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Intuitive Redesign of a Copy Paper Supply Chain with the Application of Simulation and Multiple Criteria Decision Making (MCDM) Methodology

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Abstract:

Purpose: *The study addresses the gap in logistics research on supply chain redesign by proposing an Intuitive/ Heuristic approach supported by simulation and quantitative analysis for constructing alternatives/variants of the supply chain and then evaluation with the application of MCDM methods.*
Design/Methodology/Approach: *The study uses intuitive design techniques, computational simulation and Multiple Criteria Decision Making methodology.*
Findings: *Supply chain redesign can be formulated as a Multiple Criteria Ranking Problem which can be solved with the application of MCDM methods.*
Practical Implications: *The proposed supply chain redesign addresses a variety of aspects that should be taken into account while redesigning the supply chain and allows for the selection of the most desirable variant of the supply chain consistent with the expectations and preferences of the decision maker (DM).*
Originality/Value: *The study contributes to logistics research in a supply chain redesign based on intuitive simulation and multiple criteria ranking methods.*

Keywords: *Supply Chain Redesign, Multiple Criteria Decision Making*.

JEL Codes: *R41.*

Paper Type: *Research article.*

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1. Introduction

In today's globalized economy, supply chains have become increasingly complex, spanning multiple regions, stakeholders, and processes. A supply chain refers to the network of organizations, people, activities, information, and resources involved in the production and delivery of a product or service from suppliers to end customers (Christopher, 2023). It encompasses all stages of production, from raw material procurement to the distribution of finished goods. An effective supply chain is critical for organizations to remain competitive and responsive to market dynamics (Cecere, 2015).

Redesigning supply chains is crucial for enhancing efficiency, sustainability, and resilience in response to evolving market demands and external disruptions. The process involves re-evaluating and modifying supply chain structures to optimize performance, reduce costs, and address environmental and social responsibilities. This strategic approach is essential for businesses to remain competitive and adaptable in a rapidly changing global landscape.

The term "Redesign" in general refers to the process of analyzing, restructuring, and improving an existing system, process, or product to enhance its performance, efficiency, or adaptability. This can involve modifications to the design, layout, or operational procedures to better meet current and future demands (Agostino, 2022). The supply chain redesign refers to the strategic reconfiguration of existing supply chain networks to improve efficiency, reduce costs, and enhance sustainability. This process is crucial for adapting to changing market conditions, technological advancements, and disruptions (López and Qassim, 2023; Jorge and Wendt, 2022).

In this article, a copy paper supply chain is redesigned intuitively based on the application of expert knowledge and common sense supported by simulation/ quantitative analysis. Different variants of the redesigned supply chain have been constructed and evaluated by a set of criteria. Thus the methodolgy of Multiple Criteria Decision Making (MCDM) has been applied.

This methodology offers a structured and rational approach to solve complex decision problems (Figueira, 2016). It allows considering various important aspects in the redesign process formulated as criteria evaluating the variants of the supply chain. The proposed approach focuses on the improvement of the supply chain performance including the analysis and readjustment of the supply network, relocation and enhancement of the infrastructure and reshape of logistics processes.

2. Literature Review

Multiple Criteria Decision Making (MCDM) is a field that provides a variety of quantitative tools and methods that help the Decision Maker (DM) to make rational decisions to solve complex decision problems (Żak, 2018d). These problems are called Multiple Criteria Decision Problems (MCDPs) and can be defined as " *complex decision situations in which several – often contradictory – points of view (criteria) must be taken into account*" (Żak, 2018a). These problems can be classified as Ranking, Optimization or Sorting.

An MCDP typically involves two components (Roy, 1996); the first is the set of criteria, which represents the different dimensions of performance that must be considered in the decision-making process. The second component is the set of variants (or alternatives), which represent the potential options that can be chosen.

The MCDM methodology involves the analysis of multiple stakeholders, each with potentially different objectives and preferences. In supply chain contexts, stakeholders can include supply chain managers, suppliers, customers, and sometimes regulatory bodies. MCDM methodology allows the DM to assign importance and sensitivity to be systematically integrated into the decision-making process, which often involves the explicit modeling of decision-maker (DM) preferences (Vincke, 1992).

Trade-offs are inherent to the multiple criteria - oriented decision-making process, as improving performance on one criterion may lead to a decline in performance on another. MCDM methods are designed to handle such trade-offs by helping decision-makers understand the implications of their choices and guiding them toward a balanced solution (Saaty, 1980).

As indicated in the introduction, and based on the definitions proposed by many authors and reports, one can conclude that a supply chain can be defined as the network of entities and organizations involved, directly or indirectly within the upstream and downstream flows for delivering products and services from raw materials to end customers (CSCMP, 2023; Christopher, 2023)

Supply chain redesign is crucial for enhancing efficiency, reducing costs, and increasing resilience in the face of various challenges, such as globalization, technological advancements, and unforeseen disruptions like the COVID-19 pandemic. The digital era has further emphasized the need for supply chain redesign to enhance efficiency and responsiveness. As the redesign of a supply chain falls into the category of MCDP, next paragraphs will demonstrate works by authors that applied MCDM when redesigning a supply chain.

Several works by (Hashemi 2023; Jonker *et al.*, 2016; Huang 2021; Cambero *et al.*, 2015; Mirzae, 2023; Nurjanni, 2017), among others, highlight the growing focus on applying MCDM in supply chain redesign to address diverse criteria such as profitability, environmental friendliness and service levels. These works commonly employ different optimization models, for example Goal Programming, Mixed Integer Linear Programming and the Epsilon Constraint method to achieve compromised solutions.

It can be noticed that the dominant approach for the redesign of a supply chain in the literature is the Optimization, yet no studies explicitly used a Intuitive/Heuristic approach. However, the heuristic/intuitive approach offers several advantages that can make it a vital tool in multiple criteria decision making problems, especially when supported by simulation and ranking methods (Żak, 2018a).

Intuition in supply chain management is conceptualized as a multidimensional construct that includes experience-based, emotional, and automatic-processing dimensions. This allows decision-makers to process complex information quickly and effectively, complementing rational decision-making processes (Carter *et al.*, 2017). Intuitive approaches can also facilitate the integration of advanced technologies, such as Internet of Things (IoT) and blockchain, into supply chains.

This integration helps manage complex systems while addressing privacy and security challenges, ultimately leading to more robust and innovative supply chain solutions (Shahzad *et al.,* 2020). It was also noticed that most of the existing research in the application of MCDM/A to supply chain redesign primarily focuses on two or three criteria, such as cost minimization and/or Environmental Friendliness and/or time, while redesigning the supply chain.

3. Research Methodology

The supply chain redesign approach outlined in this article is structured to systematically address the complexities and challenges faced by modern supply chains. It integrates a comprehensive diagnostic phase with a robust readjustment phase. The methodology begins with a thorough diagnosis of the existing supply chain, identifying key weaknesses and defining the scope of improvement. Following this, the readjustment phase utilizes advanced analytical frameworks and decision-making methodologies to explore and evaluate various redesign options.

In this work, an Intuitive/ Heuristic approach supported by simulation and multiple criteria ranking will be utilized to redesign a supply chain. The decision-makers aim to evaluate various redesign solutions and will ultimately select the most satisfactory or desired option. This process is particularly useful when decision-makers prioritize understanding trade-offs between multiple criteria without relying on complicated mathematical formulations.

To support this approach, quantitative analysis is employed via simulation, which allows for assessing different variants and understanding the implications of various redesign alternatives. The process is followed by generating a final ranking of the variants using multi-criteria evaluation, addressing it as a multi-criteria ranking problem. To enrich this approach, we have used two ranking methods AHP and ELECTRE. The results were compared against each other, ensuring a robust evaluation of redesign options.

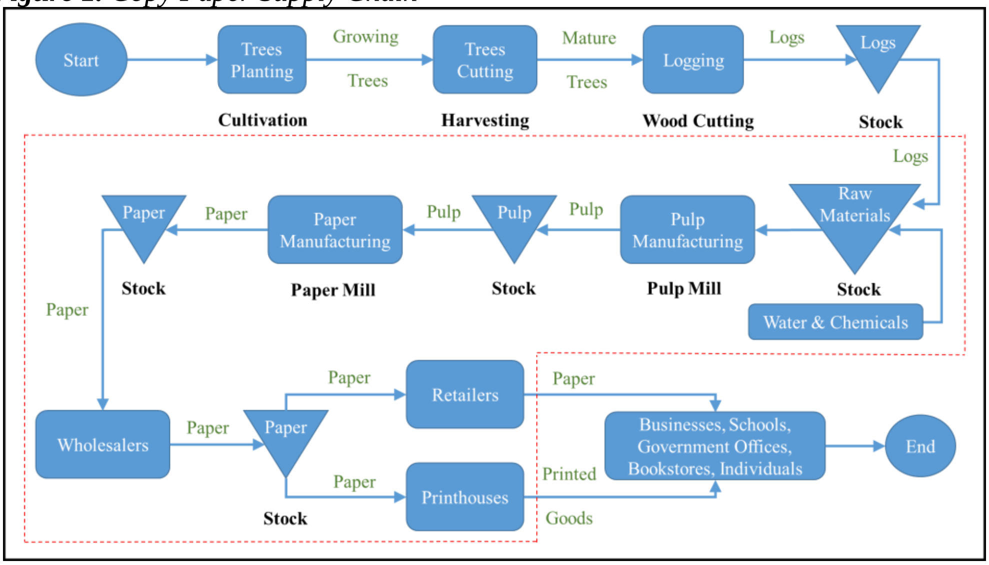
4. Research Results

4.1 Analysis and Evaluation of the Copy Paper Supply Chain Operations

The analysis is carried out for a copy paper supply chain in Poland (presented in Figure 1), composed of various stages/links, including: Cultivation, where trees are planted, grown, and allrowed to mature. Once ready, the process moves to Harvesting, where mature trees are cut before being logged and to be sent to the manufacturing plant.

At the Pulp Manufacturing stage, raw materials including wood, water and checmicals are used to produce the pulp at the pulp mill. This is followed by Paper Manufacturing, where the pulp is transformed into finished paper at the paper mill. The supply chain then enters the Distribution Phase, delivering finished paper to wholesalers. From these points, the paper is distributed to Printhouses and Retailers. Finally, the finished paper/ printed goods reaches consumers such as businesses, schools, government offices, bookstores, and individuals.

Figure 1. *Copy Paper Supply Chain*



Source: *Authors' calculations.*

As presented in Figure 1, the authors of this article focus their analysis on a limted segment of the above described copy paper supply chain, that encompasses the links/ operations of raw materials (wood, chmiclas and water) delivery, pulp and paper manufacturing through physical distribution of finshed product (copy paper) to print houses and retailers, marked by a dotted red line. The analyzed segment of the copy paper supply chain operates in Poland. It is a four layer supply chain that includes: raw material suppliers (3 entities - S1, S2 and S3), manufacturing plant (1 entity -

MP), wholesalers (2 entities – WH1 and WH2) and printhouses (5 entities – PR1-PR5) and retailers (14 entities – RT1-RT14).

The focal link in the analysis of the supply chain in this supply chain is the manufacturing plant (MP) which is situated in the western part of Poznan city. The MP can operate at a capacity of 42 tons of paper per week. The manufacturing process involves mainly two different technological components, i.e. pulp manufacturing and paper manufacturing. The pulp production technological line has a capacity of 42 tons per week. All the pulp produced is fed into the paper production line using conveyers. This paper production line is more advanced than the pulp line as it has a production capacity of 72 tons per week, yet it is limited by the capacity of pulp supplied. Final products are then stored in the plant warehouse (PW).

During the last 10 months this supply chain has experienced substantial difficulties resulting from the increase of the market demand for paper from 42 to approximately 60 tons per week. Based on the information gathered from site visits and interviews, the supply chain was analyzed to identify bottlenecks, inefficiencies, and areas of strength.

A SWOT analysis was employed by the author to evaluate the strengths, weaknesses, opportunities, and threats within the supply chain. This analytical approach enabled the identification of critical improvement areas and strategic opportunities to enhance overall supply chain efficiency. The results of the SWOT analysis applied to this supply chain can be breifed as below:

Strengths

- The manufacturing plant has a well-established process that includes both pulp and paper production. This process has been running efficiently under normal demand conditions.
- The structure of the existing warehouses is solid enough to allow for the construction of a second floor, which could increase storage capacity.
- The plant owns its fleet of trucks, which provides control over transportation schedules and costs.

Weaknesses

- The pulp production line is a bottleneck, limiting the overall production capacity.
- Current warehouse capacities are inadequate to store the increased production required to meet the new demand.
- The current fleet is insufficient to handle the logistics required for increased production and distribution, leading to potential delays and inefficiencies.
- Freuqent delays of deliveries and many customers’ complaints concerning level of service.

- With the increased demand, the overall utilization of the supply chain is expected to increase leading to further inefficiencies and breakdowns.

Opportunities

- Expanding the fleet or considering outsourcing transportation to third-party logistics providers could help meet the increased demand without overburdening the current resources.
- Implementing advanced logistics and supply chain management software could optimize delivery schedules, inventory management, and overall supply chain performance.
- Sourcing additional suppliers for raw materials, particularly wood logs, could increase flexibility and reduce dependency on a single supplier.

Threats

- The significant increase in market demand poses a serious threat to the current supply chain's ability to meet customer needs, potentially leading to backorders, customer dissatisfaction, and loss of business.
- Competitors who are better equipped to meet the increased demand may capture market share, especially if they can offer more reliable and timely delivery services.

4.2 Formulation of the Supply Chain Redesign Problem

The SWOT analysis highlights the critical need for supply chain redesign to address the weaknesses and threats while leveraging strengths and opportunities. Top managers of the organizational units representing major links of the copy paper supply chain being the decision makers (DMs) in the redesign process noticed the above mentioned weaknesses and threats. They understand the need for redesign that should focus on expanding production capacity, optimizing warehouse and logistics operations, and improving overall supply chain efficiency.

The task is to generate variants then rank them from the most desirable to the least in order for the analyst to make the final decision concerning which combination/variant is most desirable. In this redesign, the proposed variants constitute the supply chain redesign alternatives taking into account the core business functions such as production, physical distribution and customer service. Each variant is a combination of proposed solutions for issues in areas such as production, fleet, capacity of warehouses and deliveries schedule. Characterstics of generated variants can be illustrated as follows:

V1.

- This variant represents the current status of the considered segments of the supply chain before applying any modifications or enhancement. This has been described in the supply chain analyais section 3.1 above.

V2.

- Additional supplier is added to procure the required quantity of wood.
- The pulp machine is upgraded to a higher production rate to fulfill the new demand and to increase the maximum capacity.
- An additional warehouse PN, with a capacity of 40 Tons, is purchased near the plant to stock final products before shipping to wholesalers.
- One 20-Ton and Six 8-Ton trucks are added to the fleet to assist in deliveries fulfilling the demand.
- New customers can be assigned to two additional wholesalers WH3 and WH4 which warehouses shall be utilized to stock and ship from to those customers. An average of 20 Tons of warehouse capacity for each warehouse.
- The manufactured paper orders will be transferred on Mondays to customers PR1-PR3 & RT1-RT6 to PW while orders for PR4-PR5 & RT7-RT14 are transferred to the new plant warehouse PN. Orders for PR1-PR2 & RT1-RT3 are then transferred to WH1, PR3 & RT4-RT6 are transferred to WH2, PR4 & RT7-RT10 are transferred to WH3 and PR5 & RT11-RT14 are transferred to WH4.

V3.

- A pulp supplier S3 will be added to make up the additional quantity required to meet the new demand.
- The plant warehouse PW is upgraded to increase the capacity. This is done by constructing a second floor steel platform that will result in an increase of 25 Tons for a total of 67 Tons.
- One 20-Ton and Six 8-Ton vehicles are added to the fleet to assist in delivering the paper from plant to wholesalers and then to customers.
- One wholesaler WH3, is added to the network to serve the new customers' areas with a capacity of 25 Tons.
- The manufactured paper orders of PR1-PR3 & RT1-RT6 is stocked in PW then transferred to WH1, PR4 & RT7-RT10 are transferred to WH2, and PR5 & RT11-RT14 are transferred to WH3.

V4.

- Extra supplier S2 is added to procure the required quantity of wood.
- The pulp machine is upgraded to a higher production rate to fulfill the new demand and to increase the maximum capacity.
- Deliveries to the plant warehouse has been modified to be twice a week instead of once. This will negates the need to increase the capacity of the plant and/ or the wholesalers storage capacity.
- No fleet modification required as owned fleet will be used twice a week.
- All the manufactured paper orders of will be stocked in PW. The orders from customers PR1-PR3 & RT1-RT6 are transferred on Mondays and Tuesdays to WH1 while PR4-PR5 & RT7-RT14 are transferred to WH2 on

Mondays and Thursdays. Deliveries to customers are carried out the next day.

V5.

- The same wood supplier will be kept and additional quantities will be requested to meet the demand.
- A pulp supplier S3 will be added. This pulp will be fed directly to the paper machine to make up the additional quantity required to meet the new demand.
- PW is upgraded to additional 25 Tons for a total of 65 Tons.
- The two 8-Ton vehicles will be sold. The deliveries from the WH1 And WH2 will be handled by an outsourcing company. Shipment tracking service shall be available for customers.
- Warehouses for WH1 and WH2 are upgraded for an additional 12 Tons for a total of 32 Tons each.
- The schedule of deliveries from PW to WH1 and WH2 are carried on Mondays and Tuesdays while the outsourcing company will deliver to customers next day.

V6.

- The same wood supplier will be kept but more quantities will be requested to meet the demand.
- The pulp machine is upgraded to increase the maximum capacity.
- Additional warehouse WN, with a capacity of 30 Tons, is rented nearby the plant to stoke the final products before shipping to wholesalers.
- Six 8-Ton vehicles are added to the fleet to assist in delivering the paper from plant to wholesalers then to customers.
- New wholesalers are added to the network WH3 and WH4 to serve the new customers' areas with a capacity of 20 Tons each.
- The manufactured paper will be transferred on Mondays, for PR1-PR3 & RT1-RT6 to PW while orders for PR4-PR5 & RT7-RT14 are transferred to the new plant warehouse PN. Orders for PR1-PR2 & RT1-RT3 are then transferred to WH1 on Tuesdays, PR3 & RT4-RT6 are transferred to WH3 on Fridays PR4 & RT7-RT10 are transferred to WH2 on Wednesdays and PR5 & RT11-RT14 are transferred to WH4 on Fridays.

V7.

- Same wood supplier, a Pulp supplier S3 will be added.
- Deliveries to PW has been modified to be twice a week. This will negates the need to increase the capacity of the plant and warehouses.
- Deliveries from the wholesalers will be handled by an outsourcing company. Two 8-Ton vehicles will be sold.
- No need to add/ modify the storage capacities for the wholesalers as deliveries will be carried out twice a week.

V8.

- A Pulp supplier S3 will be added.
- An additional warehouse, WN, with a capacity of 20 Tons, is rented near by the plant to stoke the final products before shipping to wholesalers.
- One 20-Ton and Six 8-Ton vehicles are added to the fleet to assist in delivering the paper from plant to wholesalers and then to customers.
- One additional wholesaler WH4, is added to the network to serve the new customers. The wholesaler has a storage capacity of 20 Tons.
- The manufactured paper will be transferred on Mondays and Wednesdays from the plant to WH1, WH2 and WN. Orders for PR1-PR2 & RT1-RT3 are then transferred to WH1, PR3 & RT4-RT6 are transferred to WH4 from WN, PR4 & RT7-RT10 will be distributed directly from WN to customers without transferring to further warehouse, while orders from PR5 & RT11-RT14 will be delivered to WH2.

V9.

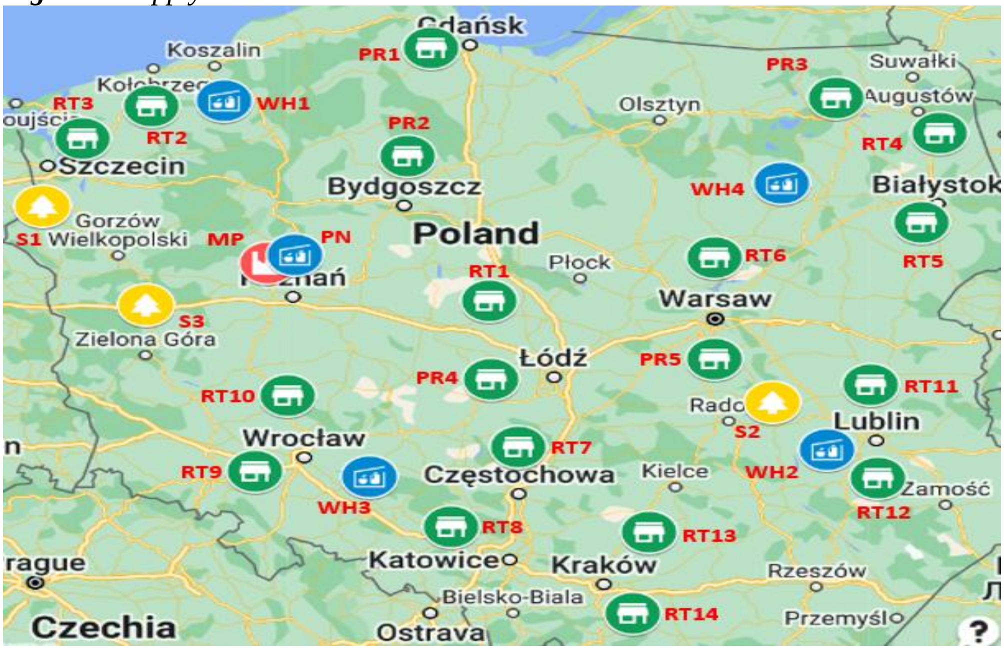
- The same wood supplier will be kept however more quantities will be requested to meet the demand.
- The pulp machine is upgraded to a higher production rate to fulfill the new demand and to increase the maximum capacity.
- PW is upgraded to increase 25 Tons capacity of for a total of 65 Tons.
- The two 8-Ton vehicles owned will be sold. The deliveries from wholesalers will be handled by an outsourcing company.
- Storage capacities of wholesalers WH1 and WH2 are upgraded with an increase of 12 Tons for a total of 32 Tons each.

V10.

- Additional supplier S2 is added to procure the required wood quantity.
- The pulp machine is upgraded to a higher production rate to fulfill the new demand and to increase the maximum capacity.
- Deliveries to PW has been modified to be twice a week instead of once.
- Six 8-Ton vehicles are added to the fleet to assist in delivering the paper from plant to wholesalers amd then to customers.
- Storage capacities of wholesalers WH1 and WH2 are upgraded with an increase of 12 Tons for a total of 32 Tons each.

Figure 2 below illustrates the location of the elements/ nodes mentioned in the alternatives above including the Manufacturing plant (in red), the existing and suggested wholesalers (in blue), the existing and suggested suppliers (in yellow) and the customers (in green).

Figure 2. *Supply Chain Elements and Locations*



Source: *Authors' calculations.*

Criteria:

Based on the works of (Żak 2018b; Redmer, 2012; Beamon, 1999; Seuring, 2013; Alazzawi, 2019, 2020) and expressed expectations of the aforementioned DM and stakeholders the following consistent family of criteria has been constructed/ defined:

- C1 – Operational Costs [PLN] – a minimized criterion denominating the overall monthly costs associated with the fulfillment of the customers' orders for copy paper. It is constructed as a sum of monthly costs of fuel consumption and maintenance of a fleet used for product delivery and salaries of employees responsible for order fulfilment.
- C2 – Investment Costs [PLN] – a minimized criterion denominating the overall amount of money required to implement each variant of the Supply Chain redesign. This criterion includes the costs associated with introducing new equipment/ technologies (e.g. automatic warehousing systems, tracking and tracing solutions), purchasing/ renting of new warehouses and/ or upgrading the existing ones, changing and recomposing the fleet of vehicles.
- C3 – Capacity Utilization [%] – a minimized criterion defined as the absolute value of the deviation from the optimal overall utilization of the fixed assets of the supply chain, including the machinery and building space in the manufacturing plant, capacity of the warehouses and fleet used in the whole Supply Chain. In the definition of this criterion, the optimal capacity utilization is defined at the level of 85%.

- C4 – Customer Satisfaction [0-10 points] – a maximized criterion expressing the overall quality and reliability of the customer service. It is constructed as a sum of such elements as: timeliness of the order fulfillment (0-4 points), share (percentage) of the quantity of copy paper being delivered undamaged (0-3 points); the availability and quality of the real – time shipment tracking system (0-3 points).
- C5 – Flexibility/Agility [0-10 points] - a maximized criterion representing an overall assessment of how flexible/agile each variant of the Supply Chain redesign is, while taking into consideration such elements as: number of suppliers and cooperation rules with them (0-2 points), allocation of customers to points of delivery (0-1 points), layers of the Supply Chain and reporting hierarchy (0-1 points), outsourcing policy applied in the whole Supply Chain (0-2 points), share (percentage) of the value of owned and rented/ leased warehouses, fleet and machinery in the whole Supply Chain (0-2 points), Communication/ IT System used in the whole Supply Chain (0-1 point), Reaction Time in the Supply Chain in case of unexpected events (0-1 point).
- C6 – Environmental Friendliness [Points] – a minimized criterion measuring the overall amount of carbon dioxide (CO_2) emitted annually in the whole Supply Chain, including: suppliers, manufacturing plant, wholesalers (warehouses), printhouses and retailers as well as fleet being used in the copy paper delivery process. It takes into consideration as well the chemicals usage in production and energy consumption in the network.
- C7 – Delivery Time [Days] – a minimized criterion representing the overall order fulfilment time for copy paper in the Supply Chain. The criterion is measured as a time elapsed between placing an order by a customer (Printhouse, Retailer) and receiving a successful delivery.

4.3 Computational Experiments

4.3.1 MCDM Method Appied in the Computational Experiment

In the computational phase two popular Multiple Criteria Ranking Methods – ELECTRE III/ IV ((Roy, 1990a; Vincke, 1992) and Analytic Hierarchy Process (Satty, 1980) have been applied.

4.3.1.1 ELECTRE III/IV Method

The ELECTRE III/ IV method belongs to the European school of Multiple Criteria Decision Making and it is based on the concept of the outranking relation ***S(a,b)***, which indicates the extent to which **"*a*** outranks ***b*"** overall. The ELECTRE III/ IV method orders/ ranks a finite set of variants ***A*** from the best to the worst as a result of their pair wise evaluation on a family of criteria ***F***, and with an input information from the DM about his/her preferences (Roy, 1990b).

The method comprises three main stages: **Stage1 -** Definition of a set of variants ***A*** and a consistent family of criteria ***F*** combined with construction of an evaluation matrix and definition of the model of the DM's preferences; **Stage 2 -** Construction of an Outranking Relation ***S(a,b)*** based on concordance indicator and discordence indexes. **Stage 3** – Exploitation of the Outranking Relation in which descending and ascending complete preorders of variants are generated (Roy, 1990a; Vincke, 1992; Figueira 2016).

The final results, being the intersection of the above mentioned complete pre orders, can be presented either in the form of the ranking matrix or in the form of the outranking graph. They define the pairwise relationships between variants, including: indifference (I), preference (P or >), lack of preference (P~ or <) and incomparability (R) (Żak, 2011, 2018c). The specific feature of the ELECTRE III/IV method is that allows variants to be incomparable in the final ranking.

4.3.1.2 Analytic Hierarchy Process

The AHP (Analytic Hierarchy Process) method (Satty, 1995) is a multiple criteria ranking procedure focused on the hierarchical analysis of the decision problem. Thus, the method structures the considered decision problem in the form of a hierarchy of an overall goal, criteria, sub-criteria and variants.

It belongs to the American school of Multiple Criteria Decision Making and it is based on the Multi Attribute Utility Theory (Kenney & Raiffa, 1993), and thus aggregates all evaluations of variants on all criteria and sub-criteria into one utility function.

On each level of the hierarchy, based on the pair-wise comparisons of criteria, sub criteria and variants, the DM's preferential information is defined in the form of relative weights $\boldsymbol{W_r}$ on the 1 to 9 point grading scale (see Table 3).

Each evaluation represents relative strength of the compared element against another and has a compensatory character, i.e.: the value characterizing the less important element (1/2, 1/5, 1/9) is the inverse of the value characterizing the more important element in the compared pair. This preferential information is checked for consistency by computing the consistency indexes ***CI-s*** (CI<0.1).

In the next step of the AHP algorithm a set of vectors containing normalized, absolute values of weights $\boldsymbol{W_a}$ for criteria, sub criteria and variants is generated. The absolute weights $\boldsymbol{W_a}$ are aggregated by an additive utility function. The utility $\boldsymbol{U_i}$ represents the contribution of variant $\boldsymbol{i}$ in reaching an overall goal and constitutes its aggregated evaluation that defines its position in the final ranking (Saaty 1995).

As opposed to ELECTRE III/IV method the AHP algorithm does not allow variants to be incomparable ***(R)***. In the final classification generated by the AHP method a certain variant can be either indifferent ***(I)*** – equal utility $\boldsymbol{U_i}$ or preferred ***(P or >)*** against another variants – higher utility $\boldsymbol{U_i}$.

4.3.2 Computational Results

4.3.2.1 Application of the ELECTRE III/IV Method

As indicated above the computational experiment carried out with the application of ELECTRE III/IV method is initiated (Stage 1) by the construction of the Evaluation Matrix (see Table 1) that includes 10 variants evaluated by 7 criteria. In addirition, the DM's preference model has been constructed with the application of indifference q_j, preference p_j and veto v_j thresholds as well as the weights w_j, defined for each criterion. Thresholds define the sensitivity of the DM to the changes of the criteria values and the weights w_j, express the importance of each criterion. Table 2 shows the preference model for ELECTRE III/IV method while Figure 4 presents the final ranking of the experiment.

Table 1. *Evaluation Matrix for the variants of the redesign of the Copy Paper Supply Chain*

Var	C1 Operational Costs [zł] Min	C2 Investment Costs [zł] Min	C3 Capacity Utilization [%] Min	C4 Customer Satisfaction (points) Max	C5 Flexibility/ Agility (points) Max	C6 Environmental Friendliness (points) Min	C7 Delivery Time [days] Min
V1	2,132,957	0.00	20.00%	4.5	1.0	8.7	16
V2	2,925,457	2,515,000	1.53%	6.6	6.0	4.7	11
V3	5,129,586	1,685,000	5.49%	7.1	5.0	4.7	4
V4	2,255,720	490,000	3.21%	7.0	3.0	2.3	10
V5	4,328,786	25,000	0.48%	9.2	4.0	4.3	5
V6	3,146,354	1,690,000	1.12%	7.0	6.0	3.3	6
V7	4,342,373	-80,000	9.24%	9.2	6.0	5.7	5
V8	4,856,116	1,500,000	7.32%	6.9	6.0	4.3	10
V9	2,131,181	515,000	1.14%	9.2	7.0	5.3	5
V10	2,359,712	1,760,000	6.96%	6.6	3.0	3.7	9

Source: *Authors' calculations*

In addition, the DM's model of preference is constructed with the application of indifference q_j, preference p_j and veto v_j thresholds as well as the weights w_j defined for each criterion. Thresholds define the sensitivity of the DM to the changes of the criteria values and the weights w_j express the importance of each criterion. Table 2 shows the DM's model of preference for ELECTRE III/IV method.

Table 2*. The DM's Model of Preferences used in the ELECTRE III/IV Method*

Criterion	Preference Direction	Weight	Indifference	Preference	Veto
C1 Operational Costs	Decreasing	8	200,000	1,000,000	2,750,000
C2 Investment	Decreasing	6	300,000	1,000,000	2,000,000

Costs					
C3 Capacity Utilization	Decreasing	5	0.02	0.04	0.09
C4 Customer Satisfaction	Increasing	9	1	2	4
C5 Flaxibility/ Agility	Increasing	4	1	3	6
C6 Environmental Friendliness	Decreasing	3	1	2	5
C7 Delivery Time	Decreasing	7	1	3	6

Source: *Authors' calculations*

Based on the above presented data (Tables 1 and 2), stages 2 and 3 of the computational procedure of ELECTRE III/IV Method have been performed. Stage 2 focused on the construction of the outranking relation ***S(a,b)*** is carried out using a computer software and generates the degrees of credibility ***d(a,b),*** being from the interval [0,1] and representing the degree to which variant ***a*** outranks variant ***b***. In stage 3 - Exploitation of the outranking relation the values of ***d(a,b)*** are used to generate two preliminary rankings (complete preorders) of the variants.

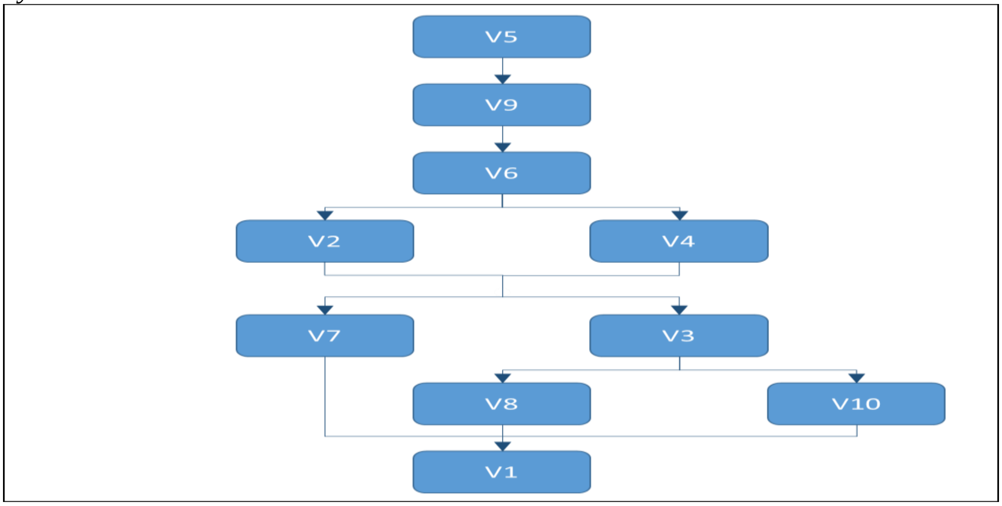
One of them, called descending distillation constructs the ranking starting from the selection of the best variant, which is placed at the top of the ranking. In the second one, called ascending distillation the variants are ranked in the inverse order. Both descending and ascending distillations resulted from the experiment are shown in Table 3. Final ranking of variants generated as an intersection of the above mentioned complete preorders is presented in Figure 3.

Table 3. *The Results of Descending and Ascending Distillations of Copy Paper Supply Chain Redesign Variants Generated by ELECTRE III/IV Method*

Variant	**Place in Descending Distillation**	**Place in Ascending Distillation**
V1	10	10
V2	5	4
V3	6	7
V4	4	5
V5	1	1
V6	3	3
V7	9	6
V8	8	8
V9	2	2
V10	7	9

Source: *Authors' calculations*

Figure 3 *Final Ranking of Copy Paper Supply Chain Redesign Variants Generated by ELECTRE III/IV Method*



Source: *Authors' calculations.*

4.3.2.2 Application of the AHP Method

As presented above the computational procedure of the AHP method starts with the construction of the hierarchy of the decision problem at stake. In the analyzed case the hierarchy is composed of the overall goal, 7 criteria and 10 variants of the redesign of the Copy Paper Supply Chain. The overall goal of the analysis is to rank the variants from the best to the worst and recommend the most desired option. In the next step of the AHP method the DM's model of preference is built and the values of the relative weights W_r are defined for criteria and variants. The examples of the definition of W_r for criteria (C1, C2, ... C7) and for variants (V1, V2, ..., V10) along criterion C1 are presented in Table 4 a and b, respectively.

Table 4. *The DM's Model of Preferences Applied in the AHP Method*

a) For Criteria

Criteria	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**
C1	1	3	4	1/2	5	6	2
C2	1/3	1	2	1/4	3	4	1/2
C3	1/4	1/2	1	1/5	2	3	1/3
C4	2	4	5	1	6	7	3
C5	1/5	1/3	1/2	1/6	1	2	1/4
C6	1/6	1/4	1/3	1/7	1/2	1	1/5
C7	1/2	2	3	1/3	4	5	1

Source: *Authors' calculations.*

b) For Variants along Criterion C1

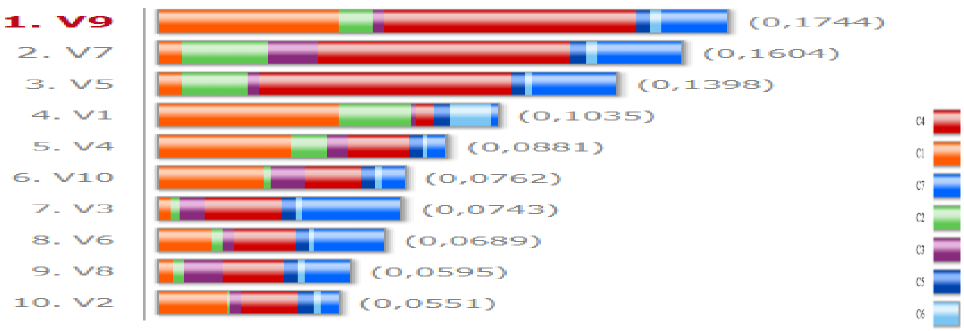
Variant	**v1**	**v2**	**v3**	**v4**	**v5**	**v6**	**v7**	**v8**	**v9**	**v10**
v1	1	4	8	2	7	5	7	8	1	3
v2	1/4	1	7	1/3	5	3	5	6	1/4	1/3
v3	1/8	1/7	1	1/9	1/4	1/6	1/4	1/3	1/9	1/9
v4	1/2	3	9	1	7	4	7	8	1/2	2
v5	1/7	1/5	4	1/7	1	1/5	1	3	1/7	1/6
v6	1/5	1/3	6	1/4	5	1	5	6	1/5	1/4
v7	1/7	1/5	4	1/7	1	1/5	1	3	1/7	1/6
v8	1/8	1/6	3	1/8	1/3	1/6	1/3	1	1/8	1/8
v9	1	4	9	2	7	5	7	8	1	3
v10	1/3	3	9	1/2	6	4	6	8	1/3	1

Source: *Authors' calculations*

After the definition of relative weights W_r at each level of hierarchy the defined preferential information is checked for consistency. The values of consistency indexes CI-s are computed. For all analyzed criteria and variants CI-s < 0.1, which indicates that the model of preferences is defined consistently and the proposed values of the weights are within the acceptable level of error. The consistency value for this experiment was 0.03.

Based on the values of $\boldsymbol{W_r}$ the eigen vector problem (Howard, 1987; John, 2006) is solved at each level of the hierarchy and as a result the vectors containing normalized, absolute values of weights $\boldsymbol{W_a}$ for criteria and variants along each criterion are computed and finally aggregated by the additive utility function. The overall value of the utility $\boldsymbol{U_i}$ of each variant $\boldsymbol{i}$ defines its position in the final ranking. The final ranking of the variants of the redesign of the Copy Paper Supply Chain is presented in Figure 4. Contribution of each criterion to overall utility of each variant is marked by specific color is presented in Figure 4.

Figure 4. *The Final Ranking of Variants of the Redesign of the Copy Paper Supply Chain Generated by AHP Method with Related Ui*



Source: *Authors' calculations*

5. Discussion

As presented in Figures 3 and 4 the final rankings of the redesign variants of the copy paper supply chain generated by ELECTRE III/IV and AHP Methods, respectively are substantially different but demonstrate certain resemblance at the same time. The ranking produced by ELECTRE III/IV method shows that the most preferred variants are V5, V9 and V6. The leading variants in the ranking generated by AHP Method are V9, V7 and V5.

At the bottom of both rankings are placed such variants as: V1, V8 and V10 (ELECTRE III/IV method) and V2, V8, V6 (AHP method). The positions of three variants: V1, V7 and V2 are significantly different in both rankings. These differences of the rankings produced by ELECTRE III/IV and AHP methods are due to different modeling and aggregation approaches used in each of them and their axiomatic differences.

The final ranking generated by ELECTRE III/IV Method shows the position of the variants, only without presenting the distance between them. At the same time this ranking enriches the classical model of preference by introducing the cluster of incomparability between variants (see Table 5). The ranking generated by the AHP method shows the position of the variants and their overall utility $\boldsymbol{U_i}$**.** Based on that information the distance between variants can be assessed. At the same time the AHP-based ranking includes the statuses of Indifference (I) and Preference (P or >) between variants without demonstrating incomparabilty between them.

Table 5. *ELECTRE III/IV Relation Matrix*

Variant	V1	V2	V3	V4	V5	V6	V7	V8	V9	V10
V1	I	<	<	<	<	<	<	<	<	<
V2	>	I	>	R	<	<	>	>	<	>
V3	>	<	I	<	<	<	R	>	<	>
V4	>	R	>	I	<	<	>	>	<	>
V5	>	>	>	>	I	>	>	>	>	>
V6	>	>	>	>	<	I	>	>	<	>
V7	>	<	R	<	<	<	I	R	<	R
V8	>	<	<	<	<	<	R	I	<	R
V9	>	>	>	>	<	>	>	>	I	>
V10	>	<	<	<	<	<	R	R	<	I

Source: *Authors' calculations.*

Based on both rankings two variants V5 and V9 seem to be the most desired. Their high positions are achieved due to having the top desired values for such criteria as: C2 – Investment Costs, C3 – Capacity Utilization, C4 – Customer Satisfaction and

C7 – Delivery Time. Two of these criteria: C4 and C2 are featured by the highest weights (importance) – 9 and 8, respectively.

6. Limitation of Research

It is worth mentioning that the limitation of this research is the fact that Intuitive/ Heuristic methods often rely on scenario planning and expert judgment, which can be subjective and limited by the knowledge and experience of the analysts. As a result, uncertainties or future market conditions that are not anticipated during the planning process may not be properly addressed.

7. Conclusions

The major contribution of this paper is the universal methodology of redesigning and evaluating a real world supply chain. The proposed approach can be split into two general stages, including:

- A heuristic/ intuitive construction of the supply chain redesign variants supported by simulation / quantitative analysis.
- Multiple criteria evaluation of these variants.

The authors of this article demonstrate the value of the heuristic/ intuitive design of the variants of the supply chain (stage 1) as a method that utilizes common sense and human creativity. The method also allows to generate solutions through brainstorming, sharing experience, expert knowledge, unconstrained, imaginative thinking with the application of multidisciplinary skills.

The design process is based on the analysis of different aspects affecting the supply chain, such as: technical, economic, social, safety-oriented and environmental as well as satisfy the interests of the DM and different stakeholders, including: owners and top managers of the organizations representing major links of the supply chain, customers and employees.

The important component of the proposed approach is a comprehensive, multiple criteria evaluation of the generated variants (stage 2). In this phase, the multiple criteria assessment of variants permits to check how efficient and satisfactory the design process was. It allows verifying whether the variants satisfy critical aspects and interests of important stakeholders.

The multiple criteria evaluation of variants is a ridged, systematic verification of the concepts generated in the first stage. The authors have shown that the evaluation of the redesign variants of the supply chain can be formulated as a multiple criteria ranking problem. They have shown how the ranking process should be performed.

A universal, consistent family of criteria, suitable for the evaluation of different redesign variants of any supply chain has been defined. The process of modelling the DM's and stakeholders' preferences has been presented and computational experiments have been shown. As a result, the rankings of the designed variants have been generated.

In the computational phase, in order to select the best/compromise solution the authors have applied two MCDM ranking methods: Electre III/IV and AHP. 10 considered variants (V1-V10) developed heuristically in the first stage of the proposed approach have been evaluated according to 7 criteria and ranked from the best to the worst. By the performed computational experiment it is indicated that in the evaluation phase different multiple criteria ranking methods can be applied.

From a practical point of view, the results of this paper can be concluded as follows:

The authors (acting as analysts) support the customer – oriented transformation of the copy paper supply chain characteristic for variants V5 and V9. These variants, being the winners of the generated rankings, are both low – investment and high customer satisfaction variants. They are characterized by short delivery times and high standards of customers' service. Both are focused on efficient fixed assets management, reasonable outsorcing policy and development of an appropriate balance between supply and demand (excellent capacity utilization).

The redesign of the copy paper supply chain has generated the following benefits:

Implementation of variants V5 or V9 results in double improvement of customer satisfaction (more than 100% in each of the variants); roughly 30% increase of the capacity utilization rate and 70% reduction of the delivery time.

Variants V9 is the most flexible and agile from all the variants while variant V5 belongs to the leaders in terms of the incurred investment costs.

Based on AHP method ranking, one can conclude about the distance between the variants unlike ELECTRE where one can only figure out the sequence of variants. In addition, the important feature of AHP method ranking is its ability to illustrate the contribution of each criterion to the final ranking of each variant. On the other hand, ELECTRE consumes less time solving the problem than AHP while ranking the variants. In ELECTRE III/IV it is possible to demonstrate the incomparability as well between variants.

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