Production chains configuration based on a systematic approach

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Abstract. The formalization of production tasks has been carried out, including the tasks of selecting individual links in the production chain (suppliers, carriers, warehouses) and choosing production chains based on the principles of a systematic approach. Hierarchical structures are constructed (basic criteria and alternatives are defined) for two classes of production problems of choice - the choice of a link in a production system and the choice of a configuration option for a production chain (network). As calculation methods, it is proposed to use methods for processing inaccurate pairwise comparisons to solve multi-criteria decision-making problems. An extension of the DS/AHP method is proposed in the paper. A new method for analyzing hierarchies to solve the problem of multi-criteria decision making using the Dempster-Scheifer theory differs from existing methods in that pairwise comparisons of elements, both at the level of alternatives and at the level of criteria, are replaced by the choice of the most preferred groups of elements. It takes into account the fact that the multi-criteria decision problem might have several levels of criteria. Moreover, it is assumed that expert judgments concerning the criteria are imprecise and incomplete. A numerical example explains in detail and illustrates the proposed approach.

1. Introduction
At present, the development of the international market for the production of goods follows the path of specialization and simultaneous integration, when industrial enterprises concentrate on the direction of their work, which they consider to be the main one, and give secondary functions (transport, warehouse, sales) to logistics intermediaries (suppliers, transport carriers, freight forwarders, etc.). An integrative approach requires the integration of various functional areas and their participants into a single logistics system or chain. The enterprises united in the supply chain receive undeniable advantages over the others: their independent risks are combined, costs are reduced, and the quality of the functioning of the entire logistics system is improved. And in modern economic conditions, it is not individual enterprises that compete with each other, but the logistics chains of which these enterprises are part [1-2].
Today, only in some functional areas of logistics there is an advanced analytical apparatus that allows solving particular problems of optimization of transport, storage and distribution processes in industrial, transport and trade enterprises.

Currently, supply chains are built on the basis of one key indicator, for example, total logistics costs, quality of service, productivity, etc. If possible, the desire to take into account most of the key factors leads to the necessity of applying the multi-criteria optimization methodology. However, the application of a multicriteria approach to the problems under consideration is constrained by a number of factors such as: 1) the criteria are multidirectional; 2) their heterogeneous nature (quantitative and qualitative criteria, the latter tend to dominate); 3) inaccuracy, incompleteness and subjectivity of information about the parameters of the designed system; 4) with a large number of logistics intermediaries (links in the logistics chain) performing the corresponding operations, there is a large number of alternative configuration options for the logistics chains formed of various links [3].

Thus, the need for a systematic analysis of supply chains based on the development of new multi-criteria decision-making methods that take into account the fact that the assessments of experts or decision makers are usually inaccurate is obvious.

2. Methods and Algorithms

2.1. Choosing a logistics network configuration option

Configuration of a logistics network is defined as the composition of the links of the logistics system, their capacity and placement in space in accordance with the adopted logistics strategy.

In general, the supplier and consumer of the material flow are two micro-logistics systems connected by a logistics channel (distribution channel). A logistics channel is a partially ordered set of various intermediaries carrying the flow of material from a specific producer to its consumers. The set is partially ordered until specific participants in the process of moving the material flow from supplier to consumer have been chosen. After that, the logistics channel is transformed into a logistics chain. The set of supply chains forms the logistics network of the enterprise.

When deciding on the type of a distribution channel, a choice is made between the types of distribution of goods - transit or storage, and when deciding on the type of a logistics chain - the choice of a specific carrier, insurer, freight forwarder, distributor, banker, etc. The choice of the optimal configuration of a logistics network has to be made from a large number of predefined alternatives.

The classical approach to designing means a transition from particular to general (induction). This approach to designing the supply chain structure does not take into account the integrative qualities of the logistics system. Integrative qualities cannot be applied to any of the individual elements, but can be characterized by the definition “the effect of the sum exceeds the sum of the effects”.

The functional approach is based on the sequential evaluation of the chain links according to the functional criterion, when the output stream of each previous link of the logistics chain is the input for the next. The resulting material flow is the output stream of the last link in the supply chain. The strengths of this approach is the ability to evaluate alternatives that belong to the same functional area in relation to the parameters of the previous one. However, this does not take into account the fact that there is a number of criteria that, while not decisive at the current functional stage, affect the effectiveness of subsequent stages. A systematic approach involves a gradual transition from a general to a particular, when it is based on the common goal for which the system is created.

Consider the options for building logistics networks for a manufacturing enterprise in the production process $A_i$ consisting of various components $A_{ij}$. 
Figure 1. Logistic network of the enterprise: Logistic Channel; Z - purchase, T - transport, C - warehouse, Pr - production, P - distribution.

The starting point of the material flow is the supplier’s warehouse $A_i$, and the end is the consumer’s warehouse $A_j$. We denote $P = (P_1, P_2, ..., P_p)$ - many suppliers providing their services $P(A_{ij}) = (P_1(A_{ij}), P_2(A_{ij}), ..., P_n(A_{ij}))$ - many product manufacturers of $A_j$ (suppliers); $Cons(A_{ij})$ - consumer of the product $A_j$; and $Cons(A_i)$ - consumer of the product $A_i$.

Alternative 1: The producer is the initiator of the supply chain $A_i$, which is connected with the suppliers of the initial products for its activity and with the consumers of its products through a direct supply channel, when there are no intermediaries between the supplier and the consumer and all operations related to transportation, storage and distribution of materials and finished products is performed by the manufacturer $A_i$. The logistics channel in this case has the following structure: $P_p(A_{ij}) \rightarrow Pr(A_{ij}) \rightarrow Cons(A_{ij})$. The logistics system (LS, figure 1) is a combination of four logistics chains, each of which is composed of three links: supplier of $A_i$, manufacturer of $A_i$ and consumer of the product $A_i$. Each of the links of the LS is a micro-logical system composed of subsystems: supply (Z, T, C), production (P), sales (C, T). Some industrial or commercial enterprises may act as suppliers of components $A_j$ and consumers of products $A_i$.

Alternative 2: A form of a transit movement with the possibility of attracting forwarding companies (logistics intermediaries). The logistics channel has the following structure: $P_p(A_{ij}) \rightarrow T(A_{ij}) \rightarrow Pr(A_{ij}) - T(A_{ij}) - Cons(A_{ij})$.

In this case, it is necessary to make a decision whether the function of transporting materials and/or finished products is outsourced.

Figure 1 shows the case of a single-link production of a product $A_i$ when components $A_j$ are required for its production, i.e. $A_i = \sum_{j=1}^{n} A_{ij}$, where $n$ is the number of product components $A_i$. Each of the components $A_j$ can be either a material or a semi-finished product, $A_{ij} = \sum_{k=1}^{m} A_{ijk}$, where $m$ is the number of components of the product $A_j$, and so on. In modern industrial enterprises, the number of components can be in the hundreds and thousands of units. The solution to the issue of whether to produce or to buy is in some cases key to maintaining the image and competitiveness of the enterprise, as it is strategic in nature and affects the structure of the supply chain. Traditionally, such a decision has been made on the basis of comparing the costs of outsourcing and insourcing, and more often the decision has been made in favour of the insourcing, which meant expanding the production base. In
recent years, due to increasing demands for the flexibility and competitiveness of enterprises, the decision to “produce or buy” is increasingly being made in favor of finding an external supplier.

2.2. Evaluation criteria for logistics networks
The key criteria when comparing different options for supply chains are: general costs; the duration of order execution; maximization of competitive advantages; quality of logistics service; uncertainty and risk.

Consider in more detail selected key criteria. In most cases, the criteria $C_1$ and $C_2$ are quantitative, and $C_3$, $C_4$, and $C_5$ are qualitative. However, often at the time of decision-making there is no information that allows an objective assessment of quantitative criteria. But since a decision must be made, the information gap must be filled in. This can only be done with the participation of people on the basis of their experience and intuition, that is, with the involvement of experts.

In the proposed algorithm (figure 2) as calculation methods, it has been proposed to use methods for processing inaccurate pairwise comparisons to solve multi-criteria decision-making problems [4-10].

**Figure 2.** The algorithm for the selection of logistics intermediaries.
3. Calculation Example

As an example, we consider possible configuration options for production chains for a timber company LLC Akvilon engaged in the manufacture of edged softwood boards and doors for country houses. In connection with the decision to expand the range of products at LLC Akvilon, the task arose to revise its production chain. To synthesize possible options for constructing the production chain, we consider the production and technological scheme of the forest industry complex, of which this enterprise is a part (figure 3). The dashed arrows in figure 3 indicate possible material flows of LLC Akvilon.

**Figure 3.** Production and technological chain of the forest industry complex.

Based on the analysis of figure 3, we can draw the following conclusions about possible options for building the production chain: 1) The raw material for production is roundwood, which is currently being purchased from a number of logging enterprises and dealers. An alternative to this option of organizing the material flow may be a forest industry chain, which starts not from a logging company, but from a forestry enterprise, when the timber processing enterprise takes over the logging function. 2) During the processing of wood, waste is generated, which is currently burned in the boiler room. With small production volumes this is quite acceptable, but with an increase in production volume it makes sense to consider the option when the wood waste is transformed into wood chips, which are then delivered to pulp and paper mills, fuel pellet plants, etc. 3) Finished products are delivered to the final consumer with the involvement of private carriers. A variant of organizing production with its own transport division is possible.

*Alternative 1:* Only the logging enterprises are included in the production chain (LLC Les, PiM LLC, LODBALTLES LLP, Timberg Holding OJSC, Domozhirovsky Lespromkhoz OJSC, Georgievsky Lesokombinat, Aurora OAZT), i.e. the enterprise does not carry out logging, and carries out transportation by itself. Window blocks are added to the product range of the enterprise.

*Alternative 2:* The difference from the previous alternative is that the transportation function is transferred to private carriers.

*Alternative 3:* The production chain includes the logging enterprises (the same as in alternative 1), a pulp and paper mill (or a plant for the production of fuel pellets), and a set of private carriers. Window blocks and technological chips are added to the product range of the enterprise; the enterprise performs the transportation function independently.
Alternative 4: Forestry enterprises (State Forestry Enterprise, Forestry Enterprise Lodeinopolsky, Oyatsky Forestry), i.e. the enterprise performs logging and transportation on its own. Window blocks are added to the product range of the enterprise.

Alternative 5: The difference from the previous alternative is that the transportation function is transferred to private carriers.

Alternative 6: Forestry enterprises (State Forestry Enterprise, Forestry Enterprise Lodeynopolsky, Oyatsky Forestry), Pulp and Paper Mill (or a plant for the production of fuel pellets), and a set of private carriers. Window blocks are added to the product range of the enterprise.

The expert group included: 1 - the general director of the enterprise; 2 - technical director; 3 - commercial director; 4 - chief economist; 5 - chief engineer; 6 - chief mechanic; 7 - head of sawmill production; 8 - the head of the carpentry unit; 9 - power engineer; 10 - head of the department of logistics and external cooperation; 11, 12, 13, 14 - process engineers of the sawmill.

Imagine the problem in the form of a two-level hierarchy (figure 4).

Figure 4. Hierarchical structure of the task of choosing a forest industry chain.

Let us introduce the notation:

\( A = \{A_1, A_2, ..., A_n\} \) - many alternatives consisting of \( n \) elements; \( P_0(A) \) - a set of cardinalities of alternatives, the elements of which are all possible combinations of alternatives of a universal set of alternatives \( A \); \( P_0(A) = \{B_1, B_2, ..., B_l\}, l = 2^n - 1 \) (the empty set is excluded from consideration); \( C = \{C_1, C_2, ..., C_r\} \) - set of criteria consisting of \( r \) elements; \( P_0(C) \) - set of criteria cardinality, elements of which are all possible combinations of criteria for the universal set \( C \), \( P_0(C) = \{C^{(1)}, C^{(2)}, ..., C^{(k)}\}, k = 1, r, C^{(k)} = \{C_{1}^{(k)}, C_{2}^{(k)}, ..., C_{s}^{(k)}\} \) - is the set of all subsets of criteria of length \( k \).

Each of the experts selects the subset of criteria that, in his opinion, is the most preferable in comparison with the entire set of criteria

\[
\begin{cases}
    c_{ni}^{(k)} = 1, & \text{if the } n \text{ expert selects a subset } C_{i}^{(k)}, \; t. \; e. \; c_{i}^{(k)} > C \\
    c_{ni}^{(k)} = 0, & \text{otherwise}
\end{cases}
\]

For example, an expert's choice of a pair of \( C_3 \) and \( C_4 \) criteria means that this expert cannot determine the most preferable criterion from \( C_3 \) and \( C_4 \) - both criteria are the most important.

After polling all \( N_c \) experts, the number of occurrences of the selected subsets is calculated

\[
c_i^{(k)} = \sum_{n=1}^{N_c} c_{ni}^{(k)}
\]
At the second stage, the expert, in accordance with the given criterion \( C_i, i = 1, \ldots, r \) selects a certain subset \( B_j \in P_0(A) \) as the most preferable among the whole set of alternatives \( A \).

\[
\begin{align*}
\{ c_{nji} = 1, & \quad \text{if the } B_j > A \\
\{ c_{nji} = 0, & \quad \text{otherwise}
\end{align*}
\]

\[ c_{ij} = \sum_{n=1}^{N^{(i)}_A} c_{nji}, \quad N^{(i)}_A \] - the total number of assessments of alternatives (groups of alternatives) by criterion \( i \).

During the survey, the experts provided inaccurate pairwise comparisons of the criteria (table 1) and alternatives in accordance with a given criterion (tables 2 – 5).

**Table 1.** Expanded matrix of pairwise comparisons of subsets of criteria.

|        | \( C_1 \) | \( C_2 \) | \( C_3 \) | \( C_4 \) | \( C_5 \) | \( C_1C_2 \) | \( C_1C_3 \) | \( C_1C_4 \) | \( C_1C_5 \) | \( C_2C_3 \) | \( C_2C_4 \) | \( C_2C_5 \) | \( C_3C_4 \) | \( C_3C_5 \) | \( C_4C_5 \) | \( C \) |
|--------|----------|----------|----------|----------|----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|--------|
| \( C_1 \) | -        | 4        | -        | 2        | -        | -          | 1          | -          | -          | 1          | -          | 1          | -          | 1          | -        | 4      |
| \( C_2 \) | -        | -        | -        | -        | -        | -          | 1          | -          | -          | 1          | -          | 1          | -          | 1          | -        | 6      |
| \( C_3 \) | -        | -        | -        | 2        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -      |
| \( C_4 \) | -        | -        | -        | 1        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -      |
| \( C_1C_2 \) | -        | -        | -        | -        | -        | 2          | -          | -          | -          | -          | 1          | -          | 1          | -          | -        | 3      |
| \( C_1C_3 \) | -        | -        | -        | 1        | -        | -          | 1          | -          | -          | -          | -          | -          | -          | -          | -        | -      |
| \( C_1C_4 \) | -        | -        | -        | -        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 1      |
| \( C_1C_2C_3 \) | -        | -        | -        | -        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -      |
| \( C_1C_2C_3C_4 \) | -        | -        | -        | -        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 1      |

**Table 2.** Expanded matrix of pairwise comparisons of forest industry chains according to the criterion of total costs.

|        | \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_1A_2 \) | \( A_1A_3 \) | \( A_1A_4 \) | \( A_1A_5 \) | \( A_2A_3 \) | \( A_2A_4 \) | \( A_2A_5 \) | \( A_3A_4 \) | \( A_3A_5 \) | \( A_4A_5 \) | \( A \) |
|--------|----------|----------|----------|----------|----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|--------|
| \( A_1 \) | -        | -        | -        | -        | -        | 2          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 2      |
| \( A_2 \) | 5        | -        | -        | 3        | -        | 2          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 2      |
| \( A_3 \) | 1        | -        | -        | -        | -        | 1          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 1      |
| \( A_4 \) | 1        | -        | -        | -        | -        | 1          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 2      |
| \( A_5 \) | 1        | -        | -        | -        | -        | 1          | -          | -          | -          | -          | -          | -          | -          | -          | -        | 2      |

**Table 3.** Expanded matrix of paired comparisons of forest industry chains according to the criterion of reliability.

|        | \( A_1 \) | \( A_2 \) | \( A_3 \) | \( A_4 \) | \( A_5 \) | \( A_1A_2 \) | \( A_1A_3 \) | \( A_1A_4 \) | \( A_1A_5 \) | \( A_2A_3 \) | \( A_2A_4 \) | \( A_2A_5 \) | \( A_3A_4 \) | \( A_3A_5 \) | \( A_4A_5 \) | \( A \) |
|--------|----------|----------|----------|----------|----------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|--------|
| \( A_2 \) | -        | 1        | -        | 4        | -        | -          | -          | -          | -          | -          | -          | -          | -          | -          | -        | -      |
Table 4. Expanded matrix of pairwise comparisons of forest industry chains in accordance with the criterion of service quality.

|      | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A$ |
|------|-------|-------|-------|-------|-------|-------|-----|
| $A_1$ | 2     | -     | -     | -     | -     | -     | 3   |
| $A_2$ | -     | 2     | -     | 1     | -     | -     | 1   |
| $A_3$ | -     | -     | 1     | -     | -     | -     | 2   |
| $A_4$ | -     | -     | -     | -     | -     | -     | 8   |

Table 5. Expanded matrix of pairwise comparisons of subsets of criteria according to the criterion duration of order execution.

|      | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ | $A$ |
|------|-------|-------|-------|-------|-------|-------|-----|
| $A_1$ | 1     | -     | 2     | -     | 1     | -     | -   |
| $A_2$ | -     | 2     | -     | 1     | -     | -     | 1   |
| $A_3$ | -     | -     | 2     | -     | -     | -     | 5   |

According to the criterion of uncertainty and risk, ten experts were not able to identify subsets of alternatives, i.e. provided an assessment $A \geq A$, two experts - $A_3A_4A_5 \geq A$, one expert - $A_2A_4 \geq A_5$, and one expert - $A_2A_5 \geq A$.

In table 6, the results of calculations performed in accordance with the general method of pairwise comparisons are given.

Table 6. Lower and upper boundaries of the probabilities of forest industry chains.

|      | $A_1$ | $A_2$ | $A_3$ | $A_4$ | $A_5$ | $A_6$ |
|------|-------|-------|-------|-------|-------|-------|
| $Bel(B_i)$ | 0.06  | 0.14  | 0.05  | 0.07  | 0.18  | 0.10  |
| $Pl(B_i)$  | 0.80  | 0.85  | 0.43  | 0.82  | 0.78  | 0.76  |
In figure 5, rating dependence \( Y = \gamma \cdot Bel(B_i) + (1 - \gamma) \cdot Pl(B_i) \) from the attitude of the LPR to the risk is presented. The general director of LLC Akvilon acted as an LPR, who assessed his attitude to risk by a value \( \gamma = 0.4 \). When \( \gamma = 0.4 \), alternatives are ranked as follows: \( A_2 \geq A_6 \geq A_4 \geq A_5 \geq A_3 \geq A_1 \).

**Conclusion**

The formalization of production tasks has been carried out, including the tasks of selecting individual links in the production chain (suppliers, carriers, warehouses) and choosing production chains based on the principles of a systematic approach. As calculation methods, it is proposed to use methods for processing inaccurate pairwise comparisons to solve multi-criteria decision-making problems. An extension of the DS/AHP method is proposed in the paper.

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