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SIMULATION-BASED OPTIMIZATION OF A COMPLEX MAIL TRANSPORTATION NETWORK

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ABSTRACT

The Swedish Postal Services receives and distributes over 22 million pieces of mail every day. Mail transportation takes place overnight by airplanes, trains, trucks, and cars in a transportation network comprising a huge number of possible routes. For testing and analysis of different transport solutions, a discrete-event simulation model of the transportation network has been developed. This paper describes the optimization of transport solutions using evolutionary algorithms coupled with the simulation model. The vast transportation network in combination with a large number of possible transportation configurations and conflicting optimization criteria make the optimization problem very challenging. A large number of simulation evaluations are needed before an acceptable solution is found, making the computational cost of the problem severe. To address this problem, a computationally cheap surrogate model is used to offload the optimization process.

1 INTRODUCTION

Posten is the Swedish postal services, entirely owned by the Swedish Government <www.posten.se>. Core business comprises distribution of post/mail and logistics, and Posten is one of the largest actors in these areas in the Nordic region. With more than 30 000 employees and a revenue of approximately 25 billion SEK, Posten is also one of the largest corporations in Sweden. Posten is mandated to make postal services available all over the nation, which includes serving 4.5 million households and 900 000 businesses daily. The mandate states that mail must be collected and delivered on every workday and at least five days a week nationwide. Furthermore, Posten must guarantee that at least 85 percent of priority mail posted before a specific time must be delivered during the following workday – wherever it is addressed to in Sweden.

Administrative mail services, a market that is worth approximately 22 billion SEK, is Posten's main business. Every day, Posten handles over 20 million pieces of mail. Mail from companies and public authorities accounts for more than 90 percent of the volume, while the main recipient group is households. The fees for administrative mail are regulated by the Swedish state and Posten is not allowed to freely set the price of the services. As the Nordic postal market is fully deregulated, mail business is a highly competitive market. New operators are becoming established, especially in larger cities, and can compete with lower fees as they are not covered by the same regulations as Posten. Facing national and international actors operating in the same business areas puts high demands on efficient mail operations, and additional pressure arises from the legal directives that Posten is obligated to follow, specifying that mail operations must be fast, reliable, and cost-efficient. These challenges are not unique for the Swedish postal market, but postal administrations all over the world face the same requirement to continuously analyze and improve their services (Larsen 2003).

Requirements regarding environmental efficiency from the transportation sector also constantly increase as awareness of the greenhouse effects and climate change grows. Posten's transports log more than 300 million kilometers on the road each year (~850 000 kilometers per night), producing approximately 185,000 tons of carbon dioxide emissions. Posten tries to continuously improve its environmental efforts to reduce greenhouse gas emissions from its transportations. After several years of decreases in carbon dioxide emissions, the level of emission grew in 2005 due to increased mail volumes and structural changes in the mail distribution. Additional increase in volumes and further structural changes are expected to in-

crease the level of emissions even more. Posten must therefore improve its environmental efficiency even more in the future to reduce its environmental impact.

In the next section, Posten's mail transportation is described in further detail.

2 MAIL TRANSPORTATION

This section introduces the mail flow through different stages of the postal transportation chain. The optimization problem within this process being studied in this paper is also described.

2.1 Mail Distribution Process

The mail distribution process basically consists of the following operations (Figure 1):

1. Collection (3 - 8 pm)
Mail are collected from about 30 000 collection boxes and 3 000 retail service outlets during the afternoon and brought to the closest mail processing facility.

2. Input sorting (8 - 11 pm)
At the 11 mail processing facilities, all mail are automatically sorted and coded with a barcode according to the destination mail processing facility.

3. Inter-regional transportation (11 pm - 3 am)
Overnight airplanes, freight trains, and trucks move the mail from the origin mail processing facility to the destination mail processing facility.

4. Output sorting (3 - 5 am)
All mail are automatically sorted again, this time to determine their regional mail carrier centre.

5. Intra-regional transportation (5 - 9 am)
The mail are transported to the regional mail carrier centre (there are about 600 regional mail carrier centers) where a postman sorts them according to the delivery route.

6. Distribution (9 am – 2 pm)
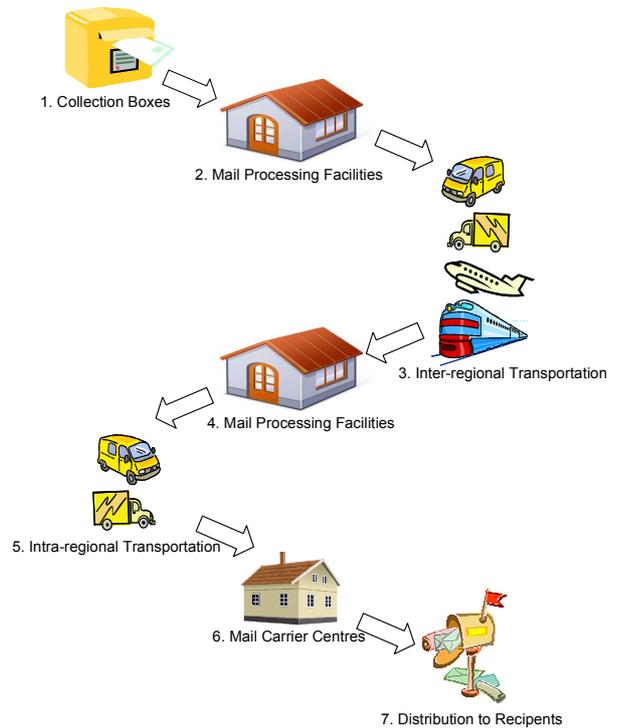About 15 000 mail carriers deliver the mail to the final addresses.

Figure 1: Distribution Process

2.2 Problem Specification

The focus of this paper is on the inter-regional transportation between mail processing facilities, corresponding to step 3 in the postal transportation chain illustrated in Figure 1. Strategic aspects such as configuration of the distribution network or the location of the mail processing facilities are not being addressed.

In general terms, the overall operational problem considered is to transport a number of mail bundles from origins to destinations in a complex routing network by a fleet of heterogeneous vehicles. A mail bundle is a quantity of mail that have the same origin and destination location, and pick-up and delivery time window. A complete solution to the problem consists of a number of transports, each defined by a vehicle type, a route (not necessarily between two mail processing facilities), a departure time, and a number of mail bundles. Five types of vehicles with different speed, cost, carbon dioxide emission, and capacity exist: trucks, trucks with trailer, cars, trains, and airplanes. Each vehicle type has specific attributes, such as number of carts for trains. Preferably, a transportation solution should achieve:

- On-time deliveries
- Low cost operations
- Low carbon dioxide emissions

These are to a large extent conflicting objectives which makes finding a good transportation solution a difficult task involving many important trade-off decisions. Additional complexity is added by the practical constraints that must be considered, such as:

- The number of vehicles and vehicle types at each location is limited
- Trains and air flights often have fixed and pre-defined schedules
- Restrictions on mixing mail for different postal code areas in one vehicle.

A property of the transportation network adding further complexity to the problem is that transports can be merged and split at consolidation hubs (Figure 2). This means that transports do not start and end only at mail processing facilities, but also on consolidation hubs.
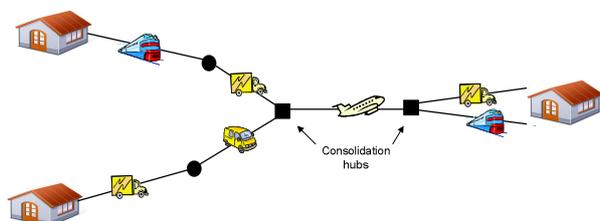

Figure 2: Example of Merging and Splitting of Transports

To make it possible to analyze different mail transportation solutions, a Discrete-Event Simulation (DES) model of the transportation network has been developed and is described in the next section. The size and complexity of the mail transportation network make DES superior to analytical modeling, which is a commonly used method in the literature to deal with similar transportation problems.

2.3 Simulation of Transportation Solutions

The simulation model, built using the Arena software package <www.arenasimulation.com>, supports manual planning and "what-if" analysis of transportation solutions. Experimenting on the real system is both impractical and extremely costly, and the simulation provides a convenient no-risk environment for analysis of alternative scenarios.

Mainly, the simulation model represents the following characteristics of the real mail transportation network:

- Mail arrival profiles, representing mail volumes entering the different mail processing facilities by time of day

- Mail processing facilities and consolidation hubs (including parameters such as capacity and load/unload times at platform)
- Transports routes and distances between mail processing facilities and consolidation hubs (road, rail, and air)
- Fleet of vehicles and time tables for trains and airplanes
- Unpredictable perturbations in the network (car accidents, road reparations, etc.)

During a simulation, various statistics are collected and presented at the end of the simulation to the user as an overview of how a transportation solution performed. This information includes, amongst others, estimation of transportation costs, carbon dioxide emissions, missed deadlines, and utilization of vehicles.

In the next section, related work within the area of mail transportation is presented.

3 RELATED WORK

The general problem of distributing goods between different hubs is an old problem that has been considered in many papers. Starting in the early days with simple single-depot problems, nowadays complicated distribution problems are being modeled and solved with various approaches (for an overview, see Savelsbergh and Sol 1997). There have also been some efforts in the area of postal mail distribution, which are described in this section.

Larsen (2003) describes how postal organizations have benefited from DES to accelerate and add confidence to decision making. A configurable and flexible tool called "Postal Network Planner" is introduced for end-to-end analysis of the postal logistic value chain. The author presents a number of examples of how the postal industry can be benefited from using simulation. The optimization of the postal networks is, however, not discussed.

Grünet and Sebastian (2000) describe an optimization of the German mail transportation network. The transportation problem is divided into two parts handled separately; air transportation and ground transportation. The air and ground transportation networks are represented using analytical models. Both problems are optimized using analytical methods, such as the column generation algorithm.

Jansen et al. (2004) presents another optimization of the German postal distribution network, focusing specifically on the daily transportation of containers on trains and trucks. A system for automatic planning of transport orders is described, in which the overall transportation problem is divided into a number of sub-problems that are

modeled analytically. The analytical models are optimized separately using path-search algorithms.

With a difference from previous studies, this paper presents the optimization of a mail transportation problem using DES and Evolutionary Algorithms (EAs). EAs are powerful search algorithms that have proven to be successful in various domains such as network design, operational planning, and scheduling. While traditional optimization methods have been unable to cope with the complexities of many real-world problems represented by DES, EAs have proven to be highly useful in these scenarios (Laguna and Marti 2002). In the next section, the design and implementation of the EA adopted to optimize mail transports is described.

4 OPTIMIZATION OF MAIL TRANSPORTS

EAs are population-based search algorithms inspired by theories from natural evolution. The basic idea behind these algorithms is that a population of individuals represents possible solutions of a given problem. Through recombination of solutions, offspring are created which form a new generation of the population. Some of the solutions are better suited for the problem being optimized and these are given more opportunities to reproduce and pass their features to the next generation, similar to the process of natural selection.

EAs have been proven to be very flexible and reliable in searching for global solutions (Baesler and Sepulveda 2000), and also capable of solving complex scheduling problems (Azzaro-Pantel et al. 1998). Furthermore, they can easily be coupled with any DES model, in contrast with some other heuristic methods which are more suitable only to certain problems (Azzaro-Pantel et al. 1998). The rest of this section describes the EA implemented for solving the optimization problem of mail transportation considered in this paper.

4.1 Problem Representation

In the optimization, the transportation network is represented as a directed multi-graph, where each vertex corresponds to a geographical point and each edge corresponds to a transport connection. Each edge has a cost, a time, and a capacity attribute. Each vertex can either be a mail processing facility or a consolidation hub. Splitting and merging of transports can be done both at mail processing facilities and consolidation hubs.

In the initial state, all mail are located at mail processing facilities. The goal is to transport all mail to their destination mail processing facilities within the given deadline. Transports can start and stop both at mail processing facilities and consolidation hubs. A transport is defined by a departure time and a list of connected edges. A transport solution is a set of transports.

4.2 Representation of Solutions

An EA encodes possible solutions as genomes and each genome instance represents a single solution to the problem – in this case an transport solution. Each gene in the genome represents a specific transport, which has attributes such as start point, start time, and end point. In Figure 3, a simplified example of a genome is presented. This genome consists of three transports: the first and second ones starts at mail processing facilities (MPFs) and ends at consolidation hub number three, while the third one merges the first two transports and carries the mail to mail processing facility number seven.

In representing a complete transport solution, at least 500 transports are necessary, which means that the genome is quite extensive. A disadvantage of this is that the search space becomes large as a consequence of the great number of possible solutions. EAs can, however, generally search large search spaces efficiently (Montana 1998).

Trp no. 1	Trp no. 2	Trp no. 3
Start: MPF 4 Start time: 9:14 pm End: Hub 3 Type: Car Formats: A4 Merge trp no: -	Start: MPF 1 Start time: 10:03 pm End: Hub 3 Type: Truck Formats: A4, C5 Merge trp no: -	Start: Hub 3 Start time: 11:33 pm End: MPF 7 Type: Truck+trailer Formats: A4, C5 Merge trp no: 1 & 2

Figure 3: Example of Simplified Genome

4.2.1 Genetic Operators

During each successive generation of the EA, a proportion of the existing population is selected to breed a new generation. Individual solutions are chosen for mating through tournament selection, in which two solutions are chosen randomly and the one with best fitness is chosen as the winner. Thus, solutions with higher fitness values are more likely to be selected, but a small number of solutions with worse fitness also have some probability of being selected. This selection procedure maintains the diversity in the population and prevents premature convergence. By mating selected solutions, offspring solutions for the next generation is created, a process called crossover. So called one-point crossover is being used in this work, in which a single point on both parents' genome is selected and the resulting sub-genomes are swapped, according to Figure 4.
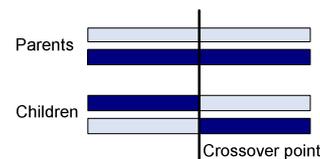
Figure 4: One-Point Crossover

To further maintain the genetic diversity from one generation to the next, some of the offspring solutions are mutated. In the mutation procedure, all transports are iterated through and an attribute of a transport is slightly modified (for example, delaying the start time with 20 minutes) with a probability of 0.1. To improve the performance of the optimisation, bonus is given to solutions that use consolidation hubs, since these have potential to decrease the number of transports (and thus the cost) if further developed.

4.3   Fitness Function

A fitness function quantifies the quality of a transport solution by calculating a value corresponding to its performance. The fitness value is based on the formula

$$f\left(c,t,e\right) = w_c c + w_t t + w_e e \qquad (1)$$

where c is the total cost, t is the number of tardy mail, e is the total amount of carbon dioxide emissions, and w_i is the user-defined weighted importance of objective i. The goal of the optimization is to minimize the fitness function value.

The three objectives in the fitness function are all represented using different measurement units. To allow a fair performance comparison of the different objectives, all measurements are normalized to values between 0 and 1:

$$u_i = \frac{o_i - worst_i}{best_i - worst_i}$$

where u_i is the utility of objective o_i, o_i^{out} is the measured output value of o_i, $worst_i$ is the worst possible value of o_i, $best_i$ is the best possible value of o_i and an optimal value of u_i is 1.

4.4   Optimization Algorithm

The optimisation algorithm implemented is a hybrid of two EAs: Evolution Strategies (ES) and Genetic Algorithms (GA). Basically, the algorithm is a steady-state variant of a $\left(\mu,\lambda\right)$-ES (Beyer and Schwefel 2002) inspired by concepts from GA. A steady-state approach supports a high degree of parallelism, which is a very important efficiency factor when simulation runs are computationally expensive. In steady-state approaches, one individual at a time is generated and inserted into the population, in differences with generational approaches in which a complete new generation is generated at a time. The generational approach is not optimal with respect to parallel efficiency since results for a complete generation must be awaited for in order for the search to proceed.

This is inefficient if the population size is not divisible by the number of processing nodes, or if simulations on different nodes take different amounts of time. Furthermore, if the population size is less than the number of processing nodes, all computing resources will not be utilized. In comparison, a steady-state design enables a higher degree of parallelism, since new solutions are continuously created and the number of parallel evaluations is not limited by the population size. Besides parallel efficiency, steady-state algorithms have also been considered being more efficient on complex optimizations problems and are able to find good solutions in less time compared to generational algorithms (Lacksonen 2001).

To increase the overall efficiency, the algorithm also incorporates a computationally efficient surrogate model in the optimization process. The surrogate model is a computationally cheap, but less accurate, representation of the simulation. It is implemented in C++ and performs fast, but rough, estimation of solutions. While the simulation model takes a couple of minutes to run, the surrogate model takes only about 40 milliseconds. The surrogate model is a less complex version of the original simulation and does not cover all aspects of it. For example, the surrogate model uses a simplified representation of the loading of vehicles, and does not include stochastic events representing unpredictable perturbations in the transportation network (car accidents, road reparations, etc.). In the algorithm, the surrogate model is used to screen candidate solutions and identify the most promising one. Instead of generating only a single offspring, which is normally done in steady-state algorithms, a pool of multiple offspring is created. Each of the offspring is evaluated by the surrogate, and the best one is simulated and inserted into the population.

In Figure 5, the implementation of the algorithm is presented with pseudo code. An initial population of 20 random solutions is first generated. Before the actual optimization starts, the solutions in the initial population are refined since pure random transport solutions are extremely poor. This is done by applying a hill climbing algorithm to optimize each solution for 20 minutes (using only the surrogate for evaluations). When the initial population has been created, the solutions are simulated. From the population, 10 offspring are generated from parents chosen using the GA concept of tournament selection based on simulation fitness. The offspring are evaluated using the surrogate model and one of them is chosen to be simulated, once again using tournament selection but this time based on surrogate fitness. The simulated offspring is inserted into the population and the worst solution in the population (which might be the newly inserted offspring) is then removed to keep the population size constant.

```
function Main
    population ← Generate RandomSolutions( )
    for each individual in population
        Simulate(individual)
    end
    while (not StopOptimization( )) do
        offspring ← ∅
        repeat λ times
            parent ← SelectForReproduction(population)
            individual ← Mutate(parent)
            SurrogateEvaluation(individual)
            offspring.Add(individual)
        end
        replacement _individual ← SelectFor Replacement(offspring)
        Simulate(replacement _individual)
        population.Remove(Select ForRemoval(population))
        population.Add(replacement _individual)
    end
return best _solutions
```

Figure 5: Pseudo Code of Evolutionary Algorithm

5   OPTIMIZATION RESULTS

The optimization was evaluated using different real-world scenarios and the test results look very promising. In comparison with transportation solutions created manually by domain experts, the optimization is able to find solutions with 10-12% lower cost, 20-25% less tardiness, and 3-4% lower carbon dioxide emissions. These numbers have, however, so far only been verified in the simulation model. In future, the optimized transport solutions can hopefully be partially or completely implemented and evaluated also in reality.

Compared to the manual approach of creating schedules used at Posten so far, the optimization implemented has advantages not only with respect to the results, but also with respect to efficiency. Since no manual control or intervention in the optimization process is necessary, a lot of time and effort are saved for the expert responsible for creating transport solutions. The optimization application also makes it easy to obtain transport solutions with certain focuses, for example, low carbon dioxide emissions, as the decision makers' preferences are considered in the optimization process.

6   SUMMARY

This paper presented the simulation-based optimization of a complex mail transportation problem. In this optimization, a DES model was coupled with an EA to find transport solutions that achieve on-time deliveries, low cost operation, and low carbon dioxide emissions. To make the overall optimization process more efficient, a computa-

tionally cheap surrogate model was used to offload the optimization process. A surrogate model is particularly useful in optimization problems like the one considered in this paper, involving an immense number of possible solutions.

To improve the optimization results further, future work includes studying how domain expert knowledge can be captured and incorporated in the optimization process. A human expert may have extensive knowledge valuable for the optimization, and incorporating this knowledge in the optimization strategy may be a way to obtain faster and more accurate optimization results.

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