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Tamas BANYAI^{1*}
Adam FRANCUZ¹

A NEW DESIGN APPROACH FOR MILKRUN-BASED IN-PLANT SUPPLY IN MANUFACTURING SYSTEMS

In manufacturing technologies milkrun and water-spider-based material handling represents up-to-date solutions, especially in the case of just-in-time and just-in-sequence in-plant supply. The objective of this research work is to show how to support the design of milkrun-based in-plant supply with heuristic optimisation in manufacturing processes. This paper proposes a new optimisation approach that can determine the optimal parameters of material handling operations of manufacturing technologies focusing on milkrun-based in-plant supply of manufacturing and assembly cells and lines. After a careful systematic literature review, this paper introduces a structural model to formulate the problem of routing of milkrun trolleys in manufacturing and assembly processes. Next, a potential mathematical model is described. Numerical results demonstrate how the proposed approach supports the decision making process in milkrun design focusing on the optimisation of the required number of milkrun trolleys and the routing of them.

1. INTRODUCTION

In order to serve customers faster and more flexibly, efforts must be made to reduce not only production time but also material flow time. To improve logistics processes, a new systems theory was developed in Japan in the 50s. At the Toyota automobile company, a new production paradigm was developed to achieve the right quantity, quality and material flow time. The main goals of the Toyota Production System (TPS) are the followings: error-free operation, maximum added value, continuous elimination of losses, continuous material flow and the development of a material flow in production that is adapted to the changing needs of the customer. TPS has made enormous progress in the second half of the 20th century, and its operation and development have put the Japanese automotive industry at the forefront of the world by the 1980s.

The optimisation of manufacturing processes integrates a wide range of design tasks, including purchasing, production, distribution and reverse processes and it focuses on problems in the field of layout planning, scheduling, routing, packaging, building of loading units.

¹ Institute of Logistics, University of Miskolc, Miskolc, Hungary

* E-mail: alttamas@uni-miskolc.hu

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This production system is the basis of the lean management, which is still the dominant system today. The lean philosophy is inseparable from Toyota Production System; the term lean has been used since 1988. The main objective of lean management is to eliminate and reduce waste. Losses can be defined as overproduction, overstocking, waiting, unnecessary movement and activity, or the production of defective products. Due to the demands of customers, the lean philosophy pays attention to minimising logistics and material flow processes in addition to the proper implementation of production.

One of the most important tasks of logistics processes is to service production according to the 7M principle. The supply of raw materials to production lines plays an important role in the production logistics of the automotive industry. To achieve this, system processes based on the lean philosophy have been developed to supply the production lines with the right amount of raw materials at the right time and in the right flexible way. Milkrun solutions are such a system process.

Milkrun is a system for replenishing variable quantities of components at specific times. In fact, it means the scheduled delivery and replenishment of raw materials and/or semi-finished products used in production according to their current consumption.

The motivation of this paper is that in-plant supply must be not only be cost efficient and reliable but also sustainable and, therefore, new optimization models and methods can be developed and applied. This paper is organized, as follows. Section 2 presents a systematic literature review to summarize the research background focusing on the design and optimisation of milkrun-based in-plant supply. Section 3 presents the functional model. Section 4 presents the mathematical model. Section 5 describes a new heuristic optimisation algorithm to solve the integrated resource allocation and routing problem. Conclusions, discussions and future research directions are discussed in the last section.

2. LITERATURE REVIEW

The aim of this chapter is to review the existing research findings through a systematic literature review and to identify areas where further research is needed. This chapter is structured in three parts. In the first part we are focusing on the descriptive analysis of available sources, in the second part we will summarise the results of content analysis, while in the third part we discuss the main conclusions of literature review.

As a first step in the literature review, we have to define search criteria to identify literature sources that fit the predefined research objective. This is a critical part of the literature review process; as wrong keywords can lead to a wrong research direction showing a false picture of the current state of the art in a particular research direction. We have used the Scopus database and searched using the keyword combination (TITLE (milkrun) AND TITLE-ABS-KEY (logistics)). The search was carried out on 12 March 2022, so it is possible that new results have been published in the literature since then, which are not included in this article.

The search resulted 63 publications, grouped by topic as shown in Fig. 1. As this classification shows, the research area fits well with engineering and applies knowledge from both computer science and mathematics. This is explained by the fact, that since milkrun

solutions are mainly developed in multinational companies, especially in automotive industry, they usually perform complex in-plant supply operations with many input and output objects, and their optimal design requires the development of new mathematical models and solution algorithms. The importance of information science in this research area is particularly justified by the fact that the design of milkrun supply systems has become more complex problem, especially with the strengthening of the fourth industrial revolution and the transformation of conventional manufacturing systems into cyber-physical systems [1].

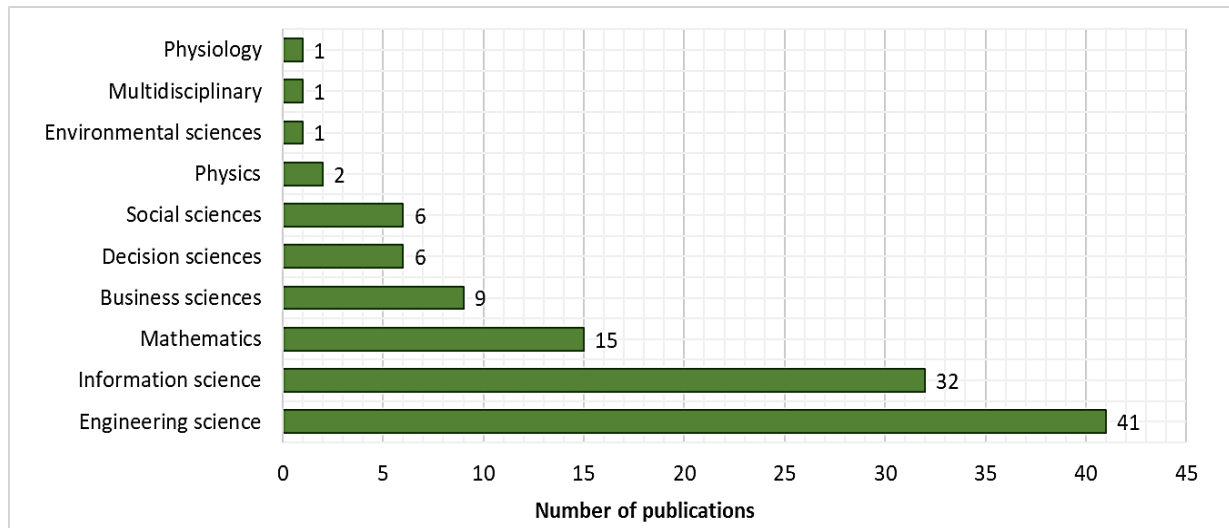


Fig. 1. Classification of articles considering subject areas based on search in Scopus database using keywords (TITLE (milkrun) AND TITLE-ABS-KEY (logistics))

As Fig. 2 shows, the research of milkrun-based material supply goes back more than 15 years. The first article was published in 2007 and defines the concept of milkrun material supply in the context of a hybrid supply model [2]. The number of publications has increased significantly in the last five years, which also underlines the importance of this research area.

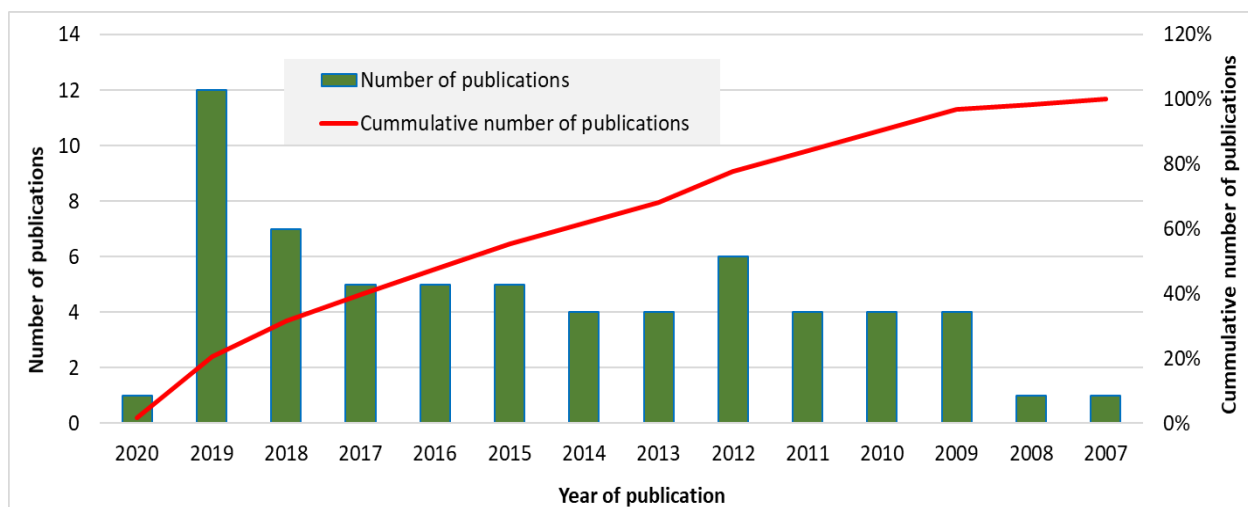


Fig. 2. Classification of published articles considering the year of publication based on search in Scopus

An internationally accepted method for evaluating scientific publications is to examine citation. Figure 3 shows the citation data for the ten articles with the highest citation rates. In the literature, there are summary works that evaluate existing sources [3], usually the number of citations received for these tends to be very high.

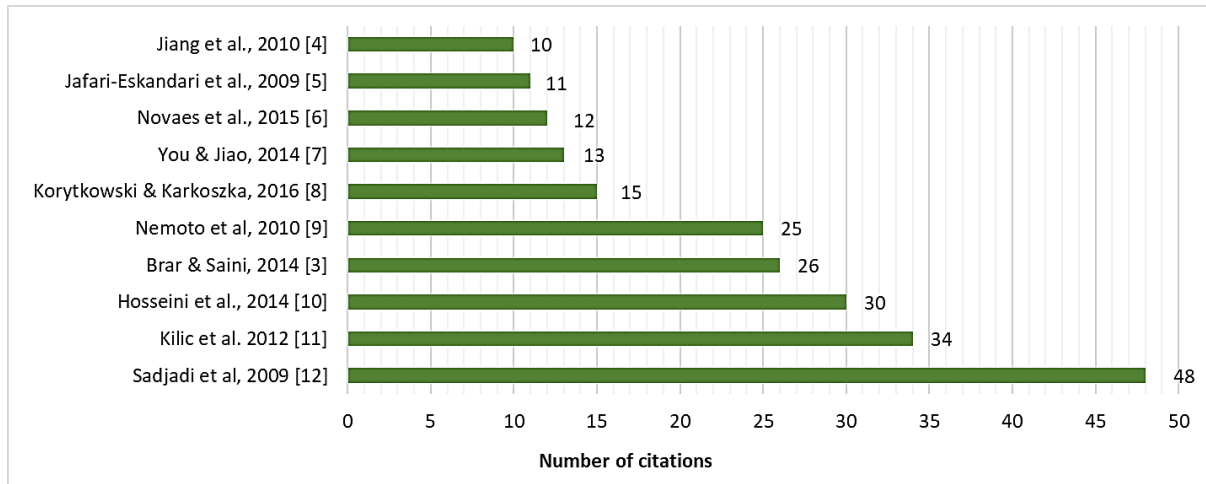


Fig. 3. The 10 most cited articles based on the search results in Scopus

Next, we analysed the search results from used keywords point of view. In our opinion, this classification gives a more accurate description on the milkrun related publications than a classification by subject. Figure 4 shows the result of this keywords-based classification. The most frequently used keywords are logistics, optimisation, material handling, manufacturing, simulation, transportation cost, routing, automotive, mathematical modelling.

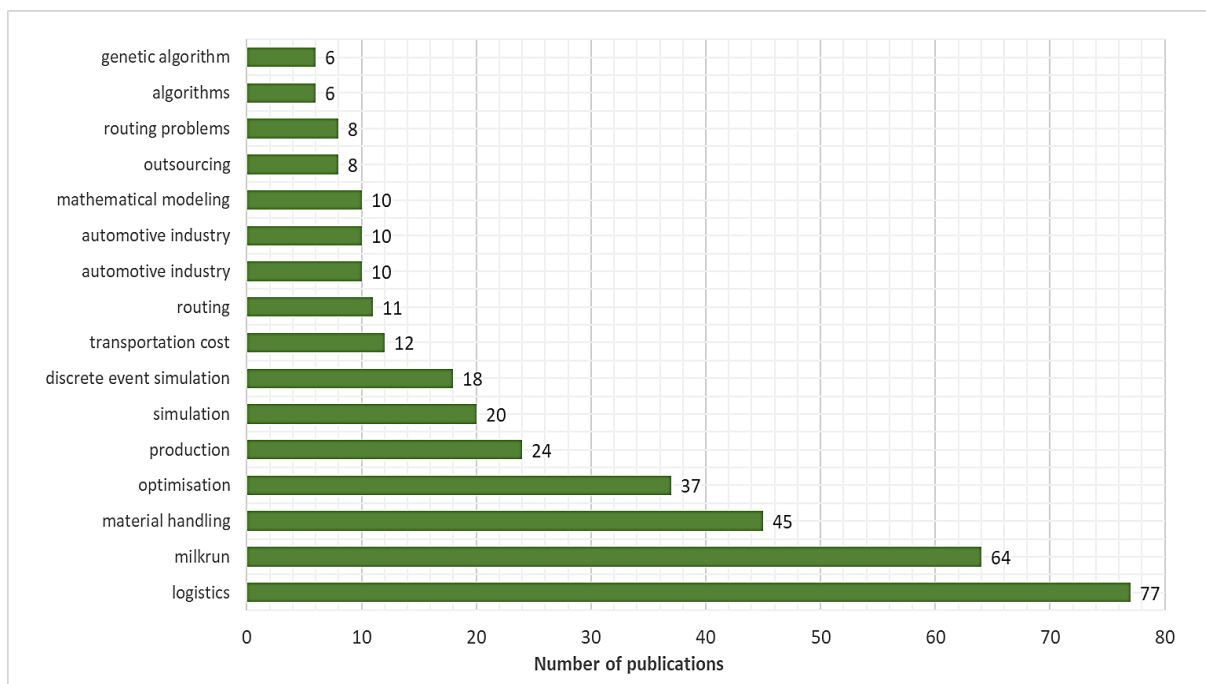


Fig. 4. Classification of articles from used keywords point of view based on the search results in Scopus

The design of milkrun supply is of great importance for both in-plant [4] and external [5] processes. The literature basically discusses milkrun solutions both in production and service environment [6]. A number of methods for designing milkrun routes can be found in the literature that are well suited for designing processes of different complexity. Perhaps the most basic approach is the formal approach, where analytical tools are used to determine optimal system parameters [7]. Other important approach is optimisation, which is mainly applied to the design of large-scale complex milkrun processes, since in most cases NP-hard problems have to be solved [8]. In particular, the use of heuristic algorithms has become widespread in the field of optimisation. Among them, the genetic algorithm [9], the saving algorithm [10], the harmony search algorithm [11], hybrid models such as hybrid optimization simulation models [12] or simulated annealing [13] are widely used in the design of milkrun systems. Several literature sources provide examples of the application of linear temporal logic to the design of milkrun systems [14] or the application of Yamazumi analysis with simulation tools [4]. In addition to deterministic models, approaches to account for uncertainties in systems are increasingly used. One of the best examples is the use of fuzzy models [15]. In the case of complex systems, the most commonly used solution and modelling method is simulation [16]. Finally, it is worth mentioning integrated optimization algorithms [17], which combine the positive properties of different algorithms to become an effective tool for solving complex design problems. It is important to highlight case studies when analysing the literature of milkrun design, as they can be used to demonstrate the practical applicability of the design methods in the literature. The case studies show that milkrun design is not only a current task in the automotive industry [18], but also an important design task in the mechatronic assembly industry, cable manufacturing [19] and semiconductor manufacturing [20]. Application examples can be found in the literature through case studies of companies in Germany [21], Indonesia [22] and Thailand [23].

In milkrun planning, a number of objective functions can be formulated. In terms of objective functions, the literature provides a number of options, among which we would like to highlight the followings: cost reduction [24], increasing utilization and process stability [25], reducing physical work [26], reducing errors [27], meeting ergonomic requirements, increasing sustainability. In addition to objective functions, the correct choice and formulation of the constraints is important in optimization. In addition to capacity [28] and time [29] constraints, models discussed in the literature often use loading mode constraints and consider routing in specific environments such as congested transport environments [30].

Finally, it is worth mentioning a few areas where there has also been significant research on the optimal design of milkrun routes:

- Management strategies in the design and operation of milkrun [31].
- Milkrun-based solutions operating in cyber-physical environments [32].
- Impact of advanced product identification solutions [33].
- The use of electric vehicles in milkrun solutions [34].
- Application of routing methods, dynamic and real-time routing solutions [35].
- Scheduling theories for milkrun planning [36].
- The role of human resources in milkrun processes [37].
- Lean tools [38] and Kanban [39] in the design of in-plant material supply systems.
- First mile and last mile logistics solutions [39].

3. FUNCTIONAL MODELLING OF MILKRUN-BASED IN-PLANT SUPPLY IN MANUFACTURING SYSTEMS

The main objective of this research is to create a time-minimized milkrun route that takes into consideration the distance of the production lines to the warehouse and to each other, the number of available milkrun trolleys and their time capacity. In our model, the time capacity means the upper time limit of one milk run route, which depends on the capacity of batteries of milk run trolleys, the length of milk run routes and the weight of loading of the milk run trolley. In addition, the suggested methodology balances the loads of the given Milkrun routes, which means, that the length of the routes is nearly the same. As a result, we can define routes that lead to increased utilization, stabilize material flow, reduce physical work and reduce errors. Within the frame of this chapter the following basic information are taken into consideration:

- Map of the production line (Fig. 5): The methodology is presented using a real production line for better understanding. In the production line map, we can distinguish starting locations, production line locations, junctions and road sections.

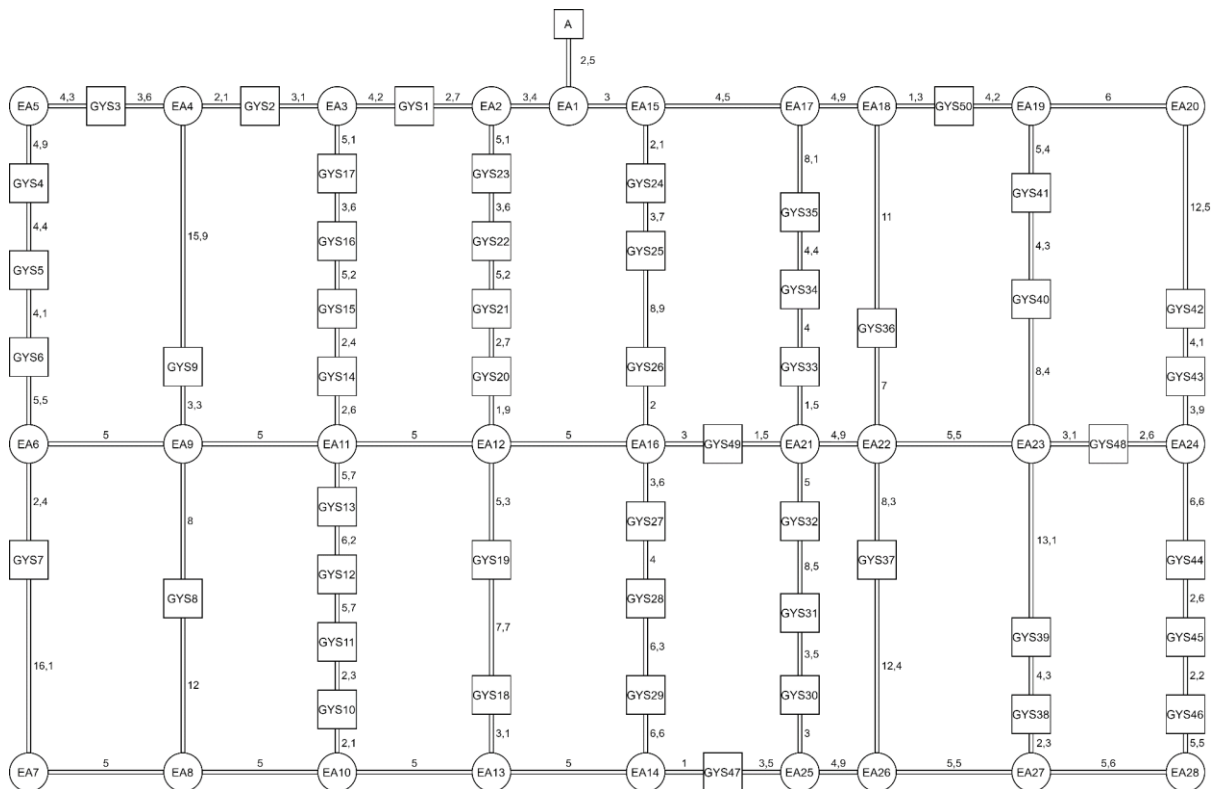


Fig. 5. Map of the production plant including production lines, junctions and warehouse exit

- The exit of the warehouse as starting location of milkrun routes: this location is marked as location A. The objective of the optimisation is to create a round route, so the starting location and the arrival location are both in the warehouse exit, so that the return time for the milkrun trolleys has not to be taken into consideration and the used empty containers or packaging materials can be returned to the warehouse.

- The locations of production lines: these locations are marked as “GYS” locations. In the map, the production lines are marked with rectangular icons. The required time of loading and unloading operations at each production line is also given. If we define a small loading and unloading time, then the time-related objective takes mostly the required transportation time (delivery time) into consideration.
- Junctions: junctions are marked as “EA” locations (with circle icon).
- Distances in production line – production line, production line – junction or junction – junction relations: We can take these distances as a straight line section of a potential route into consideration. I consider the sections as a straight line. The length of a section is a ratio, without units of measurement, in relation to each other. There is a direct proportionality between the length of a section and the time it takes to cover it.
- The constraints of milkrun trolleys: the time capacity of a milkrun trolley is 15 minutes, the objective is to create as few milkrun routes as possible. The time capacity of a milkrun can be influenced by human source, such as lunch break, end of working hours, or it can come from a technical source, such as battery capacity. The number of available milkrun trolleys are also taken into consideration.

4. MATHEMATICAL MODELLING OF MILKRUN-BASED IN-PLANT SUPPLY IN MANUFACTURING SYSTEMS

The first phase of mathematical modelling is to define the objective and its associated input parameters, objective functions and constraints. In this chapter the input and output parameters, the objective function and the constraints are defined, and in the next chapters a potential algorithm will be described.

The objective of the optimisation problem is to find time-optimized milkrun routes, taking into consideration the time and capacity related constraints (upper time limit of milkrun routes and the available milkrun trolleys). In addition, the routes should be created in such a way that both arrival and the destination location of each milkrun route are the same warehouse exit, thus achieving a round route, which results a bidirectional material flow including the transportation of raw materials and components from the warehouse to the manufacturing lines and the collection and transportation of final products from manufacturing lines to the warehouse. Important constraint is, that each production line is supplied exactly ones in a single route. Available information includes the location of production lines, junctions and the location of warehouse exit, distances between adjacent objects, shortest routes between two production lines, specific consumption of milkrun trolleys and raw material requirements of the production lines from the master production plan.

4.1. INPUT PARAMETERS OF THE MODEL

Within the frame of this chapter the input parameters of the model are defined, as follows:

- Number of production lines: n_g . Production lines are workstations that have in-plant supply needs regarding raw materials, components and finished products, so these are the locations through which the milkrun route must pass.
- Number of junctions: n_e . Junctions are locations, which are used to define straight sections for an increased transparency of potential material handling routes throughout the production hall.
- Number of objectives: $n_o = n_g + n_e + 1$. Objects are warehouse locations, production lines and junctions.
- Identifier of production lines: G_p and $p = 0 \dots n_g$. G_0 is the identifier of the warehouse exit.
- Object identifier: ID_i and $i = 0 \dots n_g + n_e$. ID_0 is the identifier of the warehouse exit.
- Adjacency matrix: $SZ^o = [sz_{ij}^o]$, where

$$sz_{ij}^o = \begin{cases} 0, & \text{if } ID_i = ID_j \\ 0, & \text{if } ID_i \text{ and } ID_j \text{ are not adjacent,} \\ 1, & \text{if } ID_i \text{ and } ID_j \text{ are adjacent} \end{cases} \quad (1)$$

and $j = 0 \dots (n_g + n_e)$.

- The l_{ij}^o element of the object distance matrix shows whether objects ID_i and ID_j are adjacent or not, and if so, l_{ij}^o defines the length of the route segment between the neighbours. Since both the rows and columns of the matrix represent objects in the same order, the matrix is symmetric ($\bar{L} = \bar{L}^{-1}, l_{ij}^o = l_{ji}^o$).
- The element sz_{ij}^o of the adjacency matrix shows whether objects ID_i and ID_j are adjacent or not. Since both the rows and columns of the matrix represent objects in the same order, the matrix is symmetric ($\bar{SZ} = \bar{SZ}^{-1}, sz_{ij}^o = sz_{ji}^o$), and its values are binary.
- The value of adjacent elements is 1 and the value of non-adjacent elements is 0.
- Distance matrix of objects: $L^o = [l_{ij}^o]$, where

$$l_{ij}^o = \begin{cases} l_{ij}^o = 0, & \text{if } sz_{ij}^o = 0 \\ l_{ij}^o > 0, & \text{if } sz_{ij}^o = 1 \end{cases} \quad (2)$$

- Distance matrix of manufacturing lines: $L^{gym} = [l_{pq}^{gym}]$, where

$$l_{pq}^{gym} = \min \Theta_{pq}^{gy} \text{ and } p, q = 1 \dots (n_g + ID_0) \text{ and } p \neq q. \quad (3)$$

The distance matrix of production lines defines the shortest routes between the p^{th} and q^{th} production lines that can only pass through route sections and not through other production lines. If a route section is crossed by a production line, the section is split into two separate route sections by the production line and it is deleted from the distance matrix of production lines. Since both the rows and columns of the matrix represent production lines in the same order, the matrix is symmetric ($\bar{L}^{gym} = \bar{L}^{gym^{-1}}, l_{pq}^{gym} = l_{qp}^{gym}$).

- Raw material and component demands: $Q_{A_p}^{gy}$, where $p = 0 \dots n_g$. Each production line has a raw material or component requirement, which shows how much raw material the milkrun trolley needs to deliver to that production line.

- Final product demands: $Q_{K_p}^{gy}$, where $p = 0 \cdots n_g$. Each production line has a finished product demand, which shows how much finished product the milkrun trolley needs to deliver to the arrival point.
- Specific energy consumption of milkrun trolleys: γ . Specific energy consumption defines the consumption depending on the weight and length of the milkrun trolley.
- Weight of the milkrun trolley: m .
- Loading capacity of milkrun trolleys: q^{max} .
- Upper limit of available time for each milkrun route: τ .
- Number of available milkrun trolleys: Φ .

4.2. OUTPUT PARAMETERS OF THE MODEL

The first output parameter is the number of required milkrun routes, which determines how many routes need to be created in order to ensure that the time required to cover the routes meets the time capacity constraints of milkrun trolleys. Route number: x .

The second output parameter is the route matrix, which gives the minimized routes, sorted by production lines and distributed over the defined milkrun routes. The different rows of the matrix define the milkrun trolleys and the columns define the routes. The values of the first and $m_x \leq y \leq \max_x m_x$ columns are 0, since the origin and the destination are both the identifier of the warehouse exit location.

The permutation matrix defines the order of production lines within the optimised routes: $ER = [er_{x, \max_x m_x}]$, where

$$\forall x: er_{x,0} = 0 \text{ and } \forall m_x \leq y \leq \max_x m_x: er_{x,y} = 0. \quad (4)$$

4.3. OBJECTIVE FUNCTIONS OF THE MODEL

The objective function of the mentioned milkrun-based in-plant supply optimisation is the minimisation of the sum of the length of the route sections:

$$C(s) = C_s = \sum_{c=1}^x (\sum_{b=1}^{m_x-2} l_{er_{c,b}, er_{c,b+1}}^{gym} + l_{0,0, er_{c,1}}^{gym} + l_{er_{c,m_x-2}, 0,0}^{gym}). \quad (5)$$

where: l^{gym} – the minimum distance between production lines, $l_{er_{c,b}, er_{c,b+1}}^{gym}$ – the minimum production line distance between the b^{th} production line of the c^{th} route and the $(b+1)^{\text{th}}$ production line of the c^{th} route. The distance between each two production lines of a route shall be added:

$$A = \sum_{b=1}^{m_x-1} l_{er_{c,b}, er_{c,b+1}}^{gym}, \quad (6)$$

where: m_x – the number of objects in a given route including the starting and arriving warehouse exit location, so the addition should only go up to $m_x - 2$, thus excluding the warehouse exit location. However, not only the distance between the production lines, but

also the minimum distance between the starting point and the first production line $l_{0,0,er_{c,1}}^{gym}$ and the minimum distance between the last production line and the arrival point $l_{er_{c,m_x-2},0,0}^{gym}$ must be added to the A value:

$$A^* = \sum_{b=1}^{m_x-1} l_{er_{c,b},er_{c,b+1}}^{gym} + l_{0,0,er_{c,1}}^{gym} + l_{er_{c,m_x-2},0,0}^{gym}. \quad (7)$$

Once the formula gives the length for a route, the function must be extended to all routes: $c = 1 \dots x$.

The main constraints of the problem is that the capacity of the milkrun trolleys is given as a function of time, so the objective function must be transformed from length to time:

$$C(t) = C_t = \frac{1}{v} * [\sum_{c=1}^x (\sum_{b=1}^{m_x-2} l_{er_{c,b},er_{c,b+1}}^{gym} + l_{0,0,er_{c,1}}^{gym} + l_{er_{c,m_x-2},0,0}^{gym})]. \quad (8)$$

The objective function can be also defined as a function of energy, length of route and time. In this case, the net weight of the milkrun trolley and the weight of the load must be taken into consideration. The initial weight of a milkrun trolley at the warehouse exit can be defined as follows:

$$q_x^{init} = m + \sum_{p=1}^{m_x} Q_{Ap}^{gy}, \quad \forall Q_{Ap}^{gy} > 0. \quad (9)$$

Each production line has a raw material delivery ID and a finished product pick-up ID, so the current weight of the milkrun trolley can be calculated in the following way:

$$q_x^{curr} = q_x^{init} - \sum_{p=1}^b Q_{Ap}^{gy} + \sum_{p=1}^b Q_{Kp}^{gy}. \quad (10)$$

The unknown value of $l_{er_{c,b},er_{c,b+1}}^{gym}$ denotes the shortest distance between the b^{th} production line of the c^{th} route and the $(b+1)^{\text{th}}$ production line of the c^{th} route, therefore the first part of the objective function can be defined as follows.

$$C_1(E) = \sum_{c=1}^x \sum_{b=1}^{m_x-2} \gamma \cdot l_{er_{c,b},er_{c,b+1}}^{gym} \cdot q_x^{curr}. \quad (11)$$

In addition to the distances between the two production lines, the objective function should also include the distance from the starting location to the first production line and the distance from the last production line to the arrival location. This value can be calculated using the following equation:

$$C_2(E) = l_{0,0,er_{c,1}}^{gym} \cdot q_x^{init} \cdot \gamma + l_{er_{c,m_x},0,0}^{gym} \cdot (m + \sum_{p=1}^{m_x} Q_{Kp}^{gy}) \cdot \gamma. \quad (12)$$

The final objective function can be defined in the following form:

$$C(E) = C_1(E) + C_2(E). \quad (13)$$

4.4. CONSTRAINTS OF THE MODEL

The optimisation problem has two main constraints. The most important constraint is that the optimisation must be performed in such a way that the resulting time does not exceed the time limit of the milkrun trolley, which may be due to technical reasons (e.g. battery replacement) or human reasons (e.g. lunch break, shift change, etc.).

$$\forall x, m_x: \frac{1}{v} \cdot (\sum_{c=1}^x \sum_{b=1}^{m_x-2} l_{er_{c,b},er_{c,b+1}}^{gymmin} + l_{0,0,er_{c,1}}^{gymmin} + l_{er_{c,m_x},0,0}^{gymmin}) \leq \tau. \quad (14)$$

The predefined time-related constraint has 3 main parts. Instead of the global time limit constraint, a constraint can now be specified for the route sections.

In the first case, we can define an upper limit for the time required to cover the $l_{0,0,er_{c,1}}^{gymmin}$ minimum distance from the warehouse exit location to the first production line.

$$\tau_1^{max} \leq \frac{1}{v} l_{0,0,er_{c,1}}^{gymmin} \leq \tau_1^{max}. \quad (15)$$

The constraint can also be defined for each required time span to travel from the starting location to any e^{th} production line. In such a case, the time depend on the minimum time required to cover the minimum distance from the starting location to the first production line, and from the first production line to the e^{th} production line.

$$\forall e \in [2; m_x - 2]: \tau_e^{max} \leq \sum_{c=1}^x \sum_{b=1}^e \frac{1}{v} l_{er_{c,b},er_{c,b+1}}^{gymmin} + \frac{1}{v} l_{0,0,er_{c,1}}^{gymmin} \leq \tau_e^{max}. \quad (16)$$

The constraint can be defined by maximizing the required time required to travel the route to the last production line. In such a case, the change compared to the previous case is that the parameter e , which gives the current production line, is set to $e = m_x - 1$.

$$\tau_{m_x-1}^{max} \leq \sum_{c=1}^x \sum_{b=1}^{m_x-1} \frac{1}{v} l_{er_{c,b},er_{c,b+1}}^{gymmin} + \frac{1}{v} l_{0,0,er_{c,1}}^{gymmin} \leq \tau_{m_x-1}^{max}. \quad (17)$$

The second constraint is that there should be no more routes than milkrun trolleys available. In case the time-related constraint cannot be met, the optimization has to be performed again by increasing the number of trolleys. If neither condition can be met, the optimisation cannot be performed.

$$x \leq \Phi. \quad (18)$$

Based on the above mentioned input parameters, output parameters, objective functions and constraints, we have developed a new optimisation methodology to define the optimal milk run routes in the production plant. This optimisation methodology is discussed in the next chapter.

5. OPTIMISATION APPROACH FOR THE SOLUTION OF THE MILKRUN-BASED IN-PLANT SUPPLY DESIGN PROBLEM

The optimisation problem is solved with the Excel Solver extension programmed with built-in Visual Basics programming. The first step of the solution is to minimize the route to a given production line so that each production line is supplied exactly once and the starting and destination location of the milkrun trolleys are both the warehouse exit location. The optimized route is then converted from road unit to time unit. If the resulting unit of time is less than the time capacity of the milkrun trolley, the constraints are met, the minimization is done.

If the time required for a milkrun trolley to travel the minimised route is greater than the predefined upper time limit, the number of milkrun trolleys must be increased by one and the optimisation must be started again.

In the first case, as an initial number of milkrun trolleys we can choose two trolleys. The first step when analysing multiple milkruns is to determine the shortest route to each production line. After obtaining the shortest route to each production line, we can analyse the number of same route sequences for production line pairs. Dividing the sum of the shortest path lengths of the production line pairs by the number of route combinations, we obtain a ratio that can be used for further calculations. This ratio shows, how closely the shortest routes of production line pairs are related, and to what extent their shortest routes coincide (Fig. 6).

After computing the ratio for each pair of production lines, we can define a lower and upper bound. The production lines whose ratio numbers fall between the two bounds are called grouped production lines and will be counted as one production line for the remaining part of the optimisation. If a production line is part of several pairs of production lines their computed ratio falls between the lower and upper bounds, then a grouped production line may contain more production lines.

Thanks to this grouping, the number of production lines can be significantly decreased. The previous steps of the optimisation should then be repeated.

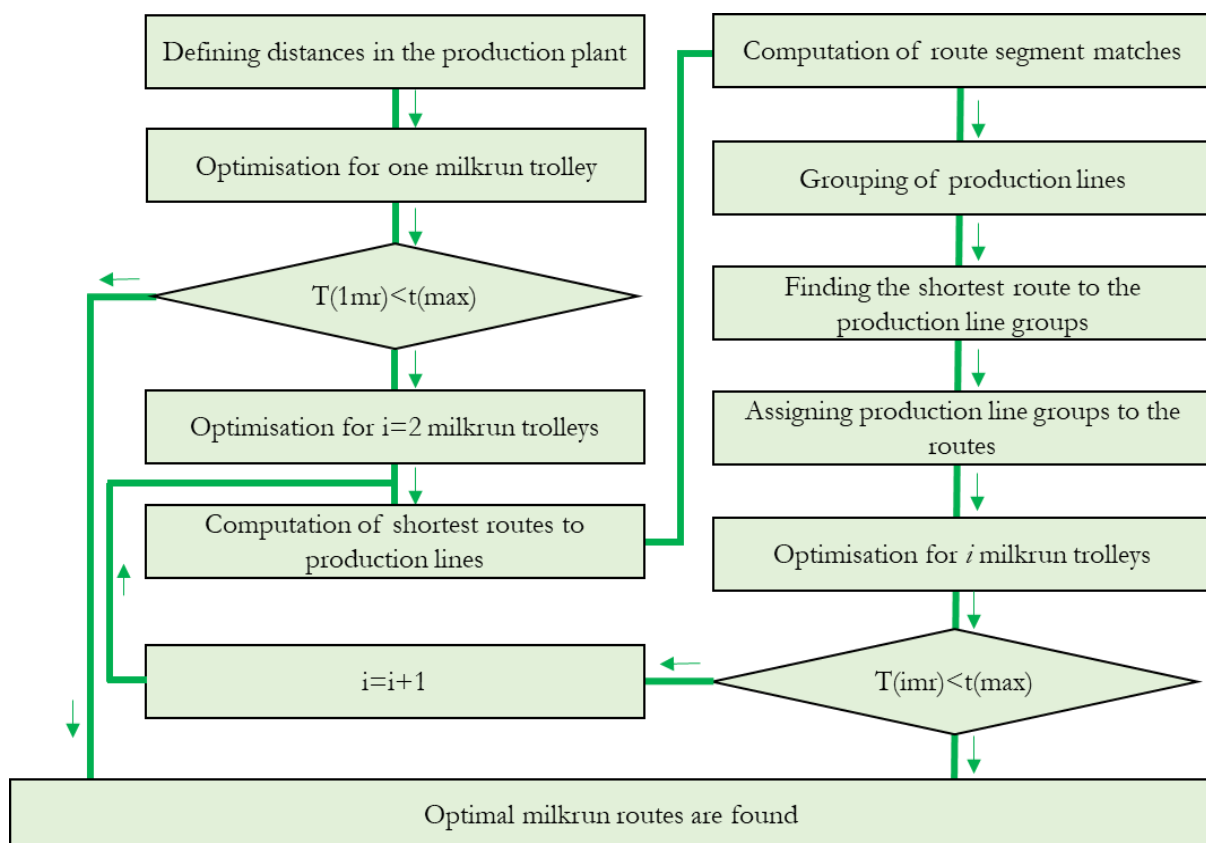


Fig. 6. Flowchart of the proposed optimisation methodology

We can determine the shortest routes to the grouped production lines and to the production lines that we could not group due to the predefined constraints. As a next step, we can analyse the number of same route sequences for production line pairs again and then form

the aforementioned ratio depending on the shortest route length and number of common route segments. Again, we can group the production lines, but this time we define the upper and lower bounds of the ratio so that the current production lines can be clustered into two different sets, because in this case the optimization is done for two milkrun trolleys. This way, we can decompose the grouped production lines back to the original production lines and perform the optimization for the two groups of production lines such that each production line can only belong to one set and each production line can only be supplied exactly once per route. After that, we can convert the resulting minimized routes into time units. If the resulted time unit is less than the predefined time-related constraint of the milkrun trolley, then the optimisation process is finished.

If the resulted time unit is greater than the predefined time-related constraint, then the number of milkrun trolleys must be increased, taking care that the number of trolleys does not exceed the number of available trolleys. If this is not feasible, the number of available trolleys must be increased, otherwise the optimisation cannot be performed.

The next chapters are discussing the above-mentioned optimisation process as follows:

- computation of the shortest route to each production line,
- finding the same shortest routes for production line pairs,
- definition of production line groups,
- definition of shortest routes to the defined production line groups,
- definition of the number of matching route segments,
- regrouping of production lines,
- results of optimisation.

5.1. COMPUTATION OF THE SHORTEST ROUTE TO EACH PRODUCTION LINE

The first step of the multiple milkrun optimisation is to determine the shortest route from the warehouse exit location to each production line. This is important because we can use the resulting routes to form production line pairs based on the number of route combinations. The optimum route is also determined using the Excel Solver extension based on the given parameters. We can perform the optimization for each production line, so in this case the Solver will not run from the GUI, but we can automate the optimization using the Visual Basic Application to make batch-optimisation scripts for the Solver.

5.2. FINDING THE SAME SHORTEST ROUTES FOR PRODUCTION LINE PAIRS

We can examine the shortest routes to all production lines defined by Solver and their route segments. We can define pairs of production lines and analyse the number of common route segments. The number of possible cases can be calculated as follows:

$$\vartheta = 0.5 \cdot n \cdot (n - 1) \quad (19)$$

where n is the number of production lines.

The function can be executed using three for loops. The first step is to define the three stages of the function junctions into the program code using the loops and defining the periods. As a result of the junctions, for each pair of production lines it has been determined at which segment of the route they match, these are written into separate columns in the data tables. In the next step, we can use a function in the generated columns to determine how many values are in the column, i.e. how many pairs of production lines have a matching pair of route segments. After that, using the loops, we assign to each generated column the related production line ID, and then add the sum of the shortest routes of the paired production lines.

Once we have determined the number of route segment matches for each pair of production lines, and the sum of the shortest route segments of the paired production lines, we will use the program code to convert the adjacent values from a row-by-row list to a column-by-column list.

The periodic changes take place in 3 cycles in 2 dimensions. The first cycle first pairs the Go? column values of the first production line with the Go? column values of all other production lines (GYS1–GYS2; GYS1–GYS3, etc.) on a column-by-column basis. The second loop assigns to these columns the values resulting from the function junctions for each route segment, then determines the number of segment units from the sum of the values, and writes the name of the corresponding production line pair for each column.

Once the pairs of production lines are associated with the first production line, the third loop is used to shift the initial production lines, thus determining the number of route segment matches and the identifier of the pairs for all production lines. Thanks to the operation of the program code and the third cycle, it is not possible that each production line pair is calculated twice, because the third cycle only pairs the initial production line with the production lines with a higher numerical value than it, for example, a production line pair GYS2–GYS1 cannot occur, because the third cycle only generates production line pairs GYS2–GYS3, GYS2–GYS4, etc.

After finding the same shortest routes for production line pairs, we can define production line groups.

5.3. DEFINITION OF PRODUCTION LINE GROUPS

In the previous section, we determined the number of common route segments for each pair of production lines and the sum of the two shortest route lengths. The objective of this phase is to create production line groups based on the number of common route segments. Clustering production lines, conditions are set so that the production lines in a group always belong to the same milkrun route in the final result. After that, we can optimize for two milkrun routes, so the constraints must be set accordingly so that final routes can be formed from the grouped route pools (Table 1). In Table 1, the number of common segments means the number of common segments between a production line pair, the amount defines the number of production lines pairs, where the number of common route segments is constant and the proportion represents the proportion of the number of production line pairs with constant common route segments and the total number of production line pairs.

In addition to the number of common route segments, we also had to determine the ratio of phase combinations to each other.

As Table 2 shows, the proportion of 10 or more common route segments is significantly smaller than the other proportions, so as a primary constraint we can define, that production line pairs with 10 or more matching route segments must be clustered into the same set of production lines.

Table 1. Number and proportion of matching route segments

Common segments	Amount	Proportion
1	621	50.69%
2	307	25.06%
3	76	6.20%
4	46	3.76%
5	35	2.86%
6	56	4.57%
7	28	2.29%
8	31	2.53%
9	13	1.06%
10	6	0.49%
11	3	0.24%
12	0	0.00%
13	2	0.16%
14	1	0.08%
15	0	0.00%

We can define, that the production line pairs must be clustered to the same production line group (Table 2). However, as the initial map (see Fig. 5) shows, these production lines are located far away from the starting warehouse exit location, the shortest routes of the production lines contain many route segments, and thus have a significantly higher chance of many matching segments than production lines that are located closer to the warehouse exit location.

Table 2. Example for the production line pairs with 10 or more matching route segments

Production line pairs	Number of matching route segments	Length of route segments	Parameter P
GYS11–GYS12	10	88.3	8.83
GYS30–GYS31	10	83.9	8.39
GYS39–GYS44	10	99.6	9.96
GYS39–GYS45	10	102.2	10.22
GYS39–GYS46	10	104.4	10.44
GYS39–GYS48	10	90.4	9.04
GYS44–GYS48	11	89.6	8.15
GYS45–GYS48	11	92.2	8.38
GYS46–GYS48	11	94.4	8.58
GYS44–GYS45	13	101.4	7.80
GYS44–GYS46	13	103.6	7.97
GYS45–GYS46	14	106.2	7.59

Therefore, to define the clusters of production lines, we will not consider the number of matching route segments directly, but rather a P ratio whose value is directly proportional to the two shortest routes and inversely proportional to the number of matching route segments. It means, that ratio P is the proportion of the length of route segments between two production lines and the number of matching route segments between the same production lines.

The first criterion was that the production line pairs with more than 10 matching route segments belong to a production line group. Adding this condition to the previously introduced ratio P , our final condition is that the production line pairs belong to a production line group whose ratio falls between the minimum and maximum P obtained by the production line pairs with more than 10 matching route segments (Table 2):

$$7.59 \leq P \leq 10.44 \quad (20)$$

The clustered production line groups can contain up to 5–6 production lines. The production line groups are formed in such a way that if, for example, the P ratio of the production line pairs GYS1–GYS2 and GYS1–GYS3 falls within the given boundaries, then production lines GYS1, GYS2, GYS3 are member of the production line group regardless of whether the P ratio of GYS2–GYS3 falls outside or inside the boundary, i.e. both the links between production line pairs and the P ratio condition must be taken into consideration.

If a production line can belong to more than one group according to the P ratio condition, the production line will belong to the group to which it is “pulled” by more production line. For example, let us define the following production line pairs: GYS1–GYS2, GYS1–GYS3, GYS2–GYS3 and GYS3–GYS4, GYS4–GYS5, GYS4–GYS6. Based on this condition and grouping method, the generated production line groups are as shown in Table 3.

Table 3. Production line groups

GYS*1:	GYS*2:	GYS*3:	GYS*4:	GYS*5:	GYS*6:
GYS2	GYS14	GYS1	GYS24	GYS33	GYS40
GYS3	GYS15	GYS20	GYS25	GYS34	GYS41
GYS4	GYS16	GYS21	GYS26	GYS35	GYS50
GYS5	GYS17	GYS22			
GYS6		GYS23			
GYS*7:	GYS*8:	GYS*9:	GYS*10:	GYS*11:	GYS*12:
GYS42	GYS7	GYS10	GYS27	GYS30	GYS37
GYS43	GYS8	GYS18	GYS28	GYS31	GYS38
	GYS11	GYS19	GYS29	GYS32	GYS39
	GYS12	GYS27	GYS47	GYS49	GYS44
	GYS13	GYS28			GYS45
					GYS46
					GYS48

The production line groups are marked with GYS*, and from now they will be taken into consideration as one production line, and these production lines will be fragmented at the end of the optimization process to determine the final routes of in-plant supply with multiple

milkruns. It is possible, that based on the predefined conditions, not all production lines can be added to a production line group. In this case this singular production lines will be taken into consideration as singular production lines (GYS9 and GYS36).

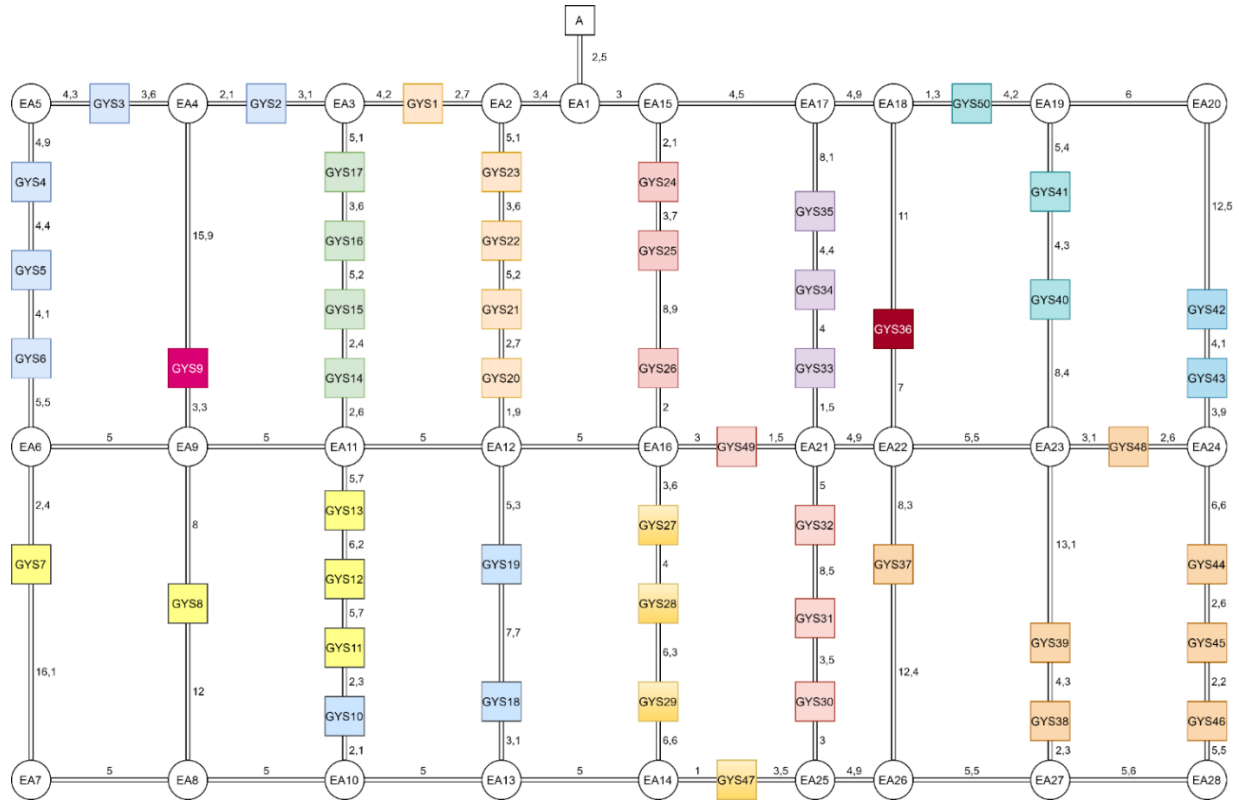


Fig. 7. Groups of production lines in the manufacturing plant

After defining production line groups, we can compute the shortest routes to the defined production line groups.

5.4. DEFINITION OF SHORTEST ROUTES TO THE DEFINED PRODUCTION LINE GROUPS

After reducing the number of initial production lines, the next phase of the optimisation is to perform further reductions. As the previous example shows, the initial 50 production lines were reduced to 14 production lines, including 12 production line groups and 2 initial production lines. The first step of this phase is to determine the shortest routes to all production lines.

Due to the definition of production line groups, the map of the manufacturing plant has to be reconfigured including the production line groups. The road segments also undergo a major transformation due to the definition of production line groups. The road segments that are connected to a production line group are those that are also connected to the original members of the production line group, but the junctions and road segments that connect two members of the production line group are merged into the production line group. For example, the elements of GYS*1 are the production lines GYS2, GYS3, GYS4, GYS5, GYS6, and the

road segments GYS2–GYS3, GYS3–GYS4, GYS4–GYS5 and GYS5–GYS6 and the junctions between them are merged into this group). Exceptions to the previous condition are those junctions that are part of a production line group, but also have a direct link to another production line group or to the remaining original production line, such as EA4, EA16 (Fig. 7).

For road segments that connect two production lines that are grouped separately, the road segments must also connect the two grouped production lines. If there are two road segments from a junction that lead to the same member of the grouped production line, the shorter one should be considered for optimisation (Fig. 8).

The purpose of the conditions just given is to take all the routes and distances from the event parameters into consideration that may be necessary to determine the optimal routes. Where the description mentions production line groups, the reference is to both generated production line groups and non-grouped production lines.

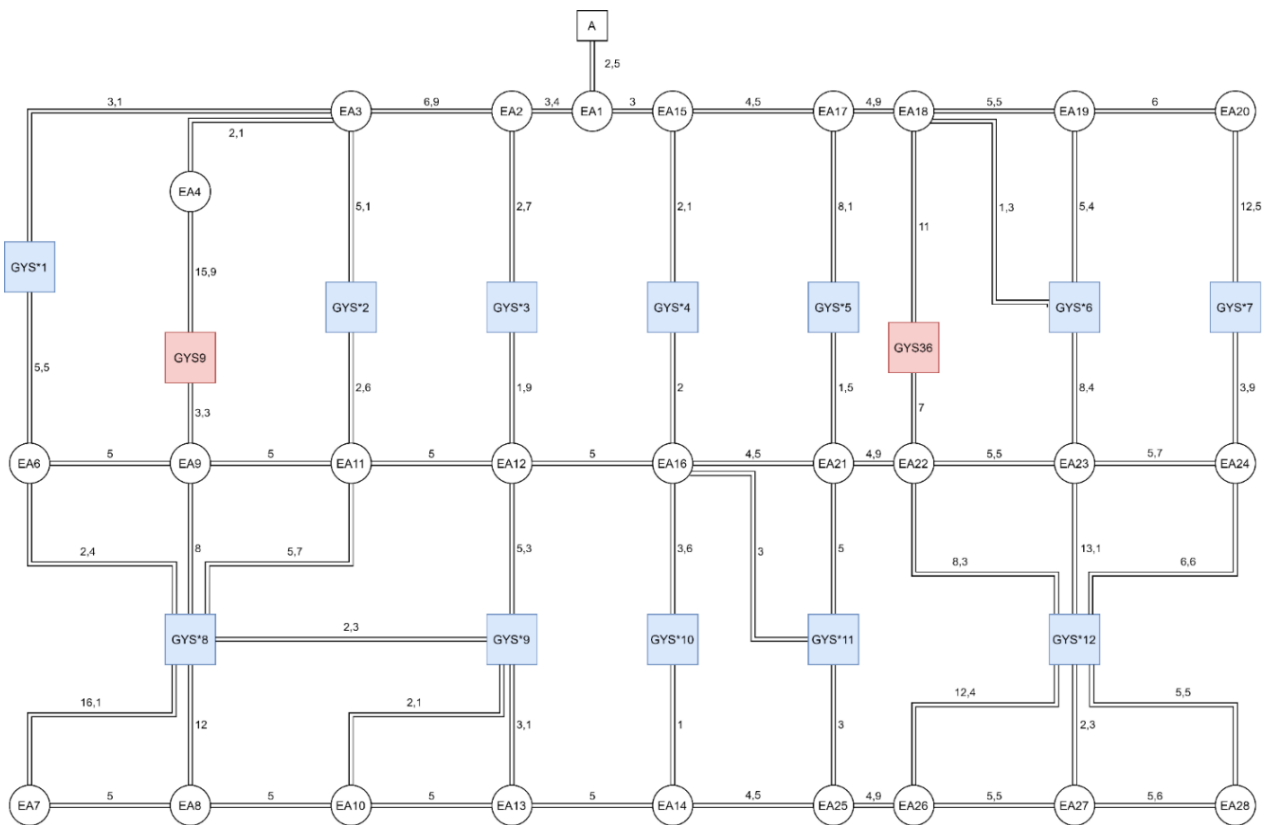


Fig. 8. The map of production plant after grouping production lines

For the minimisation we need to define all the managed road segments and their lengths. The shortest route is determined by the previously defined road segments. The method and procedure of the solution are fully identical to those used to determine the shortest paths for the original production lines. To determine the shortest routes from the warehouse exit location, we use the evolutive solver algorithm of the Solver and to perform batch optimisation the Solver is programmed by VBA.

After computing the shortest routes to the defined production line groups, we can define the number of matching route segments.

5.5. DEFINITION OF THE NUMBER OF MATCHING ROUTE SEGMENTS

Within the frame of this phase of the optimisation we can define production line pairs and count the number of segment matches of each production line pair using a VBA script. The VBA script is exactly the same as the previous determination method, only the periodicity, the loop values and the objective function are changed.

After defining the number of matching route segments, it is possible to regroup the production lines, as follows in the next chapter.

5.6. REGROUPING OF PRODUCTION LINES

After having determined the number of matching route segments of all the production line pairs, the next phase is to regroup the already grouped production line pairs to achieve the final result of the optimisation task (Table 4).

When defining the criteria for the grouping, it should be taken into account that the optimisation is currently carried out for 2 milkrun rounds and criteria should be defined accordingly.

It can be seen from Table 4, that the proportion of production line pairs with ≥ 3 route segment matches is significantly smaller than those with 1 or 2 route segment matches, and therefore the constraint will be that production line pairs with ≥ 3 route segment matches belong to the similar milkrun route.

Table 4. Matches of route segments and their proportions

Route segment matches	Number of route segments	Proportion
1	47	0.52%
2	21	0.23%
3	9	0.10%
4	10	0.11%
5	3	0.03%
6	1	0.01%

The number of route segment matches depends significantly on where the elements of the production line pair are located relative to the initial warehouse exit location. To avoid this, we can introduce a Y ratio, whose value depends on both the number of route segment matches and the length of the shortest route. Thus, the specific constraint is not that production line pairs belong to the same milkrun route with more than 2 matching route segments, but that those belong to a circle with a ratio P $0,07 \leq Y \leq 0,16$.

Thanks to the conditions, the grouped production lines will be fragmented, but not all conditions can be met. The rows highlighted in green in Table 5 show that two grouped production lines would belong to both milkrun routes, but the condition when defining

the task was that a production line can only belong to one milkrun route and only one in-plant supply operation is allowed for them. Therefore, we have to consider which of all possible cases would be the optimal.

For the GYS*4 and GYS*10 clustered production lines, the most ideal solution must be found. There are 4 groupings in total, 2 if they belong to the same route and 2 if they belong to separate routes. It is not advisable to associate them to a separate route, because there is a condition that these two grouped production lines belong to one route, and it is not certain that all our initial conditions would be fulfilled, so we associate them to one route anyway.

Table 5. Conditions for the final solution

Production line pair	Matches	Length	Parameter P
GYS*6-GYS*10	2	29.4	0.07
GYS*6-GYS*11	2	28.8	0.07
GYS*4-GYS*12	3	42.6	0.07
GYS*4-GYS*7	3	41.7	0.07
GYS*2-GYS*3	2	26	0.08
GYS*1-GYS*3	2	24.5	0.08
GYS*10-GYS*12	4	48.2	0.08
GYS*11-GYS*12	4	47.6	0.08
GYS*4-GYS*6	2	23.8	0.08
GYS*7-GYS*10	4	47.3	0.08
GYS*7-GYS*11	4	46.7	0.09
GYS*7-GYS*12	6	69.1	0.09
GYS*1-GYS*2	3	33.3	0.09
GYS*3-GYS9	3	32.4	0.09
GYS*6-GYS36	4	42.1	0.10
GYS*8-GYS9	4	41.9	0.10
GYS*5-GYS*12	5	50.6	0.10
GYS*5-GYS*7	5	49.7	0.10
GYS*9-GYS9	4	39.6	0.10
GYS*3-GYS*8	3	26.7	0.11
GYS*3-GYS*9	3	24.4	0.12
GYS*4-GYS*5	3	23.2	0.13
GYS*5-GYS*10	4	28.8	0.14
GYS*5-GYS*11	4	28.2	0.14
GYS*4-GYS*10	3	20.8	0.14
GYS*8-GYS*9	5	33.9	0.15
GYS*4-GYS*11	3	20.2	0.15
GYS*10-GYS*11	4	25.8	0.16

This means that instead of 4 groupings, we can only have 2, depending on whether we link them to the first or the second milkrun round. In the first case, we examine whether we link it to the first route, and if in such a case the lengths of the two routes differ significantly, we examine the second case.

5.7. THE RESULTS OF THE OPTIMISATION

Based on the clustering of the production lines, the initial production lines are in two different groups. The production line groups that were split into two parts are mapped back to the production lines that make up the groups, so that the original production lines can be clustered to the optimal milkrun routes (Table 6).

Table 6. The milkrun routes including the initial production lines

Production lines in the first milkrun route					
GYS1	GYS6	GYS11	GYS16	GYS21	GYS26
GYS2	GYS7	GYS12	GYS17	GYS22	GYS27
GYS3	GYS8	GYS13	GYS18	GYS23	GYS28
GYS4	GYS9	GYS14	GYS19	GYS24	GYS29
GYS5	GYS10	GYS15	GYS20	GYS25	GYS47
Production lines in the second milkrun route					
GYS30	GYS34	GYS38	GYS42	GYS46	
GYS31	GYS35	GYS39	GYS43	GYS48	
GYS32	GYS36	GYS40	GYS44	GYS49	
GYS33	GYS37	GYS41	GYS45	GYS50	

In the next step, the grouped production lines should be assigned to routes that are optimized and satisfy all initial conditions and constraints. The production line identifiers are transformed into object identifiers, the warehouse exit identifier is 0, the identifier of GYS1 is 1, etc. The objective function is the sum of the lengths of the route segments and our variable cells are the cells containing the segment identifiers. The secondary objective function was to define milkrun routes with almost equal route length. After that, we need to check whether the values obtained satisfy the time capacity condition of the milkrun trolleys.

Table 7. Time parameters of the optimised milkrun in-plant supply solution

1. Length of the route:	215.7	2. Length of the route:	215.1
1. Required time:	647.1 s	2. Required time:	645.3 s
Loading and unloading time:	60 s	Loading and unloading time:	40 s
Total time:	707.1 s	Total time:	685.3 s

In our scenario, the initial assumption is that a milkrun trolley has a time capacity of 900 s. The time required to travel the optimized route is 707.1 s \cong 12 min, and 685.3 s \cong 11 min. The times needed to cover the routes are less than the time constraints, so we have reached the end of the optimization.

In the case where the times needed to cover the routes do not meet the time constraint of the milkrun trolleys, the number of milkrun trolleys should be increased and the described method should be re-executed by changing the conditions for the grouping.

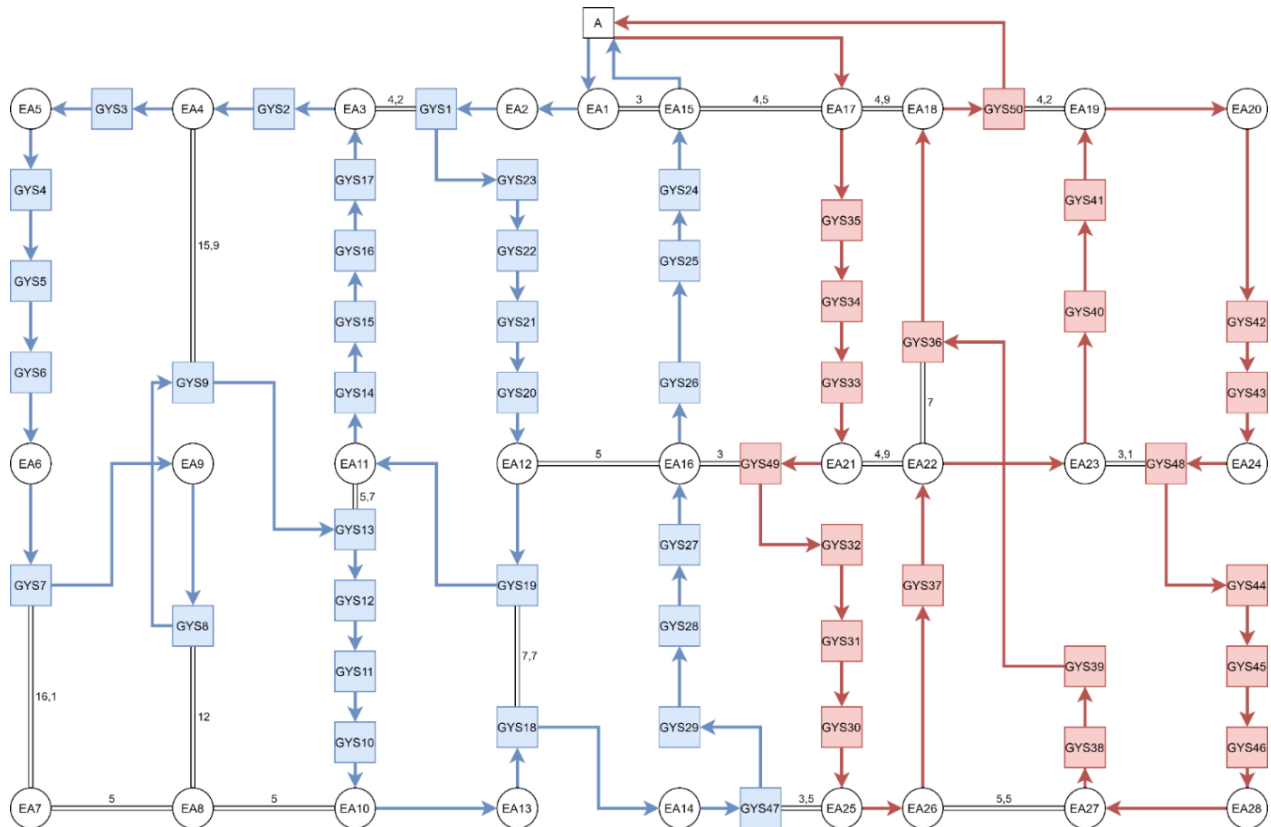


Fig. 9. Final result of optimisation

6. CONCLUSION

Every automotive supplier wanted to reduce and minimise the time of material flow operation within the company. An important material flow process in production logistics is the supply of raw materials to the production lines in the production hall. By organising this logistics process well, companies can save significant flow time and make their own logistics processes more flexible, so all companies strive to plan this process carefully.

Milkrun solutions represent a good way of supplying raw materials to production lines. With the milkrun system, a well-organised and feasible system can be created to optimise the material flow process.

Within the frame of this research work, a new optimisation approach was proposed to optimised milkrun-based in-plant supply. As the above-mentioned milk run optimization research indicates, the existing articles and research works are focusing on the application of existing heuristic optimisation methods (genetic algorithm, black hole heuristics, ant colony algorithm, bat heuristics, etc.), while only a few of them focuses on the structural optimisation of the in-plant supply based on milk run trolleys. The articles that addressed the optimization of milk run-based in-plant supply are based on a wide range of heuristics and metaheuristics, but few of the articles have aimed to research the potentials of analytic structural solution. In our opinion, this is the main difference between the presented approach and approaches presented in other publications.

As a first step of the proposed methodology, we optimized the production hall for one milkrun route, i.e. we created a minimized route. Since the time needed to travel the resulting route did not correspond to the time capacity of the milkrun trolley, it was necessary to perform the optimization for several milkrun trolleys. First, we searched and tested the optimized route for two trolleys. As a first step in the optimization for multiple milkrun trolleys, we determined the shortest route from the starting warehouse exit location to each production line. After that, we can investigate the route segment matches of the shortest routes for two production lines. We created pairs of production lines and counted the number of route segment matches for all possible cases. After that, we can define the ratio of the number of line-units divided by the length of the shortest paths.

Taking into account the number of milkrun trolleys needed for the optimization and in order to solve the problem, we can define thresholds and ratios of the line pairs. Based on this parameter, we can define production line groups and reduce the number of production lines to be taken into consideration.

We can redefine the shortest path for each grouped production line and formed new production line pairs and examined the route segment matches of the grouped pairs of production lines. Again, we can define a ratio in the same way and grouped the already grouped production lines into two groups, since the optimization was currently being performed for two groups. Finally, we found the shortest route for the two groups using the same method and conditions as for the optimization for a single milkrun trolley, and thus obtained the length of the two routes and the time needed to cover them. Since the time results obtained corresponded to the time capacity of the milkrun trolley, the task was considered complete. In the case where the optimization for two milkrun trolleys would have given such time results, the method should have been performed for one more milkrun trolley, as long as the time result obtained met the condition but did not exceed the number of available milkrun trolleys.

As a managerial impact, we would like to mention that the application of the above-described methodology can support managerial decisions regarding the strategic planning of in-plant logistics operations, investment strategy regarding logistics resources.

A further study of the proposed work would be the integration of the above-mentioned methodology with the layout planning of the manufacturing plant. Another research direction is to develop a faster computational method and algorithm to extend the proposed approach with real-time design potential.

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