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OPTIMIZATION OF ROUTING PROBLEMS IN MANUFACTURING SUPPLY

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Abstract: *The optimal design of a suitable material supply process is important for the continuous, smooth operation of manufacturing processes, which includes the transportation and handling of work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments. The most common form of implementation of these material handling processes, especially in mass production, is the milkrun supply. In this paper, the author presents a method to optimise the milkrun material supply processes in manufacturing. The author gives a brief overview of research results related to milkrun-based material supply solutions. An Excel Solver-based optimization method is presented that is suitable to support the design of an optimal material supply process in any manufacturing environment by determining optimal material supply routes and optimal number of milkrun trolleys, depending on the supply demand, location of warehouse and manufacturing cells and the capacity of the milkrun trolleys.*

Keywords: *route optimisation, manufacturing process, milkrun, capacity utilization*

1. INTRODUCTION

The improvement of the efficiency of production processes requires both modern production technology solutions and an efficient material supply system. In this paper, the author deals with the optimisation of one of the most common material supply systems today, the milkrun material supply. As a simulation-based study shows, milkrun solutions are suitable to perform the material supply operations of flexible manufacturing and assembly processes, especially in the case of high-mix low-volume demand [1]. The design of material supply of manufacturing systems can be divided into two main models. The first group of milkrun supply models discusses static supply solutions, where the characteristics of milkrun routes is not changing, while in the case of dynamic milkrun models, unexpected events, delays, changes in lead time and cycle time, inventory problems can be taken into consideration to avoid problems in the smooth and balanced manufacturing processes [2]. Milkrun solutions are generally used in two fields of industry. The first field is represented by the supply chains, where milkruns can be perform collection and distribution operations, or first-mile and last-mile deliveries [3]. The second field is the material supply of manufacturing and assembly plants, where milkrun trolleys are responsible for the material supply of machines. Other potential application field of milkrun supply is represented by milkrun order picking systems, because milkrun solution makes it possible to reduce order picking setup time and travel time of operators [4]. The application of milkrun supply solutions is especially important in the case of high-frequency, small quantity demands, therefore the supply of manufacturing and assembly plants is a potential application field of milkrun supply solutions. The design aspects can include the cost reduction, the improvement of energy efficiency and the emission reduction [5].

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The article is organized as follows. Chapter 2 focuses on the available research results related to in-plant material supply solutions. Chapter 3 presents the mathematical model of the milkrun-based material supply of manufacturing and assembly plants. Chapter 4 presents a Solver and Open Solver supported solution of the proposed models, and summarizes the results of the numerical analysis. Conclusions, managerial impacts, and future research directions are discussed in the remaining part of the article.

2. LITERATURE REVIEW

The in-plant supply solutions of different manufacturing systems are extensively discussed in the literature. Within the frame of this short literature review section II would like to highlight the main solution methodologies of in-plant supply of technological resources and validate the chosen research direction. As a metaheuristic optimization approach for matrix production shows, the optimization of material supply in smart manufacturing environment can significantly increase the efficiency of technological processes. In this research, the author focuses on the potential future form of production systems, and discusses the in-plant supply aspects of matrix production systems, where the technological and logistics processes are separated, but they are controlled by a specific software, which makes it possible to support the available, flexible, efficient, sustainable and transparent supply to perform the demands of customers. The in-plant supply model is an integrated routing and scheduling problem, which is an NP-hard optimization problem. The integrated routing and scheduling problem are solved with a hybrid multi-phase black hole and flower pollination-based metaheuristic algorithm [6]. In the case of mixed-model assembly, kit preparation and the related in-plant supply can significantly increase the efficiency of the assembly process. Within the frame of a research, Fager et al. [7] suggested a novel guidance to support and improve kit preparation flexibility, which has a great impact on the related material supply process. Fathi and Ghobakhloo [8] analyzed the competitiveness of in-plant material supply in Industry 4.0 era, where the digitlaization can improve the efficiency of in-plant supply solutions. They suggested a novel heuristic algorithm for in-plant material supply optimization, which makes it possible to optimize the material supply of mixed-model assembly lines. This approach can lead to the overall improvement of production cost efficiency, mainly via the reduction of both the material transportation and material holding costs across production lines. The design, operation and optimization of in-plant supply processes are especially challenging in high constrained industrial processes. Urru et al. [9] focuses in their work on the optimization of milk-run systems from planning and dimensioning point of view.

Not only kitting [7], but also line stocking and sequencing represent challenging in-plant supply tasks to be solved. From sequencing point of view, the ship-to-sequence, the build-to-sequence and the pick-to-sequence staregies are researched. The efficiency of in-plant supply processes is significantly infliuenced by the availability required raw materials, tools and components at the border of the manufacturing process. Sali et al. [10] discusses an empirical assessment of the performances of three line feeding modes used in the automotive sector. The empirical analyses make it possible to characterise different situations and scenarios in production lines and evaluate the different in-plant supply solutions.

Hansoon and his team research works have covered a wide range of in-plant suppy design problems, for example the comparison of kitting and continuous supply in in-plant materials supply [11], the impact analysis of unit load size on in-plant materials supply efficiency [12] or the effects of using minomi in in-plant materials supply [13]. Telek described in his research work, process-based selection of handling equipment in the automotive production has a great impact on the efficiency and flexibility of material supply, therefore it is important to find new models and methods to improve the efficiency of design processes. As the above-mentioned research results show, the optimization of in-plant supply is an important research topic in the field of manufacturing.

3. MATERIALS AND METHODS

The input parameters of the optimisation problem are the followings:

- The location of technological and logistics stations (manufacturing machines, assembly stations, quality control stations and packaging stations) to be supplied: $\bar{x} = [x_i]$, $\bar{y} = [y_i]$ and $i = 1 \dots m$.
- Location of input and output storages of technological and logistics stations: $\bar{x}^I = \left[x_j^I\right]$, $\bar{y}^I = \left[y_j^I\right]$, $\bar{x}^O = [x_k^O]$, $\bar{y}^O = [y_k^O]$ and $j = 1 \dots m$, if each technological and logistics stations has only one input storage, and $k = 1 \dots m$, if each technological and logistics stations has only one output storage, otherwise
$$j = 1 \dots \sum_{i=1}^{m} n_i^I \text{ and } k = 1 \dots \sum_{i=1}^{m} n_i^O, \tag{1}$$
where n_q^I is the number of input storages of technological and logistics station i and n_q^O is the number of output storages of technological and logistics station *i*. During the optimization process, not the technological and logistics stations, but the input and output storages of them must be taken into consideration, which means, that the total set of locations to be supplied can be written as follows:
$$\overline{loc}^x = [loc_d^x], \overline{loc}^y = \left[loc_d^y\right], d = 1..s \text{ and } s = \sum_{i=1}^{m}(n_i^I + n_i^O). \tag{2}$$
- Potential routes available for milkrun trolleys including constraints (for example width of the route, one-directional and bidirectional ways, dead routes). Based on the location of input and output storages, and the layout of potential transportation routes, we can calculate the distance matrix (dis) defining the length of minimal transportation routes between two locations to be supplied:
$$DIS = \left[dis_{d,h}(loc_d^x, loc_d^x, loc_h^x, loc_h^x)\right]. \text{ and } d, h = 1 \dots s. \tag{3}$$
- Required work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments: $\overline{dem} = [dem_d]$, where $dem_d > 0$ if work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments must be transported from the warehouse to location d, and $dem_d < 0$ if work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments must be transported to the warehouse from the location *d*.
- Available loading capacity of milkrun trolleys: c. The capacity can be given as loading unit, weight, volume or piece.
- Speed of milkrun trolleys: v. In the case of heavy cargo, the speed of the milkrun trolleys can be defined as a function of loading weight: $v = v(m)$.
- Energy consumption of milkrun trolleys: e. In the case of heavy cargo, the energy consumption of the milkrun trolleys can be defined as a function of loading weight: $e = e(m)$.

- Material handling time at the manufacturing machines, assembly stations, quality control stations and packaging stations: $\bar{t}^H = [t_d^H]$. In the case of heavy cargo, the required material handling time can be defined as a function of loading weight: $t_d^H = t_d^H(m)$.

We can define different objective functions, depending on the design goal as follows:

- Minimisation of the total length of routes of milkrun trolleys within the analysed time window,

$$L = \sum_{r=1}^{r^{max}} \sum_{w=1}^{w_r^{max}-1} dis_{a_{r,w},a_{r,w+1}} \rightarrow min., \quad (4)$$

  where r^{max} is the total number of material supply routes, w_r^{max} is the total number of milkrun stops in route *r*.

- Minimisation of the energy consumption of milkrun trolleys within the analysed time window,

$$E = \sum_{r=1}^{r^{max}} \sum_{w=1}^{w_r^{max}-1} e(m_{r,w}) \cdot dis_{a_{r,w},a_{r,w+1}} \rightarrow min., \quad (5)$$

  where $e(m_{r,w})$ is the specific energy consumption of the milkrun trolley in [USD/m] depending on the weight of the load and $m_{r,w}$ is the current load of the milkrun trolley (including net weight) passing stop *w-1*.

- Minimisation of the required time of material supply of technological and logistics stations within the analysed time window:

$$T = \sum_{r=1}^{r^{max}} \sum_{w=1}^{w_r^{max}-1} v(m_{r,w}) \cdot dis_{a_{r,w},a_{r,w+1}} \rightarrow min., \quad (6)$$

  where $v(m_{r,w})$ is the speed of the milkrun trolley in [m/s] depending on the current load of the milkrun trolley (including net weight).

- Smoothen and balance the utilization of milkrun trolleys:

$$SBU = \max_r \begin{matrix} \left(\sum_{r=1}^{r^{max}} \max_z\left(\sum_{w=1}^{z} dem_{a_{r,w}}\right)\right) - \\ \min_r\left(\sum_{r=1}^{r^{max}} \max_z\left(\sum_{w=1}^{z} dem_{a_{r,w}}\right)\right) \rightarrow min. \end{matrix}, \quad (7)$$

  where $z = 1 \ldots w_r^{max}$.

- Smoothen and balance the length of the milkrun routes,

$$SBL = \max_r \left(\sum_{w=1}^{w_r^{max}-1} dis_{a_{r,w},a_{r,w+1}}\right) - \min_r \left(\sum_{w=1}^{w_r^{max}-1} dis_{a_{r,w},a_{r,w+1}}\right) \rightarrow min., \quad (8)$$

- Smoothen and balance the required time of the milkrun routes:

$$SBT = \max_r \left(\sum_{w=1}^{w_r^{max}-1} v \cdot dis_{a_{r,w},a_{r,w+1}}\right) - \min_r \left(\sum_{w=1}^{w_r^{max}-1} v \cdot dis_{a_{r,w},a_{r,w+1}}\right) \rightarrow min., \quad (9)$$

The solutions of this optimisation problem are limited by the following constraints:

- Each workplace must be supplied with the required work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments:

$$\forall d: dem_d = sup_d, \quad (10)$$

  where sup_d is the number of supplied work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments to location *d*.

- It is not allowed to exceed the loading capacity of milkrun trolleys:

$$\forall r:\ \max_r\left(\sum_{r=1}^{r^{max}} \max_z\left(\sum_{w=1}^{z} dem_{a_{r,w}}\right)\right) \le c. \tag{11}$$

- All manufacturing machines, assembly stations, quality control stations and packaging stations must be supplied within the specified time window:

$$\forall r, h: t_{a_{r,w+1}}^{min} \le \sum_{w=1}^{h} v(m_{r,w}) \cdot dis_{a_{r,w},a_{r,w+1}} \le t_{a_{r,w+1}}^{max}. \tag{12}$$

  where $h = 1 \ldots w_r^{max} - 2$.

The decision variable of the optimisation problem is an assignment matrix which describes the assignment of requirements to routes and stops: $A = [a_{r,w}]$, where $a_{r,w} = d$ if demand d is assigned to stop w of route r, otherwise $a_{r,w} = 0$. The value of the first and last value of each row of the assignment matrix defines the warehouse: $\forall r: a_{r,1} = a_{r,w_r^{max}}=1$, because ID1 represents the warehouse.

The above-mentioned milkrun supply design has been solved using Excel Solver in the case of small problems, while in the case or large-scale problems the Open Solver has been applied to find the optimal routes in the manufacturing system. Figure 1 shows the optimization process of the above-described problem.

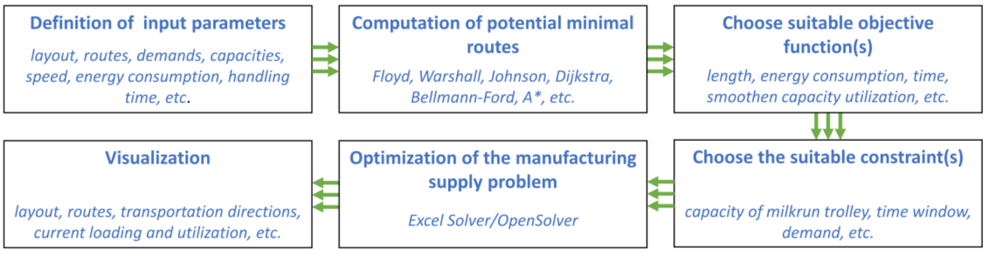

Figure 1. Process of material supply optimization in manufacturing

Based on the proposed approach, it is possible to find the optimal solution of a specified material supply problem using milkrun trolleys. The next chapter demonstrates the application of the mentioned approach and validates the model with a numerical analysis.

4. Results and Discussion

Within the frame of the scenario analysis, the above-proposed approach is tested in the case of a manufacturing system with a centralised warehouse (supermarket). The supply demands including work pieces, components, tools, equipment, pallets, packaging materials, and measuring instruments are transported from the warehouse to 33 manufacturing and quality control cells, where all cells have one integrated input/output location. The speed of the milkrun trolleys is 1.2 m/s. The location of the manufacturing and quality control stations, and their demands in loading units is given in Table 1. As loading unit, the company uses on the milkrun trolleys R-KLT4322 sized 400x300x215/195 mm. The loading units are loaded into special roll containers with door sized 800x600x1520 mm.

Table 1.

Locations and demand in the manufacturing system

Location	M01	M02	M03	M04	…	M09	M10	M11	M12
X [m]	64	45	74	92		132	45	57	65
Y [m]	50	0	20	0		20	20	20	50
Demand [pcs]		21	22	16	…	25	5	5	24
Location	M13	M14	M15	M16	…	M21	M22	M23	M24
X [m]	75	97	115	50		133	91	9	20
Y [m]	50	50	50	20		70	50	70	70
Demand [pcs]	18	13	6	10	…	19	29	15	6
Location	M25	M26	M27	M28	…	M33	M34	-	-
X [m]	38	10	20	28		16	30	-	-
Y [m]	70	50	50	50		0	20	-	-
Demand [pcs]	14	29	26	17	…	21	8	-	-

In the first scenario, the capacity of the milkrun trolleys is 150 loading units, the material handling time per stations is 25 s, and the objective function is the minimization of the total length of the routes of milkrun trolleys. The results of the optimization are shown in Fig. 2. The total length of transportation routes is 947 m. The minimized transportation time is 789 s, while the total time of performed milkruns is 1614 s. The loading diagram of the milkrun trolleys is shown in Fig. 4.

Figure 2. The optimized material supply routes of the milkrun trolleys in the case of Scenario 1

In the case of the second scenario, the capacity of the milkrun trolleys is 350 loading units, and the objective function of the optimization is the minimization of the total length of the routes of milkrun trolleys. The results of the optimization are shown in Fig. 3.

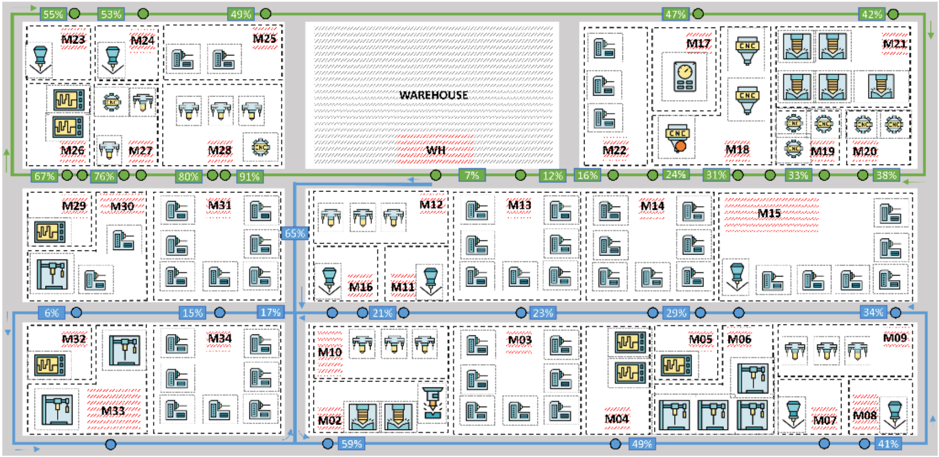

Figure 3. The optimized material supply routes of the milkrun trolleys in the case of Scenario 2.

The total length of transportation routes is 804 m. The minimized transportation time is 670 s, while the total time of performed milkruns is 1495 s. The loading diagram of the milkrun trolleys is shown in Fig. 5.

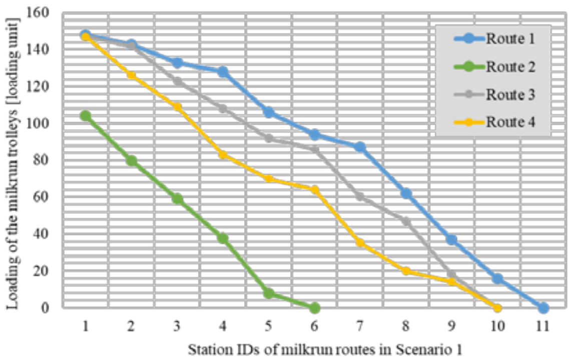

Figure 4. The loading diagram of Scenario 1

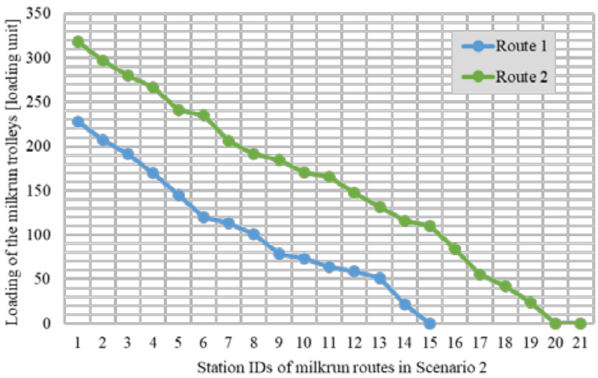

Figure 5. The loading diagram of Scenario 2

As the above-described scenarios validated, the mathematical model, the solution tools (Excel Solver and Open Solver) are suitable to optimize the material supply problem of manufacturing processes. The mathematical model makes it possible to optimize general material supply problems of different manufacturing processes, but within the frame of this article I have focused on the distance-oriented optimization.

5. CONCLUSIONS

The main findings and implications of the proposed model and solution to optimize the milkrun-based material supply of manufacturing processes can be summarized as follows. The materials handling processes of manufacturing and assembly systems are complex processes, which optimization can lead to improved productivity. The developed mathematical model makes it possible to describe the related optimization problems focusing on the minimization of distance, travel time and energy consumption, while it is also possible to balance and smooth the capacity, travel time and distance of milkrun routes. The model takes both time- and capacity-related constraints into consideration. The numerical analysis shows, that the proposed approach makes it possible to support the design of milkrun-based material supply of manufacturing systems. Potential future research direction is to integrate uncertainties into the model. This integration can lead to a dynamic design platform, which is especially important in flexible manufacturing systems.

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