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REAL-TIME SUPPLIER SELECTION USING DIGITAL TWIN TECHNOLOGY: AN ANALYTIC HIERARCHY PROCESS-BASED OPTIMIZATION APPROACH

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Abstract: *Today, the selection of the optimal suppliers plays an increasingly important role in the efficient operation of supply chains. One of the main reasons for this is that the fourth industrial revolution has seen the emergence of increasingly complex supply chains, involving a growing number of suppliers to meet increasingly diversified customer needs. While manufacturing companies use framework contracts to secure the parts needed to meet uncertain customer needs, framework contracts often fix requirements for a fixed future period in the light of past supplier performance. The Fourth Industrial Revolution is enabling the use of a number of new methods and tools to collect real-time data on supply chain operations and to define key performance indicators (KPIs) that show the performance of individual players in the value chain in real time. In this paper, the author proposes a supplier selection method based on analytic hierarchy process (AHP) that is able to determine the optimal suppliers for current component requirements in real time based on real-time information about the state of each player in the supply chain.*

Keywords: *decision making, optimization, Analytic Hierarchy Process, digital twin technology, supplier selection, purchasing cost, efficiency, key performance indicators.*

1. INTRODUCTION

The supplier selection plays an important role in the efficient operation of manufacturing companies. Verma concluded in his research on the analysis of supplier selection processes [1] in 1998, that the supplier selection processes are generally based on quality, price, flexibility and performance of delivery operations. These aspects play an important role in today's supplier selection processes, but sustainability aspects are also taken into consideration. Choi et al. [2] highlighted in a research on supplier selection in automotive industry, that the long term relationship plays a significant role in the success of manufacturer supplier success. There is a wide range of supplier selection methodology which can be used in different situations to select the appropriate supplier. De Boer et al. defined the following main groups of supplier selection methodologies: linear weighting models, toal cost of ownership (TCO) models, mathematical programming models, statistical models and artificial intelligence (AI)-based models [3]. Chai et al. make a deeper analysis of supplier selection methodologies [4] and they define a wide range of methods in the field of AI-supported solutions including genetic algorithm (GA), grey system theory (GST), neural networks (NN), rough set theory (RST), Bayesian network (BN), decision tree (DT), case-based reasoning (CBR), particle swarm optimization (PSO), support vector machine (SVM), association rule (AR), and ant colony algorithm (ACO).

Aissaoui et al. [5] define six phases of purchasing decision making processes including make or buy decision, supplier selection, contracting, forming collaboration, physical procurement, and performance analysis. In this research they stated, that before making decisions a pool of suppliers and a set of decision criteria must be defined. Spekman [6] wrote

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in his early research in 1988, that "Early failures at just-in-time (JIT) programs were often attributed to the manufacturer's approach to dealing with his suppliers. Instead of focusing on the mutual benefits and joint gains, JIT was usually interpreted to be the supplier's responsibility." This fact is true also today, because shifting all responsibilities of supply processes and supply operations to the supplier is not a good solution, because cooperation, long term collaboration is especially important in the case of an efficient supply chain solution. Bay and Sarkis mentioned in their research work the importance of sustainability [7].

Analytic hierarchy process is a good way to choose optimal suppliers. In the literature we can find a wide range of solution methods, where AHP is integrated with linear programming [8], AHP is integrated with Fuzzy models [9], AHP is used for global supply problems [10] or AHP is used with aa Fuzzy multi-objective linear programming [11]. The uncertainties in supply chains can be taken into consideration using Fuzzy models. A wide range of research works discuss the application of Fuzzy models to solve the supplier selection problem including a multi-criteria intuitionistic fuzzy group decision making for supplier selection with TOPSIS method [12], integration of supplier selection and order allocation problems using an integrated fuzzy multi criteria decision making method [13], integration of Fuzzy VIKOR methodology and entropy measure for supplier selection [14], Fuzzy DEMATEL method for developing supplier selection criteria [15], supplier selection with Fuzzy VIKOR [16], supplier selection based on fuzzy inference system [17] or Fuzzy hierarchical TOPSIS for supplier selection [18].

As the above-mentioned researches show, the uncertainties of supply chain processes can be taken into consideration using Fuzzy models, but the above-described approaches are generally used data from the Enterprise resource Planning (ERP) or from the Manufacturing Execution System (MES) and the decision making processes were not supplied by real-time status information. Within the frame of this approach, the author proposes a novel methodology, where the analytic hierarchy process uses real-time status information from the digital twin of the manufacturing and logistics processes of customers, suppliers and logistics service providers to solve the supplier selection problem. Within the frame of this article, the author describes a framework including the main players of the supply chain. These players use Industry 4.0 technologies to transform their physical processes into a digital twin, where dynamic simulation, and real-time monitoring of physical processes can be performed to collect real-time status information. This real-time status information can increase the success and performance of supplier selection process.

2. Materials and methods

Within the frame of this chapter, a novel approach is proposed to support the real-time decision making using digital twin technology-based real-time information and analytic hierarchy process. In this approach all players of the supply chain have their own digital twin solution (see Figure 1), which is required to collect real-time status information from all relevant processes of the value chain, including suppliers, customers and logistics service providers.

In the case of the customer, status information can be collected from the production system and form the logistics system by smart sensors and sensor networks. This real-time status information can be used to generate a dynamic variable simulation model, which is in effect a digital twin of the physical system. This digital twin has access to relevant information provided by the ERP through a database, of which the main elements of the procurement and purchasing module are relevant in this case, such as the procurement planning, the order management, the project management, the resource planning, the inventory management and inventory planning, the procurement scheduling and the procurement management.

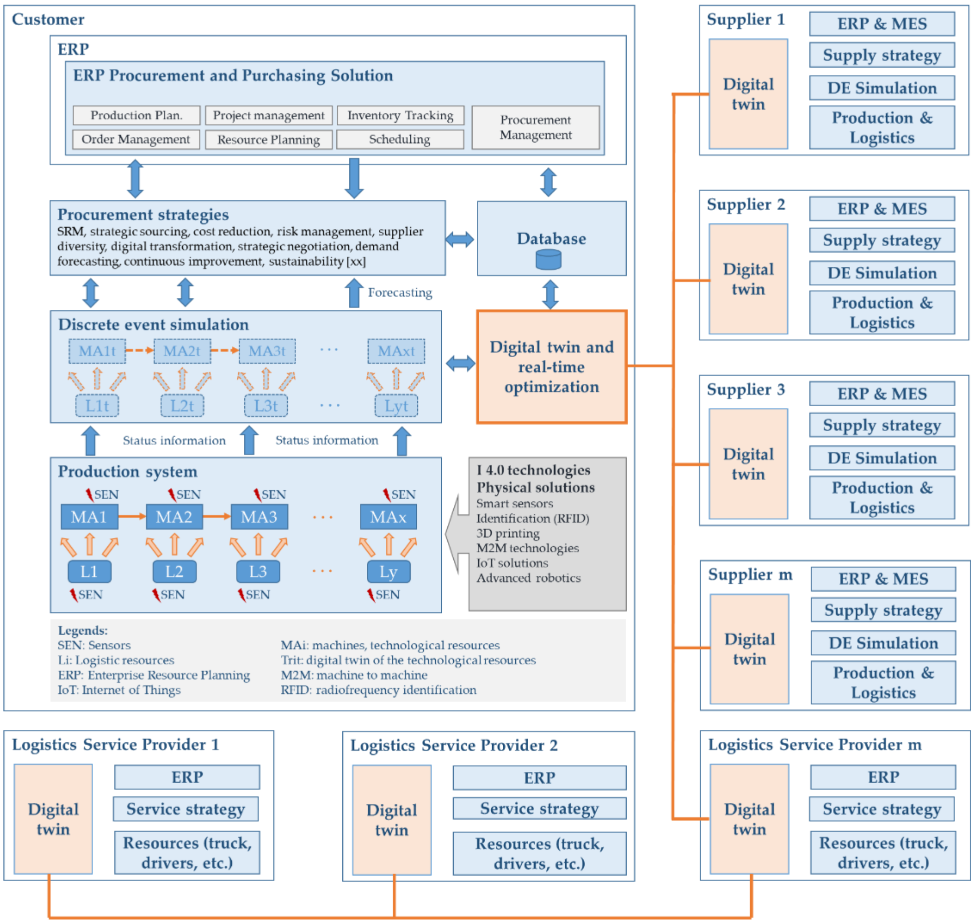

Figure 1. *Framework to support digital twin-based real-time supplier selection (Source: own research)*

Based on this information and on strategically defined procurement strategies (SRM, strategic sourcing, cost reduction, risk management, supplier diversity, digital transformation, strategic negotiation, demand forecasting, continuous improvement, sustainability [19]), the digital twin can perform the real-time selection of optimal suppliers based on information from the digital twin of suppliers and logistics service providers, based on real-time information that spans the supply chain defined by the customer, suppliers and logistics service providers.

Based on this model, it is possible to use the analytic hierarchy process to choose the best supplier for the present orders. After all decision making, the digital twins can be updated, and the supplier for the new order can also be chosen based on real-time data and present status information.

The general process of analytic hierarchy process includes the following steps: (i) define the goal and alternative solutions, (ii) describe the problem and define the decision criteria influencing the value of the objective function, (iii) calculate the priority of each criterion, (iv) compute the weights of criteria and priorities, (v) evaluate consistency of matrices. The general decision hierarchy, and their transformation into the decision problems of supplier selection is shown in Figure 2.

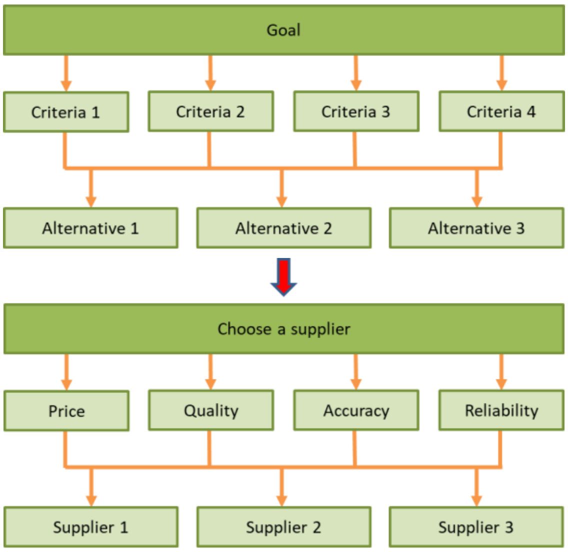

Figure 2. *Transformation of the general decision hierarchy into the decision problem of supplier selection (Source: own edition)*

The general computation process of analytic hierarchy process methodology can be summarized as follows:

- definition of decision criteria matrix including a pairwise comparison, where 1 is for equal importance, 3 is for moderate importance, 5 is for strong importance, 7 is for very strong importance and 9 is for extreme importance:

$$C = [c_{ij}], i, j = 1 \dots m, c_{ij} = \frac{1}{c_{ji}}, 1 \leq c_{ij} \leq 9 \vee \frac{1}{9} \leq c_{ji} \leq 1, \quad (1)$$

- computation of priorities of decision criteria:

$$\forall i: p_i = \left(\prod_{j=1}^{m} c_{ij}\right)^{m^{-1}}, p_{sum} = \sum_{i=1}^{m} p_i, \quad (2)$$

- computation of normalised priorities of decision criteria:

$$p_i^* = \frac{p_i}{p_{sum}} \rightarrow \sum_{i=1}^{m} p_i^* = 1, \quad (3)$$

- computation of matrix A of decision criteria:

$$\forall i: a_i = \sum_{j=1}^{m} (c_{ij} \cdot p_j^*), \quad (4)$$

- computation of matrix B of decision criteria:

$$\forall i: b_i = \frac{a_i}{p_j^*}, b_{aver} = \frac{1}{m} \cdot \sum_{i=1}^{m} b_i, \tag{5}$$

- choose the appropriate random consistency index of decision criteria depending on the size of the analyzed matrix (criteria),
- computation of inconsistency index of decision criterias:

$$CI = \frac{b_{aver} - m}{m-1}, \tag{6}$$

- computation of inconsistency ratio of decision criterias:

$$CR = \frac{CI}{RI}, \tag{7}$$

- check the consistency of the matrix of decision criterias:

$$CR < 0.1 \rightarrow Consistent\ matrix, \tag{8}$$

- compare potential solutions:

$$\forall i: S_i = [s_{igh}], g, h = 1 \dots n, s_{igh} = \frac{1}{s_{ihg}}, 1 \leq s_{igh} \leq 9 \ \vee \frac{1}{9} \leq s_{ihg} \leq 1, \tag{9}$$

- compute priority for alternative solutions:

$$\forall i, h: p_{ih}^S = \left(\prod_{g=1}^{n} s_{igh}\right)^{n^{-1}}, p_{isum}^S = \sum_{h=1}^{n} p_{ih}^{*S}, \tag{10}$$

- compute normalized priority for alternative solutions:

$$p_{ih}^{*S} = \frac{p_{ih}^S}{p_{isum}^S}, \sum_{i=1}^{m} p_{ih}^{*S} = 1, \tag{11}$$

- computation of matrix A of alternative solutions:

$$\forall i, h: a_{ih}^S = \sum_{g=1}^{n} (s_{igh} \cdot p_{ih}^{S*}), \tag{12}$$

- computation of matrix B of alternative solutions:

$$\forall i, h: b_{ih}^S = \frac{a_{ih}^S}{p_{ih}^{S*}}, b_{averi}^S = \frac{1}{n} \cdot \sum_{h=1}^{n} b_{ih}^S, \tag{13}$$

- choose the appropriate random consistency index of potential solutions depending on the size of the analyzed matrix (solutions),
- computation of inconsistency index of alternative solutions:

$$CI_i = \frac{b_{averi}^S - n}{n-1}, \tag{14}$$

- computation of inconsistency ratio of alternative solutions:

$$CR_i = \frac{CI_i}{RI}, \tag{15}$$

- check the consistency of the matrix of alternative solutions:

$$CR < 0.1 \rightarrow Consistent\ matrix, \tag{16}$$

- choose the best solution form the resulted matrix:

$$\forall g, i: r_{gi} = p_i^* \cdot p_{ig}^*. \tag{17}$$

Based on the above-described methodology, the next chapter discusses a case study, which demonstrates the operation of the real-time decision-making process.

3. RESULTS

Within the frame of this chapter, the real-time optimization of supplier selection methodology will be demonstrated, where the real-time status information and key performance indicators of suppliers and individual orders are available through the digital twin. The optimization is based on analytic hierarchy process. In this scenario, four suppliers are available for the supply of tailstocks (see Figure 3) for producing CNC machines. Tailstocks offers additional support for work pieces, especially in the case of turning and threading.

The three available suppliers are the followings: East-West Machining Company, Taylor Engineering, Mike and Jack Turning Co. The three potential suppliers will be analyzed from price, quality, accuracy and reliability point of view. As a first step of the analyses, we have to define the pairwise comparison matrix, which is shown in Figure 4.

Figure 3. *Tailstock with manual body with retractable barrel (Source: https://www.smartlathe.com)*

	Price	Quality	Accuracy	Reliability	Priority	Normalised Priority
Price	1.000	4.000	3.000	7.000	3.027	0.5462
Quality	0.250	1.000	0.333	3.000	0.707	0.1276
Accuracy	0.333	3.000	1.000	5.000	1.495	0.2698
Reliability	0.143	0.333	0.200	1.000	0.312	0.0564
					5.542	1

Figure 4. *Pairwise comparison matrix with priorities and normalized priorities for criterias (Source: own calculation)*

The first step of the calculation is to calculate the priorities and the normalized priorities based on Eq. 2-3. Based on Eq. 4-5. we can define matrix A and matrix B, which are required to choose the random consistency index depending on the matrix size. The results of the calculation of matrix are the following: A=[2.260568, 0.523179, 1.116473, 0.23089] and B=[4.138413, 4.100637, 4.138013,4.096275] and the chosen random consistency index is RI=0.9.

Based on the average value of matrix B and the matrix size, we can calculate for this decision the consistency index and the consistency ratio as follows:

$$CI = \frac{b_{aver} - m}{m-1} = \frac{4.118335 - 4}{4-1} = 0.0394. \tag{18}$$

and

$$CR = \frac{CI}{RI} = \frac{0.0394}{0.9} = 0.0438. \tag{19}$$

The consistency ratio is smaller, than 0.1, therefore the pairwise comparison matrix is consistent, which means, that the pairwise comparison of evaluation criteria are consistent, no future changes are required within the frame of this phase of the real-time comparison.

The second phase of the optimization is the pairwise comparison of supplier from price point of view. Based on the available historical data regarding price of supplies, the company can compare the four available suppliers as Figure 5 shows.

Price	East-West Machinig Company	Taylor Engineering	Mike and Jack Turning Co.
East-West Machinig Company	1.000	0.250	4.000
Taylor Engineering	4.000	1.000	9.000
Mike and Jack Turning Co.	0.250	0.111	1.000

Figure 5. *Pairwise comparison of potential suppliers from price point of view (Source: own calculation)*

Based on Eq. 12-13. we can define matrix A and matrix B for the comparison matrix of suppliers from prices point of view, which are required to choose the random consistency index depending on the matrix size. The results of the calculation of matrix are the following: A=[0.659509, 2.177652, 0.199735] and B=[3.036896, 3.036896, 3.036896] and the chosen random consistency index is RI=0.58.

Based on the average value of matrix B and the matrix size, we can calculate for this decision the consistency index and the consistency ratio as follows:

$$CI = \frac{b_{aver} - m}{m-1} = \frac{3.036896 - 3}{3-1} = 0.0184, \tag{20}$$

and

$$CR = \frac{CI}{RI} = \frac{0.0184}{0.58} = 0.0318. \tag{21}$$

The consistency ratio is smaller, than 0.1, therefore the pairwise comparison matrix of suppliers from price point of view is consistent, which means, that the pairwise comparison of suppliers are consistent, no future changes are required within the frame of this phase of the real-time comparison.

The third phase of the optimization is the pairwise comparison of supplier from price point of view. Based on the available historical data regarding price of supplies, the company can compare the four available suppliers as Figure 6 shows.

Based on Eq. 12-13. we can define matrix A and matrix B for the comparison matrix of suppliers from prices point of view, which are required to choose the random consistency index depending on the matrix size. The results of the calculation of matrix are the following: A=[0.577407, 0.248137, 2.239344] and B=[3.064888, 3.064888, 30.64888] and the chosen random consistency index is RI=0.58.

Quality	East-West Machinig Company	Taylor Engineering	Mike and Jack Turning Co.
East-West Machinig Company	1.000	3.000	0.200
Taylor Engineering	0.333	1.000	0.143
Mike and Jack Turning Co.	5.000	7.000	1.000

Figure 6. *Pairwise comparison of potential suppliers from quality point of view (Source: own calculation)*

Based on the average value of matrix B and the matrix size, we can calculate for this decision the consistency index and the consistency ratio as follows:

$$CI = \frac{b_{aver} - m}{m-1} = \frac{3.064888 - 3}{3-1} = 0.0324, \quad (22)$$

and

$$CR = \frac{CI}{RI} = \frac{0.0324}{0.58} = 0.0559. \quad (23)$$

The consistency ratio is smaller, than 0.1, therefore the pairwise comparison matrix of suppliers from quality point of view is consistent, which means, that the pairwise comparison of suppliers are consistent, no future changes are required within the frame of this phase of the real-time comparison.

The fourth phase of the optimization is the pairwise comparison of supplier from accuracy point of view. Based on the available historical data regarding price of supplies, the company can compare the four available suppliers as Figure 7 shows.

Based on Eq. 12-13. we can define matrix A and matrix B for the comparison matrix of suppliers from accuracy point of view, which are required to choose the random consistency index depending on the matrix size. The results of the calculation of matrix are the following: A=[2.28154, 0.595462, 0,194263] and B=[3.071265, 3.071265, 3.071265] and the chosen random consistency index is RI=0.58.

Accuracy	East-West Machinig Company	Taylor Engineering	Mike and Jack Turning Co.
East-West Machinig Company	1.000	5.000	9.000
Taylor Engineering	0.200	1.000	4.000
Mike and Jack Turning Co.	0.111	0.250	1.000

Figure 7. *Pairwise comparison of potential suppliers from accuracy point of view (Source: own calculation)*

Based on the average value of matrix B and the matrix size, we can calculate for this decision the consistency index and the consistency ratio as follows:

$$CI = \frac{b_{aver} - m}{m-1} = \frac{3.071265 - 3}{3-1} = 0.0356, \quad (24)$$

and

$$CR = \frac{CI}{RI} = \frac{0.0356}{0.58} = 0.0614. \quad (25)$$

The consistency ratio is smaller, than 0.1, therefore the pairwise comparison matrix of suppliers from accuracy point of view is consistent, which means, that the pairwise comparison of suppliers are consistent, no future changes are required within the frame of this phase of the real-time comparison.

The fifth phase of the optimization is the pairwise comparison of supplier from reliability point of view. Based on the available historical data regarding price of supplies, the company can compare the four available suppliers as Figure 8 shows.

Based on Eq. 12-13. we can define matrix A and matrix B for the comparison matrix of suppliers from reliability point of view, which are required to choose the random consistency index depending on the matrix size. The results of the calculation of matrix are the following: A=[0.804015, 2.034396, 0.190653] and B=[3.029064, 3.029064, 3.029064] and the chosen random consistency index is RI=0.58.

Reliability	East-West Machinig Company	Taylor Engineering	Mike and Jack Turning Co.
East-West Machinig Company	1.000	0.333	5.000
Taylor Engineering	3.000	1.000	9.000
Mike and Jack Turning Co.	0.200	0.111	1.000

Figure 8. *Pairwise comparison of potential suppliers from reliability point of view (Source: own calculation)*

Based on the average value of matrix B and the matrix size, we can calculate for this decision the consistency index and the consistency ratio as follows:

$$CI = \frac{b_{aver} - m}{m-1} = \frac{3.029064-3}{3-1} = 0.0145, \tag{26}$$

and

$$CR = \frac{CI}{RI} = \frac{0.0145-3}{0.58} = 0.0251 \tag{27}$$

The consistency ratio is smaller, than 0.1, therefore the pairwise comparison matrix of suppliers from reliability point of view is consistent, which means, that the pairwise comparison of suppliers are consistent, no future changes are required within the frame of this phase of the real-time comparison.

As the last phase of the optimization, depending on the priorities of criteria and the priorities of the potential suppliers, we can compute the priorities of the suppliers depending on the real-time data regarding price, quality, accuracy and reliability. In the case of this real-time supplier selection problem, each supplier's priority is the sum of the following priority components: (i) priority of supplier multiplied by priority of price; (ii) priority of supplier multiplied by priority of quality; (iii) priority of supplier multiplied by priority of accuracy; (iv) priority of supplier multiplied by priority of reliability (see Figure 9).

	Price	Quality	Accuracy	Reliability	Total
East-West Machinig Company	0.1186	0.0240	0.2004	0.0150	0.3581
Taylor Engineering	0.3917	0.0103	0.0523	0.0379	0.4922
Mike and Jack Turning Co.	0.0359	0.0932	0.0171	0.0035	0.1498
Total	0.5462	0.1276	0.2698	0.0564	

Figure 9. *Priorities of the suppliers depending on the real-time data regarding price, quality, accuracy and reliability (Source: own calculation)*

Based on the computed priorities of the potential suppliers, the best supplier for the next order is the Taylor Engineering, because the sum of the priorities for price, quality, accuracy and reliability is the highest.

After this calculation, the procurement department can realize the order and the supplier database can be updated depending on the performed supply operations and the supplier for the next sequential order can be chosen in the same way, where the database of supplier is updated and the digital twin of the whole value chain offers real-time information regarding manufacturing and logistics.

The above described methodology makes it possible to improve the efficiency of procurement processes, because the customer's order management can be continuously updated with real-time information and the past, near past and present performance of suppliers can also significantly influence the evaluation of suppliers.

4. CONCLUSIONS

The complexity of logistic processes has increased so much in recent years that there is a need for modern methods and tools to ensure the efficiency of these complex supply chains, while ensuring sustainability, availability, flexibility and transparency. This is particularly true in the case of the optimal design of supply networks, which perform significant transport and storage operations, making the optimization of their processes of paramount importance. In this paper, the author proposes the application of a digital twin-based decision support system that determines optimal suppliers using real-time status information of customers, suppliers and logistics service providers in the supply chain, taking into account the suppliers' historical data, using AHP based on key performance indicators determined by statistical methods. For the proposed methodology, the following significant technological solutions should be highlighted:

- a digital twin of the customer's production and logistics processes can be generated from a sensor network,
- the digital twin contains real-time status information of the production and logistics processes,
- the procurement and purchasing modules of the ERP system and the procurement strategy can be used to ensure the selection of the optimal suppliers, but in the case of the present solution this is supported by an AHP-based supplier selection algorithm,
- the digital twin selects the supplier for a given order based on information from the ERP and real-time information,
- the real-time optimizer uses the information from the digital twin of suppliers and logistics service providers,
- there is a potential feedback, which makes it possible to change the operation parameters of suppliers, customers and logistics service providers depending on the solution of the supplier selection problem.

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