satisfaction level has increased during the last three years compared to competitors	
	B3	Our profitability has increased during the last three years compared to competitors	
Institutional pressure (IP)	IST1	There are frequent government inspections or audits on my firm to ensure that the firm complies with environmental laws and regulations	[45]
	IST2	Increased awareness of environmental issues among our customers and stakeholders	
Relational capital (RC)	RC1	Relationship with key suppliers is characterized by close, personal interactions at multiple levels	[61]
	RC2	Relationship with key suppliers is characterized by mutual respect at multiple levels	
	RC3	Relationship with key suppliers is characterized by mutual trust at multiple levels	

4.3 Method of analysis

This study uses the structural model to examine the path relationships among the various constructs in the proposed model (see **Figure 2**). The PLS-SEM (4.0) technique was employed to test the proposed hypotheses, as it is capable of assessing the measurement of latent variables, while also testing the relationship between latent variables with a relatively small sample size [78]. A T-test was conducted to evaluate non-response bias, and the results showed no significant differences in basic attributes, such as size, industry, sales, etc., between early and late responses. Therefore, non-response bias is not expected to impact the subsequent analysis.

5. Results and discussion

5.1 Measurement model

Confirmatory factor analysis (CFA) was used to assess the reliability and validity of the measured constructs [81]. Composite reliability and Cronbach's alpha were used to determine the reliability. **Table 3** shows that all composite reliability values for the first-order constructs exceeded the 0.6-0.7 threshold value, and Cronbach's alpha values also matched or exceeded this threshold. These findings support the model's reliability [78]. This study employed the average variance extracted (AVE) approach to assess convergent validity. The AVE values for all constructs exceed the acceptable threshold value of 0.5, indicating good convergent validity. Discriminant validity was evaluated using the Fornell-Larcker criterion, which requires that the square root of each construct's AVE exceed its correlations with other constructs. **Table 4** presents the results of the Fornell-Larcker criterion, demonstrating that the square roots of the diagonal elements (representing the construct's AVE) were greater than those of the off-diagonal correlations, providing evidence of discriminant validity.

Table 3. CFA results.

Construct and items	Loading	Cronbach's α	CR	AVE
Green entrepreneurship orientation			0.831	0.630
GEO 1	0.847	0.806		
GEO 2	0.827			
GEO 3	0.781			
GEO 4	0.714			
Green Management Practice			0.854	0.630
GSM 1	0.765	0.853		
GSM 2	0.812			
GSM 3	0.817			
GSM 4	0.833			
GSM 5	0.737			
Economic performance			0.678	0.580
B1	0.779	0.664		
B2	0.684			
B3	0.816			
Competitiveness			0.746	0.563
C1	0.735	0.743		
C2	0.754			
C3	0.782			
C4	0.729			
Institutional pressure			0.852	0.871
INST1	0.932	0.852		
INST2	0.934			
Relational Capability			0.818	0.695
RC1	0.835	0.780		
RC2	0.915			
RC3	0.741			

Table 4. Discriminant validity (Fornell-Larcker criterion).

	B	C	G	GEO	IST	RC
B	**0.762**					
C	0.064	**0.750**				
G	0.139	0.676	**0.794**			
GEO	0.086	0.527	0.543	**0.794**		
IST	0.103	0.422	0.525	0.322	**0.933**	
RC	0.134	0.405	0.528	0.678	0.346	0.833

5.2 Structural model

Based on the analysis using the PLS-SEM technique, the result of hypotheses testing is presented in **Figure 1** and **Table 5**. This study followed two steps to test the proposed study hypotheses. First, a direct path analysis of latent variables was tested for significance through bootstrapping of 5000 subsamples. Second, we analyzed the moderating effects of institutional pressure and relational capital on GSCM. The explanatory power of the structural model was examined using the R-square value of the dependent variable. The results of the structural model, as presented in **Figure 1**, demonstrate that GEO, institutional pressure, and relational capability explain 45.8% of the variance in green management practices, which in turn explains 45.6% of competitiveness, thereby providing a good explanation for the variance in each latent variable [78,81].

The association between independent and dependent variables was tested using the path coefficient β and t-statistics. According to the PLS-SEM results in **Figure 2**, GEO (H 1: β = 0.276, t-statistics = 3.019), institutional pressure (H 2-1: β = 0.348, t-statistics = 4.030), and relational capital (H 3-1: β = 0.187, t-statistics = 2.011) significantly influence the adoption of GSCM, in turn, this enhances the competitiveness of the responding firms (H 4-1: β = 0.676, t-statistics = 13.705). However, institutional pressure and relational capital do not moderate the relationship between GEO and the adoption of GSCM (H 2-2: β = 0.017, t-statistic = 0.169, and H 3-3: β = 0.053, t-statistic = 0.696, respectively). Furthermore, adopting GSCM did not improve economic performance (H 4-2: β = 0.139, t-statistics = 1.723). The findings of the hypotheses tests are summarized in **Table 5**.

5.3 Discussion

This study investigated the relationship between green-oriented leadership and the adoption of GSCM practices in the Korean manufacturing sector. The results support the first hypothesis, that green-oriented leaders are more likely to adopt GSCM practices than their non-green counterparts [54,28]. To effectively

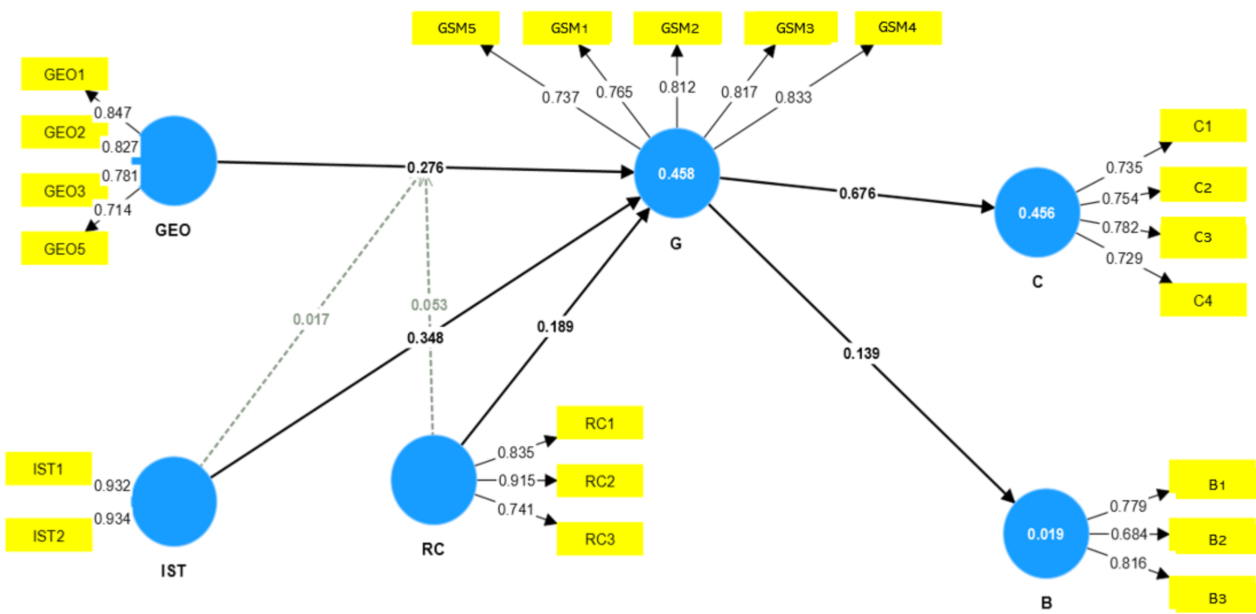

Figure 2. PLS-SEM results.

Table 5. Summary of hypotheses results.

Hypotheses	Result
H 1: Green entrepreneurial orientation (GEO) influences the adoption of GSCM practices positively.	Supported
H 2-1: Institutional pressure influences direct adoption of GSCM practices. H 2-2: The effect of GEO on GSCM practices will be stronger when institutional pressure increases.	Supported Not supported
H 3-1: Relational capital influences the adoption of GSCM practices directly. H 3-2: The effect of GEO on GSCM practices is stronger and more pronounced when a firm possesses sufficient relational capital.	Supported Not supported
H 4-1: Adopting GSCM practices has a positive impact on firm competitiveness. H 4-2: Adopting GSCM practices will positively impact a firm's economic performance.	Supported Not supported

implement GSCM, proactive efforts are required to transform traditional supply chain management practices and identify new opportunities for environmental change. Compliance with environmental regulations and the need to address public concerns in the South Korean context requires efficient use of energy and natural resources. Achieving an integrated ecological and sustainable economy through GSCM demands close collaboration with suppliers and customers, departing from decentralized management and transforming operating systems into a social-ecological economy. However, the successful implementation of GSCM practices relies on proactive and risk-taking green leaders in the Korean manufacturing sector. Their commitment and visionary attitudes drive adoption and implementation, overcoming barriers and fostering a culture of sustainability throughout the supply chain. Green leadership is vital for achieving environmental protection, social responsibility, and long-term business success.

Institutional pressures, including government regulations and incentives, have positively influenced the adoption of GSCM practices in Korean firms, as supported by this study's second hypothesis. The Korean government is committed to achieving carbon neutrality and reducing greenhouse gas emissions by 2050, leading to the implementation of ESG (environmental, social, and governance) supply chain management practices for Korean companies. The government requires ESG due diligence in the supply chain, with penalties imposed on non-compliant companies, and support for GSCM practices through various partnership programs and funding loan-use products. This study provides empirical evidence affirming the efficacy of government initiatives in promoting GSCM practices [45]. It emphasizes the significance of institutional pressure as a driving force for fostering environmentally responsible practices within the manufacturing sector. The study underscores that the successful implementation of GSCM practices hinges upon firms' willingness to undergo transformative changes in traditional supply chain management approaches. Additionally, collaboration with suppliers and customers is vital in collectively working towards the establishment of a sustainable social-ecological economy. These findings highlight the crucial role of both governmental and organizational efforts in advancing sustainable practices and fostering a more environmentally conscious and socially responsible manufacturing sector.

Previous research suggests that embracing green policies enhances institutional legitimacy and moral support for green entrepreneurs [38,15,53]. However, this study does not find evidence to support the notion that institutional pressure, as an external moderating condition, enhances or moderates Korean green entrepreneurs' propensity to adopt GSCM practices. It is commonly believed that a social policy, such as GSCM, can promote social consensus. Contrary to expectations, the findings of this study do not provide evidence to support the notion that institutional pressure, as an external moderating condition, enhances or moderates the propensity of Korean green entrepreneurs to adopt GSCM practices. While it is commonly believed that social policies, such as GSCM, can promote social consensus, the study reveals that institutional pressure for GSCM does not primarily act as a coercive force compelling Korean green entrepreneurs to conform to green government policies. Instead, the adoption of GSCM practices is driven by the entrepreneurs' personal vision and does not necessarily align with the pursuit of institutional legitimacy or social consensus. Consequently, the findings of this study do not support hypothesis 2-2, indicating a deviation from the anticipated relationship between institutional pressure and the adoption of GSCM practices among Korean green entrepreneurs.

Effective coordination between suppliers and customers forms a unique aspect of GSCM practices, distinguishing them from other practices, according to previous studies. Such close coordination facilitates knowledge sharing and collaboration and green environmental collaboration in GSCM. However, not all firms can fully realize the benefits of GSCM through close coordination and cooperation. Firms with strong relational capital, including comprehensive partner and supplier networks that provide valuable resources and information, are better positioned to exploit the benefits of GSCM. Trust and loyalty are intrinsic components of relational capital, and they can be effectively harnessed through the profound knowledge possessed by partner members. This study confirms that Korean firms with strong relational capital are more likely to adopt GSCM practices, thus supporting H 3-1. Relational capital, such as in-depth knowledge and a mutual understanding of government regulations, industry standards, and market conditions, enables firms to address complex issues more effectively. However, firms with strong relational capital may also face increased pressure from partners to adopt GSCM.

This study shows that, primarily, green entrepreneurs are not motivated to increase their engagement in GSCM practices by perceiving stronger relational capital, which does not support H 3-2. Further examination is necessary to confirm these findings. This finding can be attributed to various factors that deserve careful consideration. One potential reason is the possibility that a lack of awareness hampers the conversion of robust social capital into knowledge of GSCM practices and their associated benefits. Alternatively, green entrepreneurs, despite possessing stronger social capital, may prioritize other pressing business concerns over the adoption of GSCM practices. Moreover, cost constraints could discourage green entrepreneurs with substantial social capital from embracing GSCM practices. These multifaceted dynamics underscore the need for a comprehensive understanding of the contextual factors influencing the adoption of GSCM practices among green entrepreneurs.

H 4-1 is supported showing that GSCM practices improve firm competitiveness. Previous studies yielded mixed outcomes regarding the impact of GSCM on organizational performance, possibly because of measurement limitations and lack of empirical evidence. This study's focus on two dimensions of organizational performance—competitiveness and economic performance—clarifies the benefits of adopting GSCM. The respondents deemed that GSCM practices contributed toward a firm's competitiveness by improving the efficiency of green operations, reducing disposal costs, and avoiding penalties and future compliance costs in the global supply chain. Additionally, the adoption of GSCM practices enhances a firm's positive image, creating a competitive advantage among consumers. However, the respondents did not associate GSCM practices with short-term economic profits due to increased costs of pollution-free equipment and opportunistic behavior between partners until conformity was achieved. Thus, the respondents were not optimistic about short-term profitability and failed to support H 4-2.

6. Conclusions

This empirical study investigated the determinants and performance outcomes of adopting GSCM practices, including green suppliers and customer management targeting Korean manufacturers for the first time in the recent decade. This study identifies GEO, institutional pressure, and relational capital as determinants of GSCM adoption, with institutional pressure and relational capital acting as moderating factors. Competitiveness and economic performance were measured as the outcomes of GSCM practices. This study is both relevant and timely, given South Korea's increasing concern for global environmental conservation, particularly in the manufacturing sector, which has seen substantial growth and government support for environmental sustainability. The PLS-SEM approach provides significant theoretical and practical insights, summarized as follows:

This study makes valuable contributions to the understanding of sustainable supply chain management practices. The relationships between GEO, institutional pressure, relational capital, and GSCM adoption were explored for the first time to clarify the drivers and enablers of GSCM adoption among Korean firms. However, the absence of a moderating effect of institutional pressure and relational capital suggests that these factors may not be critical in influencing GSCM adoption, as previously deemed. Korean firms in the study may have developed strong and well-established GSCM practices that are relatively independent of external pressures or relationships with stakeholders. Their internal commitment to sustainability might be driving their GSCM adoption, rendering external moderating factors less influential. Therefore, more sophisticated statistical techniques are required to fully understand these relationships.

This study offers actionable insights for organizations and policymakers. It emphasizes the role of GEO as a driver for GSCM adoption, underscores the importance of considering multidimensional sustainability outcomes, and highlights the need to address barriers to successful GSCM implementation. First, it highlights the crucial role of GEO as a driver of GSCM adoption, and this can guide organizations in developing strategies to enhance their green orientation. This study's findings hold relevance for similar contexts in countries like Japan and Taiwan, facing comparable challenges and opportunities in Green Supply Chain Management (GSCM) practices. By examining factors influencing GSCM adoption and its impact on competitiveness in these countries, valuable insights can be gained to enhance sustainable supply chain practices. Policymakers can use these findings to formulate policies that promote sustainable supply chain management practices. For instance, they can provide tax incentives or subsidies to companies that reduce their carbon emissions, use renewable energy sources, or implement waste reduction strategies. Additionally, when evaluating the benefits of GSCM adoption, the lack of a significant impact of GSCM on economic performance emphasizes the importance of considering other factors such as environmental and social sustainability. Second, the study underscores the need for organizations to address the barriers to GSCM adoption, including lack of institutional pressure and relational capital. By actively seeking collaborations and fostering strong relationships, companies can overcome these challenges and achieve successful adoption of sustainable supply chain practices.

To provide a balanced interpretation of our findings, it is crucial to acknowledge and discuss the limitations of our study. This includes examining potential biases, limitations related to sample size and geographical scope, and other influencing constraints. The limited sample size affects the generalizability of our findings beyond this research's specific scope. Moreover, our study focused solely on the impact of GSCM on competitiveness enhancement and economic performance, omitting considerations of other potential benefits like improved environmental outcomes and stakeholder satisfaction. We also did not explore the potential moderating effects of variables such as firm size, industry type, economic context, or corporate culture. Recognizing these limitations and addressing them in future research will contribute to advancing knowledge in sustainable supply chain management. By considering biases, sample size, scope limitations, and other constraints, researchers can build upon our findings and foster a more comprehensive understanding of the subject. Acknowledging these limitations facilitates a realistic interpretation of our results and encourages further exploration in this field.

Conflict of Interest

The author(s) declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The data that has been used is confidential at the request of the participants of the study.

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