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VEHICLE ROUTING APPROACH FOR LEAN SHOP-FLOOR LOGISTICS

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In order to satisfy the material supply needs of large scale shop-floors and production systems, various logistics solutions are applied. In lean manufacturing enterprises, the material supply is pulled by the demands of manufacturing/assembly processes; therefore, a milkrun service is often applied to support the production without glitches. The milkrun logistics planning is a special case for vehicle routing problem (VRP), and requires effective approach to solution in order to satisfy various constraints, and minimize the cost of service. This study gives an overview about lean logistics as well as the most efficient VRP solver algorithms. Furthermore, a novel initial solution with generation heuristics is proposed, which is specially focused on flexible milkrun planning. In order to demonstrate the capabilities of the solution, a software environment is developed as a demonstration that focuses on the main industrial requirements of logistics planning like effective layout definition, quick response of the delivery service and effective order handling.

Keywords: vehicle routing problem, milkrun, local search, factory logistics

Introduction

The material provision of large- and medium-scale production systems requires prudent planning and control, since it influences the performance of the production and affects the order management directly and storage assignment [1]. In order to manage effectively the material provision of the production, practical transport logistics and distribution tasks are usually formulated as vehicle routing problems, whose objective is to obtain a minimum-cost route plan serving a set of customers with known demands [2].

In state-of-the art manufacturing systems, lean processes are successfully applied to eliminate the wastes on all the levels of production, and they raise the overall efficiency of the system by reducing the non-value adding activities in the process chain. The shop-floor logistics processes have to be adapted to the production system; therefore the waste reduction in the material provision also has a key role in balancing the workload and ensuring a smooth running of production. A well-operating lean logistics system keeps the inventories and operational costs on the most cost efficient levels, via by providing the materials what that are needed, exactly when they are needed. For satisfying these requirements, concepts of the lean logistics can be applied that are primarily aimed at controlling the transport services duly to the pull strategy.

The paper is focused on the 'milkrun' service, which is defined as a manually operated, cyclic transport system delivering raw materials (or sub-assemblies) and disposing empties based on consumption using a fixed route and time schedule [3]. According to this characterization, milkrun scheduling is considered as a special vehicle routing problem with time windows, a limited capacity, and number of vehicles. In this paper a novel, multi-level planning approach is proposed, which combines the advantages of existing algorithms as for example local search for vehicle routing.

First, an overview of the state-of-the-art factory logistics is given, considering the recent shop-floor characteristics and planning demands. Then the main solution approaches and algorithms are introduced, as well as the critical points of milkrun planning. In section 4, the proposed layout representation hierarchy and the novel initial solution generation heuristics method are described. The latter focuses on the real industrial criteria and give a feasible milkrun schedule. In the last section, an industrial case-study and some numerical results present the efficiency of the milkrun planning method developed.

Shop-floor logistics

The shop floor logistics are part of the production logistics in the supply chains of companies. While logistics in general is about supplying a customer with necessary goods in time, with the goal of efficiency, and the lowest possible costs, production logistics is the task of bringing necessary material to workstations and machines and transferring it to the next station. In the realm of logistics planning methodologies the lean approach, originating in the Toyota Production System, of overall waste reduction has become a major planning paradigm, constituting the lean logistics approach [4].

Principles of lean logistics

Of the seven waste categories, eliminating unnecessary transports, waiting times, superfluous movement and excess inventory are the most relevant in lean logistics. KLUG identifies the following characteristics of lean logistics [5]: synchronicity and a clocked material flow, flow orientation, standardization, pull principle, stability, integration, as well as perfection. Regarding the pull principle, as the most relevant feature, material is only transferred to a workstation if it is about to process the material thus reducing inventory levels by reducing shop floor stock to safety buffers only. Beside the above principles of lean logistics, a relatively novel issue in material provision of production is 'green logistics' that is generally about establishing an ecologically sustainable transportation system considering factors like energy consumption and air-pollution [7].

While in the general external logistics context theses planning principles are reflected in transport concepts such as the just-in-time delivery, there are also corresponding design concepts in production and shop floor logics. For the supplier/source side, establishing zones for decentralized incoming goods and supermarkets in the vicinity of assembly stations is a means of reducing transport lengths. On the receiving side, standardized shelves and reusable containers, replenishment schemes like 'kanban' are applied. For the transport system between supply and workstations, 'tugger trains' *(Fig.1)* with fixed time intervals, standardized capacity, and transport lot sizes are preferred over forklift transport in the context of lean logistics; the goal of, which is the reduction of inventory and avoiding erratic peaks in production known as the bullwhip effect [8].

This transport concept of scheduled tugger trains in the context of a lean-oriented logistics system is usually combined with the milkrun transport concept that is in the focus of this paper. Especially in production environments with a high product complexity, variety amid a complex and changing material flow, planning a system of milkrun transports is a complex planning task. Thus, an efficient system of milkruns could significantly in-crease the efficiency of the overall production logistics.

Milkrun *as a vehicle routing problem*

Vehicle routing (VRP) is a challenging combinatorial optimization problem, introduced first by DANTZIG and RAMSER in 1959 [9]. The general VRP is known as the Capacitated Vehicle Routing Problem (CVRP), were the aim is to satisfy the needs of all the customers at different locations by having a given number of vehicles with capacity constraints [11]. When milkrun is applied as a material providing system, the time constraint of the runs has also to be added to the general problem (VRP with Time Windows – VRPTW). The general objective is to minimize the costs either by minimizing the total distance travelled, or minimizing the number of vehicles applied. A specific type of VRP is the Pickup and Delivery Problem (PDP) where the vehicles not only provide the locations with materials, but also pick up materials at the stations and deliver them to another one. The milkrun problem is also a PDP, with time windows and cyclic service [12].

Several approaches from the operations science are used to solve VRPs, as for example constraint programming that manages flexibly the various specific constraints of the VRP [14]. Local search is one of the fundamental approaches to find solutions for hard computational – including constraint satisfaction – problems. The basic idea behind local search is to start with a randomly or heuristically generated candidate solution, and to iteratively improve that by means of defined functions [15].

Generating the initial solution is always a crucial point when applying local search, since it significantly affects the running time of the algorithm. Sophisticated heuristics for the VRP are the two-phased ones, which decompose the problem into a clustering- and a routing problem, with possible feedback loops between the two stages. Cluster-First Route-Second (CFRS) algorithms perform a single clustering of the vertex set and then they determine a vehicle route on each cluster. The best-known CFRS algorithm is the FISHER-JAIKUMAR algorithm, which solves the General Assignment Problem (GAP) to form the clusters [17].

The local search starts from the initial solution and subsequently moves from the present solution to a neighbouring solution in the search space where each solution has only a relatively small number of feasible neighbour solutions and each movement is determined by neighbouring operators [20]. When applying local search, the combination of the neighbourhood operators produces the next local optimum solution *(Fig.1).*

Although the most general forms of the VRP can be solved effectively with the above approaches, the milkrun planning problem is hard to interpret as a simple graph-search problem, and the general initial solution heuristics are difficult to transform for this problem. The mapping process of the factory layout also requires special processing; therefore general solution methods cannot be applied easily for such a special problem.

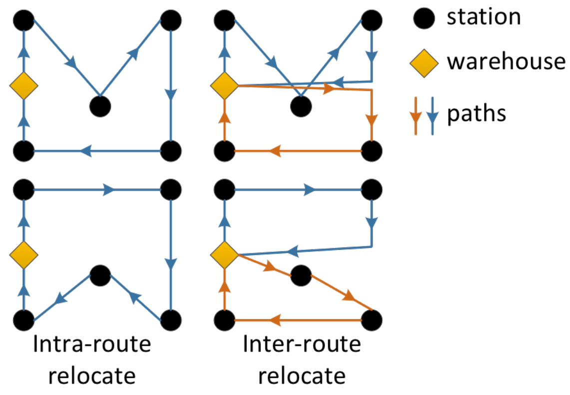

Figure 1: Inter- and intra-route relocate operators

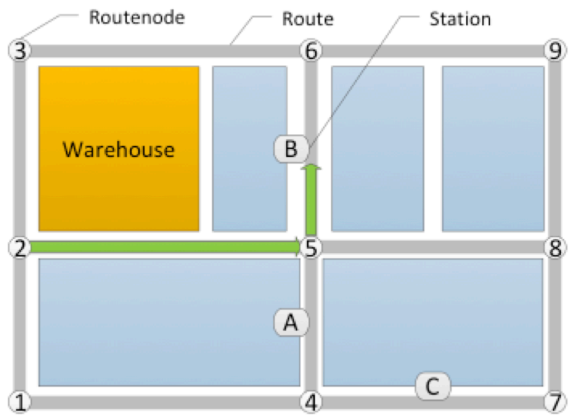

Figure 2: Layout elements and vehicle movement

Problem formulation

Hereby, we provide a definition to the milkrun planning problem. Consider a layout of the shop-floor, which is defined by a set of routes and stations. The routes can be either one- or two-way ones, and each route endpoint is defined as a "routenode". Along a specific route, there can be more stations *(Fig.2)*. The problem also considers demands that belong to the stations and defined by the amount of the transported goods in standard units and the required cycle-times of the transportation. The goods are transported by vehicles (practically by tugger trains), which are defined by their capacity and average speed.

In order to plan feasible milkruns, real-world constraints are considered, such as the capacity constraints of the vehicles, which limit the maximum number of the transported goods. Another constraint is the time limit of the plan, which means the total time consumption of a milkrun plan cannot exceed the cycle-time of the demands. The loading and unloading points can be reached from both sides of the tugger train, and the train can approach the station from both endpoints of the route that the station belongs to.

A milkrun plan is built-up by paths, where each path is given as the list of the visited stations and the list of the routes that the vehicle passes along. The plan does not partition the demands, and a visit of a particular station only occurs in a specific path. A milkrun plan is characterized by its total time consumption, which is required by the vehicle(s) to perform the plan. A milkrun plan is considered to be better than the other one only if its total time consumption is smaller, while it satisfies all the demands. The goal of milkrun planning is to minimize the number of the required vehicles via minimizing the time consumption of the plan.

The proposed planning process

Layout representation for vehicle routing

As it was mentioned in the previous section, solving the general VRP is not enough to plan feasible milkrun schedule, since most of the routing algorithms does not calculate with the physical constraints determined by the shop-floor. Most of the general solution approaches consider the problem as a graph-search, where the stations are represented by vertices and the routes are represented by edges [21].

In many cases, this representation does not support effectively the planning processes with feasible results, unless the application of the following constraints. Frequently, when representing a shop-floor by directed graphs, it turns out that the structure of the layout results some direct and indirect routing constraints. A direct case means that the additional equations can be formalized immediately when constructing the graph, such as the asymmetric edge formulas, while the others require further consideration. Indirect constraints are usually implied by the narrow and one-way corridors, which limit the abilities of the vehicles from going to a station directly from another, even if a path connects them. These constraints are implied by the moving abilities of the common applied tugger train, since it cannot turn in the middle of an aisle, and in many of the cases it have to take a detour before visiting the next station *(Fig.2)*. In order to handle the shop-floor constraints effectively and be able to avoid impossible movements of the vehicle, a novel hierarchical layout representation is proposed. The layout is defined by three main different classes, each having their own specific attributes. This structure can be handled dynamically during the path calculations, and the asymmetric nature of the distance matrix is represented together with the limitations of vehicles movements. *Fig.3* shows the hierarchy of the layout, defined by "routenodes", "routes" and "stations".

To calculate the distance matrix of the layout, storing the shortest paths between the stations, DIJKSTRA'S algorithm was applied that solves the single-source shortest path problem in logarithmic running time [22]. In this case, the input of the algorithm is a directed graph where the vertices are the set of the "routenodes" and the edges are the routes. This graph representation is able to handle all the nodes of the layout with their connections, and by applying DIJKSTRA'S algorithm the asymmetric distance matrix can be calculated.

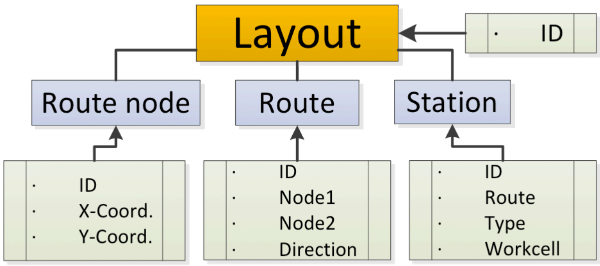

Figure 3: Hierarchy of the layout representation

Initial solution generation

In order to plan feasible milkrun cycles with the lowest operational costs, the shop-floor constraints have to be taken into consideration. To handle the constraints effectively, the routing algorithm needs to select the stations to be visited dynamically. Thus, a so-called triplet solution is applied, which helps to avoid impossible movements of the vehicle. A triplet is consisted of three identical nodes: three current, the previous and the next position of the vehicle. The next position is calculated dynamically when determining a particular path of the vehicle. The milkrun planning method strongly focuses on the industrial requirements of vehicle routing; therefore, a novel initial solution generation heuristics was implemented. The goal is to generate a solution that is as close to the criterion as possible.

The proposed heuristics can be classified as a CFRS type rule, and differs from the FISHER-JAIKUMAR algorithm by the cluster generation method, since it does not require solving time-consuming GAP, but defines the clusters based on practical reasons [18].

To generate a feasible initial solution, the algorithm calculates a path to each station applying DIJKSTRA'S shortest path algorithm. Then a greedy search algorithm is applied to calculate the next node, which must be visited by the vehicle before returning to the depot, so as to avoid violating the turnaround constraints of the vehicle. The greedy search iterates forward the nodes applying a best-first search strategy [23], and finds the first node from, which the shortest path to the depot does not contain the previous node. The "roundtrip" planning method is applied for each station, and detects all the feasible tours on the shop floor. In order to determine the set of paths for the initial solution, the paths with most visits are selected one by one while the set of unsatisfied demands is not void. Performing the services required by these cycles provides a feasible and acceptable initial solution for the planning algorithm.

The pseudo-code of the proposed algorithm is the following:

$v \in V$	set of stations
$p := \{v \mid v \in V\}$	path
$P\{p\}$	set of paths
$D = [d_{rs}] \mid (r,s) \in V$	distance matrix
$I\{p\}$	initial solution
q_i	demands of the i^{th} station
$Q = \{q_i\}$	set of demands
t_c	cycle time
c	capacity of the vehicle

initialize $V, I, Q, C\{v\}, c, tc$
foreach i in V
    `calculate` D_{0i}
    foreach v in D_{0i}
        `add` v to C_i
    `calculate` D_{i0}
    foreach v in D_{i0}
        `add` v to C_i
align C [`length`(C_i+1) < `length` (C_i)]

while $|Q| > 0$
    while `time`(C_1) > tc or `load`(C_1) > c
        `remove` rand v from C_1 ($v \neq i$)
    foreach v in C_1
        `delete` q_v from Q
    `add` C_1 to I
    `delete` C_1 from C
return I

Local search strategy and neighbourhood functions

In order to improve the initially generated solution, neighbourhood functions are applied. To be able to reach all the points of the search space, both intra- and inter-route operators are necessary to calculate with, although in this case the effect of the inter-route functions is more significant since the initial solution heuristics could provide paths with stations in a rather good sequence. The algorithm performs the local search to minimize the paths, and the cycle-time of them. Then, a simple bin-packing problem is considered, to allocate the paths to a minimal number of vehicles. To solve the problem, first fit heuristics was applied, which is a proven 11/9 OPT solution algorithm [24].

Case study and test results

The milkrun planner software, which includes both the user interface and the solver algorithms were implemented in a .NET environment using C++ language. Within the performance evaluation of the implemented software, a real production environment was modelled in order to analyse its capabilities. The purpose of the implemented application is to offer user-friendly and efficient milkrun planning environment; therefore a graphical, point-and-click layout definition interface and XML communication have been applied *(Fig.4)*.

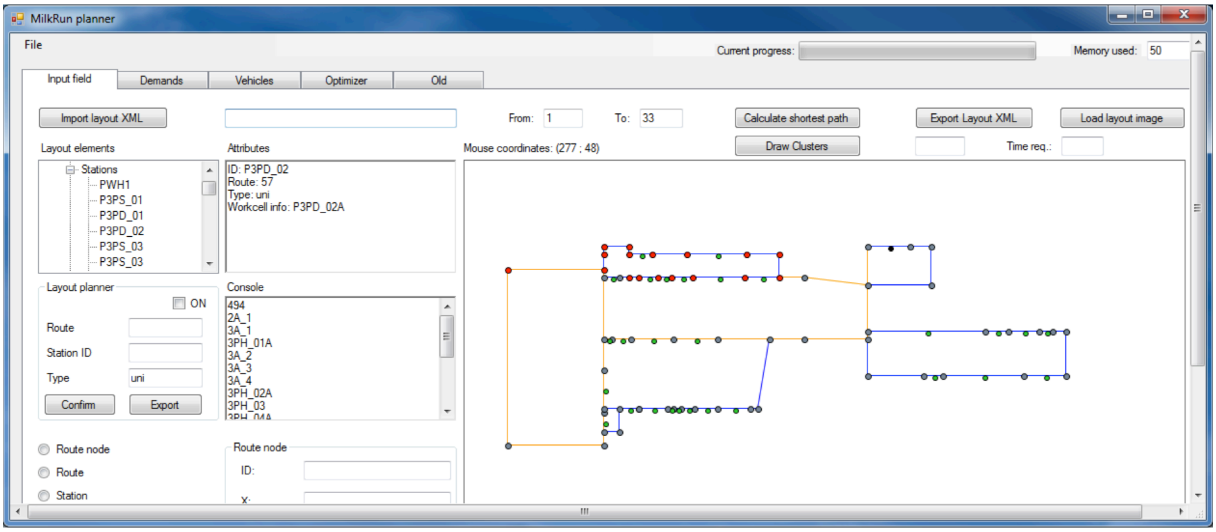

Figure 4: The user interface of the milkrun planner application

First the input parameters are processed and stored in the memory, and DIJKSTRA'S algorithm is applied to calculate the shortest path between each station. The distance matrix is built up from vectors, each having two distance elements. This data structure is required by the applied triplet-based path planning method, which selects dynamically the proper distance parameter from the vector, based on the location of the previously visited station.

The initial solution generation uses the distance matrix to create the tours, based on the station loops detected on the layout. The initial solution contains only feasible paths that satisfy the time constraints as well as the capacity constraints of the actual vehicle. To avoid overloaded vehicles, a pre-check method is performed: the vehicle is loaded by all the raw materials in the depot, and then all the other loading and unloading processes are calculated station-by-station to simulate the real milkrun process. In order to calculate with time constraints, both the travel-time (with constant average speed) and the loading/unloading time (time/item) are considered. The purpose of the generated initial paths is to satisfy all the demands by the lowest possible number of feasible cycles. The local search algorithm takes the initial paths and reduces their total time consumption by applying neighbourhood functions where it is possible. The algorithm iterates through all the combinations of the stations, and detects the possible insertions from one path to another. As local search iterates through the paths in a random sequence, different test runs can result different milkrun plans. In order to approximate the global optimum solution, the implemented application performs the local search several times and selects the most appropriate schedule from the generated solutions.

The capabilities of the algorithm were tested in a real production environment. This was a large-scale automotive production system with 2 factory halls, 67 stations and 96 routenodes. The milkrun plan has to satisfy 193 various demands in 60 minutes cycle-time.

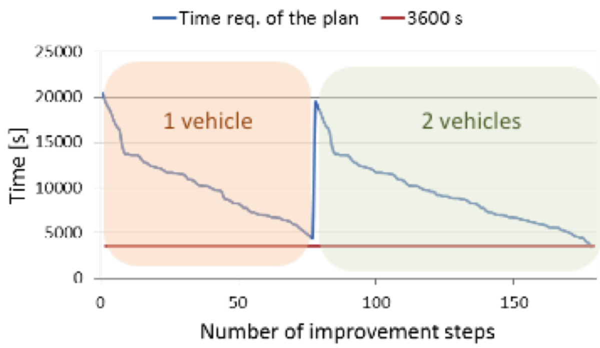

Figure 5: Test results of the case study

The analysed system requires efficient planning process, since the total length of the routes is over 2.5 km that affects critically the total time of the milkrun schedule. The application of inefficient milkrun schedule results low-utilized vehicles and high number of cycles.

In this case, the goal of the test was to minimize the number of vehicles required to perform the services via minimizing the time of the cycles. The proposed initial solution heuristically generated eight feasible paths with 20,400 seconds total time. First, the algorithm tries to optimize the plan by applying one vehicle, and increases the number of the vehicles only if the improvement steps cannot decrease the time requirement of the total plan under the cycle-time (3600 seconds). By this way, the test run could optimize the plan for two vehicles in 177 iterations, and generated a schedule, which time requirement is only 57 minutes *(Fig.5)*.

Conclusions

After an overview about the state-of-the art shop-floor logistics, and the general formulations of the vehicle routing problem, a solution was proposed that uses a novel layout representation and initial solution generation heuristics to solve the milkrun planning problem. In order to demonstrate the capabilities of the solution, a software prototype was developed and tested on real-life industrial data.

Future work includes the extension of the model with demand partitioning so as to increase capacity utilization of the transportation vehicles. Moreover, handling inhomogeneous demand types (physical aspects of material handling) requires further constraints to be included in the model. Secondly, future work will be dedicated for making the solution available in practical industrial applications. In an on going research project the milkrun planning algorithm will be implemented in a factory- and a logistics planning application currently under implementation.

Acknowledgements

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