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MULTI-START LOCAL SEARCH FOR SUGAR BEET TRANSPORTATION PROBLEM WITH EQUITY REGULATIONS FOR GROWERS

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Abstract: *The sugar beet transportation problem under growers' equity regulations is considered. The solution of the problem represents the optimal plan for the delivery of sugar beet collected by several growers at different storage piles to a single sugar mill. The vehicle fleet is homogeneous and vehicles are used several times during the day. Requirements in amount of transported beet must be satisfied for each day of the planning period. Equity regulations are related to fairness among growers, providing the equal opportunities in delivering sugar beet when it is fresh, contains large amount of sucrose, and therefore, is more profitable. Constraints related to equity regulations are formulated as the minimum percentage of beet that must be transported on the harvesting day for each grower. The goal is to minimize the number of used vehicles while maximizing the total sucrose content of the collected sugar beet. The Multi-start Local Search (MLS) metaheuristic is proposed for the considered problem, evaluated on the set of generated instances against CPLEX exact solver and an existing metaheuristic approach based on the Greedy Randomized Adaptive Search Procedure (GRASP). Our experimental results show that MLS outperforms GRASP in average and CPLEX in the case of large-sized instances.*

Keywords: *Sugar Beet Transportation, Growers' Equity, Multi-start, Metaheuristics.*

1. INTRODUCTION

Sugar beet, usually cultivated by many individual growers, is an important raw material for sugar production. It contains sucrose that decreases over time from the moment of harvesting and storing at storage piles until the beet is processed in a sugar mill. From the economic point of view, it is profitable to deliver the collected beet and process it as soon as possible. However, the resources available for the transport organization have certain limits such as: number of vehicles, their capacity, working hours, etc. Using minimal homogeneous vehicle fleet, within the defined working hours, the daily requirements of the mill in the total amount of delivered beet must be satisfied. Although the phase of sugar beet delivering and processing, known as the campaign, lasts four to six months, the plan is usually made for several days. During this planning period growers prepare the sugar beet on storage piles and hundreds of tours should be performed each day in order to supply mill with the required amounts.

The transport is organized by sugar mill company that tends to achieve the largest possible profit, but also to keep growers, as their major cooperators, satisfied. For both participant sides, growers and the company, the large amount of sucrose collected from recently harvested sugar beet is valuable. Therefore, it is necessary to create a transportation plan that provides equal opportunities for growers to transport their sugar beet shortly after it is harvested. Besides maximizing the quality of sugar beet, the other important goal refers to the transportation costs, as a direct consequence of the number of used vehicles, that should be minimized.

The concept of fairness in terms of providing equal opportunities for growers in achieving profit is included in several studies related to sugar cane production. Growers in sugar cane production in Australia (Higgins, 1999) are grouped for joint harvesting to guarantee equity between them. A large-scale Integer Programming model is proposed for the considered problem on planning harvesting terms, determining groups, meet the transportation conditions and production requirements with the goal to maximize the total net revenue of growers and miller for the period of several years. The author proposed a Local Search method in combination with the Tabu Search technique as a solution approach for the considered problem. An application software tool named SugarMax was developed (Jiao et al., 2005) to improve the profitability in sugar cane production with equity among growers provided by a constant amount of cane harvested by each harvesting group of growers throughout the harvest season. Their aim was to maximize the gain in sucrose content in three Australian sugar mill regions. The equity constrains were ensured in the problem of Sugar Cane Harvest Scheduling (Sethanan et al., 2014) by the condition that all groups of growers should have the same average sucrose content of cane per ton. A heuristic algorithm improved by Tabu Search technique was proposed for this problem. In the study (Thuankaewsing et al., 2015) in Thailand, equity is guaranteed by a harvest plan in which the gap between the productivity of each grower from the maximum one is lower by an equal percentage. The authors developed an optimization model and a Tabu Search for the considered problem. In the research (Jarumaneeroj et al., 2021) the authors included the three objectives to be maximized: sugar production, growers' equity in terms of a fair harvesting time-slot distribution, and efficiency in terms of balancing resource usage during the season for the supply chain of sugar cane. A solution approach based on a genetic algorithm is proposed and tested on real-life examples in Thailand.

In literature, several papers related to different sugar beet optimization problems (Anokić et al., 2021; Brcanov et al., 2025; Drenovac et al., 2020) can be found. To the best of our knowledge, the authors of the research (Drenovac et al., 2025) are the only authors that introduced equity constraints in the sugar beet transportation problem. They considered the problem denoted by the Sugar Beet Transportation Problem under Growers' Equity Regulations (SBT-GER). The problem consists of determining the optimal transportation plan for sugar beet collected by several growers at different storage piles. The planning period includes three days, while the equity regulations are provided by the request that a minimum percentage of the quantity of sugar beet must be collected from each grower on the day of harvest. The remaining constraints refer to the daily requirements in amount of sugar beet delivered to the mill, vehicle fleet and working hours. The objective function was composed of the two opposite goals, to maximize the total sucrose content while minimizing the number of used vehicles. For this purpose, the weighted sum method is used to combine the two objective functions and transform the bi-objective problem into a single-objective one. The authors proposed an Integer Linear Programming (ILP) model and developed two metaheuristic algorithms, based on Variable Neighborhood Search (VNS) and Greedy Randomized Adaptive Search Procedure (GRASP) for the considered problem. The experimental results of metaheuristics are mutually compared, as well as against CPLEX exact solver using a set of 80 generated instances of different sizes. For the majority of examples, VNS was superior over GRASP and the exact solver.

Multi-start Local Search (MLS) is an iterative metaheuristic algorithm consisting of two steps. The first one represents a stochastic procedure for generating an initial solution, which can be improved by the second step, Local Search. The best found solution is preserved and one iteration of the method is completed. Iterations are performed until the termination criterion is satisfied. The concept of multi-start search was proposed in (Boender et al., 1982) as a stochastic method for global optimization. A review of this simple metaheuristics is given in (Martí, 2003). Different Multi-start (MS) algorithms have been successfully applied to a variety of optimization problems. The Response Time Variability Problem that refers to arranging a list of clients in order to minimize the variability in the waiting time for resource access, was considered in (García et al., 2006). The authors developed MS, GRASP, and Particle Swarm Optimization (PSO) algorithms, where MS appears to be the best solution approach to small-sized instances, while PSO outperformed the remaining two algorithms for large-sized instances. MS and GRASP were later improved by the same authors in (Corominas et al., 2008). The MS Evolutionary Local Search, developed in (Villegas et al., 2010) for The Single Truck and Trailer Routing Problem with Satellite Depots proved to be more accurate than the hybrid GRASP and Variable Neighborhood Descent (VND), proposed as an alternative in the same study. Numerous of successful applications of MS method to different Vehicle Routing Problems can be found in the literature (López-Sánchez et al., 2014; Molina et al., 2018; Matijević et al., 2024).

This study proposes an efficient Multi-start Local Search heuristic approach developed for SBT-GER that uses the same Local Search procedure and test examples as in the GRASP approach, proposed in Drenovac et al., 2025. The reminder of the paper is organized as follows. Section 2 contains the problem definition. The description of the proposed MS metaheuristic approach is given in Section 3, while the computational results are presented and discussed in Section 4. Finally, the main conclusions are highlighted in Section 5.

2. PROBLEM DEFINITION

In the considered SBT-GER problem, the sugar mill organizes the collection and transportation of the sugar beet, prepared by several growers at different locations. It is coordinated with respect to the available vehicle fleet and the processing capacity of the mill. As the sugar beet can stay at the defined locations, i.e., storage piles for several days or even a week, depending on the weather conditions, these periods are considered as planning periods. The goal in SBT-GER is to determine the optimal vehicle assignment to a set of available storage piles for each day of the planning period to ensure the continuity of sugar mill processes and to achieve a minimum possible loss of sucrose content while using the smallest number of vehicles.

We summarize the characteristics of the SBT-GER problem as follows:

- plan refers to the period of several days known as planning period
- the homogeneous vehicles perform multiple trips (tours) during the day
- each vehicle serves only one location in each tour
- each tour starts and ends it at the single depot located at the mill
- daily requirements of the mill must be satisfied for each day during the planning period
- the level of sucrose in the delivered sugar beet is monitored at the end of the working day
- a predefined minimum percentage of beet should be transported from each grower on the day of storage
- the objective is to maximize the total amount of collected sucrose from the collected sugar beet, while simultaneously minimize the number of used vehicles.

The ILP formulation of the problem with detailed notations and descriptions is presented in (Drenovac et al., 2025). However, we explain here some details required for the interpretation and understanding of the obtained computational results. The objective function represents the weighted sum of two components. The first one is calculated based on the total level of sucrose over the sugar beet amount collected during the planning period. This value is obtained according to the formula proposed in (Asadi, 2007), that represents the decay function of the sucrose content depending on its initial value, the daily loss rate coefficient, and the number of days the sugar beet is staying at a storage pile. The total sucrose content is divided by the maximum level of sucrose (initial, without any loss) that could be obtained from the collected amount. The second component of the objective function is the total number of vehicles used, also divided by the number of available vehicles and then subtracted from 1. The division by the maximum value for both components is used for normalization of their values into the range $[0,1]$, so they can be combined, while the purpose of the subtraction is to direct the two opposite goals toward maximization. In this way, it is possible to provide the objective function as the weighted sum of these two components. In addition, the equity constraints are ensured as the minimum percentage, denoted by θ, of the quantity of sugar beet that must be collected from each grower on the day of harvest.

3. THE PROPOSED MULTI-START LOCAL SEARCH APPROACH

We develop an MLS algorithm to approach the considered SBT-GER problem. This method depends on the appropriate balance between diversification provided by Random Construction step and intensification of the search represented by Local Search (LS) step. Each iteration starts with a feasible solution constructed using certain randomness. Usually, the elements of the solution are chosen at random or they are composed by random moves to avoid performing the same iterations during the search. Then, the second step (LS) intensifies the search starting from the constructed solution, to find the local optimum that is evaluated and compared with the current best. If an improvement of the current best solution is achieved, an update is made and the next iteration starts. These steps are performed until the termination criterion is satisfied. The structure of the proposed method is presented in Algorithm1.

Algorithm 1 MLS for SBT-GER
procedure MLS ($Problem\ Data$)
$L \leftarrow List\ of\ storage\ piles$;
$first \leftarrow$ true;
repeat
  $S \leftarrow RandomConstruction(L)$;   //Random construction
  if (S *is not feasible***) then**
    $S \leftarrow Repair(S)$;
  end if
  if ($first$) **then**
    $S^* \leftarrow S$;
    $first \leftarrow$ false;
  end if
  $S \leftarrow LocalSearch(S, niter)$;   //Local Search
  if ($f(S) > f(S^*)$) **then**
    $S^* \leftarrow S$;
  end if
until ($The\ termination\ criterion\ is\ satisfied$)
return S^*;

The solution S of the SBT-GER problem is represented as a three-dimensional matrix. It is indexed by the ordinal numbers of the day d, the vehicle k used on day d, and the tour i assigned to vehicle k. The elements of the matrix S are defined as follows: $S(d,k,i)$ equals to the index of a storage pile to which a tour i of vehicle k on a day d is assigned. Empty tours of a vehicle are denoted by zeros. The dimension of the matrix S is equal to $|D| \times |K| \times G$, where $|D|$ and $|K|$ represent the number of days in the planning period and the maximum number of vehicles, respectively, while G denotes the maximum daily number of tours estimated as the floor of the quotient of the vehicle's working hours and the duration of the shortest tour.

The Algorithm 1 uses the problem data to create the list of available storage piles. A boolean variable denoted by *first* indicates the first pass through the main loop when the current best solution is initialized. In each iteration, the matrix S is constructed by the procedure *RandomConstruction***.** If it appears to be infeasible with respect to the equity constraints or the working hours, S is repaired to feasibility by the procedure *Repair*. The procedure *LocalSearch* is then applied to the solution S to improve it through the fixed number of iterations, *niter*, which represents a parameter of the procedure. If the solution obtained after LS is better than the current best, i.e., its objective function value, denoted by $f(S)$ is greater than the corresponding value of the current best $f(S^*)$, an update is completed. When the termination criterion is satisfied, the MLS procedure returns the best found solution S^*. The Random Construction procedure is described in Algorithm 2.

Algorithm 2 RANDOM CONSTRUCTION of the proposed MLS for SBT-GER
procedure $RandomConstruction\ (L)$
Initialize S;
$i \leftarrow 0$; $k \leftarrow 1$; $d \leftarrow 1$;
Generate candidate list cl *for day d;*
repeat
  Randomly select j from cl;
  repeat
    if (*vehicle* k *can be assigned to* j *at day* d) **then**
      $i \leftarrow i+1$; $S(d,k,i) \leftarrow j$;
    else
      $k \leftarrow k+1$; $i \leftarrow 1$; $S(d,k,i) \leftarrow j$;
    end if
    Decrease number of tours for storage pile j;
    if (*no tours to j left*) **then**
      $cl \leftarrow cl \backslash \{j\}$;
    end if
  until ((*no tours to j left*) or (*j is not urgent*) or (*daily requirements are satisfied*))
  if (*daily requirements are satisfied*) **then**
    $i \leftarrow 0$; $k \leftarrow 1$; $d \leftarrow d+1$;
    Generate candidate list cl *for day* d;
  end if
until ($d > |D|$)
return S;

At the beginning, the *Initialize* procedure sets all entries of the matrix S to zero. Then, the index variables d, k, and i, which correspond to the dimensions of the matrix, are initialized, and the candidate list cl of storage piles available on the first day is generated. Within the main loop, a storage pile is selected at random from cl and the tours to that storage pile are assigned to the current vehicle if possible, otherwise the next vehicle and its first tour are considered. The selected storage pile is considered until it is emptied, or no longer urgent (equity constraints for its grower are satisfied) or the daily requirements are fulfilled. If the corresponding storage pile is emptied, it is removed from the candidate list and if requirements of the mill are satisfied, the next day is considered. When the plan for the last day of the planning period is completed, the procedure for solution construction ends returning the matrix S.

The LS step of the proposed MLS is the same as LS used and described in details in (Drenovac et al., 2025) for VNS and GRASP implementations. Therefore, its description is omitted in this paper.

4. EXPERIMENTAL EVALUATION

Experimental tests are performed on Intel Xeon CPU E5-2620 v3, 2.40 GHz with 32GB RAM memory, under Linux operating system. MLS is implemented in C programming language. The set of instances generated in (Drenovac et al., 2025) is used for the evaluation. Test instances differ in two characteristics: the mill's daily requirements and the value of θ (the minimum percentage of sugar beet that must be collected from each grower on the day of harvest). The first characteristic can take 4 values: 1000, 3000, 5000, and 7000 tons, while θ could be either 20% or 30%, giving 80 instances in total for our experiments. The parameter tuning tests are conducted on the subset of instances, yielding best performing value for LS parameter $niter = 1$, the same as in (Drenovac et al., 2025). CPLEX solver execution time is limited to 1h, while MLS and GRASP are tested 30 times on each instance with the time limit of 120s in each execution.

For simplicity, the computational results presented in Table 1, contain average values per group of instances. The name of each group of 10 instances is given in the first column. The CPLEX solver results, consisting of the average objective function value over all 10 instances (best) and the average execution time (t) in seconds, are given in the next two columns. The remaining columns refer to the results of the proposed MLS algorithm and GRASP from (Drenovac et al., 2025). As they are both stochastic, each instance is tested 30 times and the best obtained objective function value is recorded along with the average gap, agap (in percent), of the obtained solution in each run from the best obtained and the average execution time, atbest (in seconds), required for reaching the best solutions. These values are additionally averaged per group of instances, leading to the values in the columns denoted by: best, agap and atbest, for both metaheuristics. The best average objective function values are bolded in each group.

Table 1: Computational results and comparisons

Group of instances	CPLEX		MLS			GRASP		
	best	t(s)	best	agap(%)	atbest(s)	best	agap(%)	atbest(s)
$G_{1000,20\%}$	**0.830649**	1705.65	0.830623	0.002	51.81	0.823115	0.417	59.74
$G_{1000,30\%}$	**0.830638**	1308.59	0.830612	0.001	50.88	0.825609	0.413	61.82
$G_{3000,20\%}$	0.836094	2712.42	**0.838869**	0.105	51.86	0.833047	0.174	55.37
$G_{3000,30\%}$	0.836912	2653.47	**0.838461**	0.060	47.36	0.833873	0.176	55.70
$G_{5000,20\%}$	0.838291	3600.30	**0.843518**	0.162	57.85	0.839015	0.124	61.04
$G_{5000,30\%}$	0.840276	3600.30	**0.843506**	0.150	60.11	0.839010	0.117	56.77
$G_{7000,20\%}$	0.825986	3600.78	**0.835032**	0.062	57.84	0.830181	0.276	62.79
$G_{7000,30\%}$	0.826705	3600.41	**0.835208**	0.083	60.01	0.830364	0.272	60.57

As presented in Table 1, with the exception of the first two groups where exact solver is expected to dominate, MLS outperforms both CPLEX and GRASP with respect to average objective function value. In addition, its average time needed to provide the best solution and the average gap from the best are less than the corresponding GRASP values for almost all groups of instances, confirming its better stability and efficiency. The number of instances per group of 10 instances, on which MLS provides a better quality solution than GRASP are: 9, 9, 6, 6, 7, 7, 10, 10. On the remaining 16 instances, the two metaheuristics coincide in the case of two instances belonging to the group $G_{3000,20\%}$, and in the case of 14 out of 80 instances, GRASP obtains solution of slightly better quality. CPLEX provided 7 optimal solutions out of 10 instances on each of the two G_{1000} groups and 3 optimal solutions out of 10 instances on each of the two G_{3000} groups. The detailed CPLEX results can be found in Drenovac et al., 2025, while the detailed MLS results on all instances are available on request.

5. CONCLUSION

An efficient Multi-start Local Search (MSL) metaheuristic is proposed for the Sugar Beet Transportation Problem under Growers' Equity Regulations (SBT-GER). It uses the same Local Search procedure as the GRASP based algorithm, previously developed for the same problem. Due to the completely random construction of the initial solution in each MSL iteration, compared to the solution construction in GRASP, guided by a restricted candidate list, GRASP is expected to be more efficient than MLS. However, computational experiments on the same set of instances and the same computer platform, have shown superiority of MLS over GRASP, with respect to average solution quality, stability and time needed for achieving the best obtained solutions for majority of test examples, as well as in comparison with CPLEX exact solver, with exception of the small-sized instances. We believe it is a consequence of the problem characteristics that require higher level of randomized diversification of the search. The future work may include adaption of the proposed MLS for similar optimization problems in different supply chains or hybridization of the method with exact solver or other metaheuristics.

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