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An Agent-Based Simulation Tool for Modelling Sustainable Logistics Systems

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Abstract:

Courier services form an important sector of urban freight traffic; leading to a daily volume of traffic that is problematic in economic and ecologic respects. New logistic concepts for reducing costs, distances and emissions could improve this situation by increased application of bicycle couriers and bundling of consignments. In this paper we summarise our previous work on the multi-agent-based simulation of alternative logistic concepts for city courier services. We discuss models of different organisation forms as well as the tools applied to their analysis. Since the logistic strategies analysed so far could not display the expected economic and ecologic benefits, a new concept named *Fixed Exchange Points* is presented that is closely related to actual work-sharing mechanisms of city couriers. We present a simulation model of this strategy and discuss first preliminary results.

Keywords: Agent-Based Simulation; Sustainability; Logistics; Courier Services; Simulation Tools

1 INTRODUCTION

Courier services form an important sector of urban freight traffic in large cities all over the world. Compared to express services, the individual delivery of consignments by couriers increases speed and flexibility of service. However, present forms of organisation lead to a daily volume of traffic that is problematic in economic and ecologic respects. New logistic concepts for reducing costs, distances and emissions could improve this situation by more selective application of bicycle couriers and increased bundling of consignments. An evaluation of such strategies must consider their economic benefit as well as their ecologic and social impact. Due to the decentralised organisation of courier services, detailed agent-based simulation models seem to be an adequate means for analysing these conflicting objectives.

At the University of Hamburg a simulation study was conducted as part of a research project funded by the Hamburg Department for Science and Research in 2003. The study was supported by two local city courier services providing data and expert knowledge. Two hub-oriented logistic strategies were compared to the actual state of courier service organisation by means of agent-based simulation models. Contrary to our expectations, the new logistic strategies could not outperform the status-quo significantly. In particular the best balance of economically, ecologically, and socially relevant measures was achieved without introducing the partly expensive infrastructures of the hub-based strategies [Page et al., 2004]. In this paper we present an additional strategy named *Fixed Exchange Points* [Deecke et al., 2003, p. 15] that supports established work-sharing mechanisms of city couriers through a simple hub-based infrastructure. A model of this strategy is currently evaluated with the aid of a toolset comprising spatially explicit discrete-event simulation, optimisation, and data mining.

The paper is organised as follows: Section 2 provides a short introduction to multi-agent-based simulation, motivates its appropriateness for the logistic domain, and presents our tools for the simulation and analysis of complex agent-based models. In Section 3 we briefly summarise our previous work regarding the simulation of alternative courier service organisations. For a more detailed discussion see [Page et al., 2004]. Section 4 introduces the new logistic strategy and the respective simulation model. In Section 5 we conclude and provide an outlook to our future work.

2 MULTI-AGENT-BASED SIMULATION

In multi-agent-based simulation (MABS), the concept of multi-agent systems (MAS) is applied to the modelling and simulation of real-world systems [see e.g. Klügl, 2001; Page and Kreutzer, 2005, Ch. 11]. MAS are aggregations of goal-oriented, interacting autonomous entities (agents) situated in some environment. Since no or only minor central control is exposed on the agents, a coherent global system behaviour emerges merely from their cooperations or competition. Compared to classical microscopic simulation world views such as event scheduling or process interaction, MABS puts a stronger focus on modelling complex and flexible behaviour of entities and (often) explicit spatial models.

This abstraction fits many target systems very well. It is especially suited for the analysis of macroscopic phenomena emerging from microscopic interactions by means of simulation. Due to the mobility and autonomous decision-making of city couriers in order evaluation and tour planning, courier services share numerous properties with MAS. It is therefore straightforward to analyse the impact of new logistic policies using MABS models [Knaak, 2002, p. 147]. The detailed modelling level allows to represent and compare different forms of organisation and cooperation rather naturally.

MABS models can be implemented in different ways; ranging from simple time-driven simulations in frameworks like *Swarm* [Minar et al., 1996] to complex models of goal-directed agents running on platforms like *JADE*[1]. For our courier service simulations, we choose a discrete-event simulation framework incorporating graph-based spatial modelling. Our *Framework for Agent-based MOdelling and Simulation* FAMOS [Knaak, 2002; Page and Kreutzer, 2005, pp. 363] extends the Java-based discrete-event simulator DESMO-J [see Page and Kreutzer, 2005, Ch. 10] for MABS. Agents in FAMOS are active entities with an internal schedule of *signals*, which they use to communicate with other agents and for scheduling their own actions (i.e. reactive and pro-active behaviour). The handling of signals is delegated to a special *behaviour object*, whose interface serves as a basis for different behaviour modelling techniques. This design is a simplified version of the behaviour modelling architectures found in agent platforms like JADE. Behaviour modelling facilities in FAMOS include (among others) graphical modelling with UML statecharts and rule-based modelling by integration with the JESS[2] expert system shell.

Organisation modelling is realised as an extended version of the *Agent-Group-Role* model by Ferber and Gutknecht [1998], which allows hierarchical and spatially defined groups. In addition, FAMOS provides an extensible framework for spatial modelling [see Meyer, 2001]. Spatial models can be defined in terms of discrete regular and irregular grids, graphs, or continuous representations. Different patterns of movement, such as random walks, following gradients, or route planning, are provided for all spatial models.

The possibility to simulate complex micro-macro relations is at the same time an opportunity and problem of MABS: Model validation, parameter calibration [see e.g. Klügl, 2001, p. 83], and the search for optimal strategies are regarded as challenging problems. To tackle these problems, we use a combination of simulation-based optimisation and data mining. We have successfully applied a tool for distributed simulation-based optimisation to automatically calibrate parameters that influence the couriers' decision-making [Gehlsen et al., 2004]. Since experiment series with MABS models result in large amounts of data, we apply data- and process-mining techniques to detect implicit interaction patterns and thereby support model validation [as e.g. proposed by Remondino and Correndo, 2005].

3 SIMULATION OF CITY COURIER SERVICES

Most courier services are organised as agencies providing services of order acceptance, mediation and accounting to the self-employed couriers [see also Page et al., 2004]: Orders being placed at a central office are announced to the courier service's fleet by radio. The courier fleet consists of motorised couriers and fewer bicycle couriers moving in the city area. Couriers compete for interesting orders and autonomously plan delivery tours. The office usually awards each order to the first applicant and exerts minor additional influence on order allocation: Orders are first offered to dedicated inactive couriers and customers' preferences of conveyance are satisfied as much as possible. Adherence to the courier service's guaranteed delivery time is enforced by constraining the number of orders a courier might execute in parallel. If an unpopular order is eventually not accepted, the radio operator applies increasing pressure on appropriate

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[1] http://jade.tilab.com

[2] http://herzberg.ca.sandia.gov/jess

couriers, who are nevertheless allowed to reject it.

A possible way of optimizing courier services is to supplement the courier concept with the hub-oriented logistics of express freight services. In a strategy named *Hub and Shuttle* [Deecke et al., 2003] some main regions with high order volumes are identified in the central city area and a hub is installed in each region. Consignments with their source and destination in different regions are brought from the sender to the hub of the source region by a courier. There, consignments destined for the same region are bundled and brought to the hub of the destination region by larger vehicles (shuttles) consorting regularly in line haul or shuttle service. Finally each consignment is delivered to the consignee by a courier in the destination region.

Another variant of hub logistics is a strategy named *Inside/Outside* [Deecke et al., 2003] that relies on a single central hub. Around this hub an *inside* region with high order volume and several *outside* regions with lower volumes are identified. Consignments with their source and destination in the inside region or the same outside region are transported in standard mode. Consignments from an outside region to the inside region (or vice versa) are processed via the central hub. Tours between the hub and outside regions are bundled and carried out by motorised vehicles while deliveries in the central area are taken on preferably by bicycle couriers.

In our simulation models the couriers and the central office are represented as agents with their behaviour described by UML statecharts. Both communicate via a mediation protocol that closely resembles the *contract-net* protocol [Smith, 1980]: When an order is placed, the office announces the request to all potential couriers in order of their priority. A consignment with bicycle preference is e.g. announced to inactive bicycle-couriers first, then to active bikers and finally to motorised couriers. The couriers rate orders according to a quantitative rating function developed by Reick [1997] and described in detail in [Page et al., 2004]. After a duration inversely proportional to the rating value they send a proposal for transportation to the office who awards the order to the first applicant. If the rating stays below a certain threshold, couriers do not answer at all and the office re-announces the order later if necessary. After a certain number of unsuccessful announcements, the office disposes the order to the idle courier located closest to the order's pickup point.

From their accepted orders the courier agents plan a delivery tour using a suboptimal strategy based on
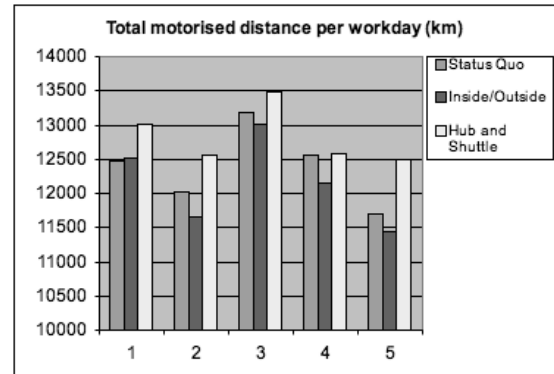
Figure 1: Comparison of the total motorised distance covered by couriers in the 3 different models per workday [adopted from Page et al., 2004]

the procedure of real city couriers. Pickup and delivery positions of new orders are inserted successively into the existing tour with least possible detour. For order delivery the couriers "move" along the edges of a detailed graph-based model of the Hamburg road-network with about $50,000$ edges. Graph routes are searched using a modified version of Dijkstra's shortest path algorithm [Domschke and Drexel, 2002] that considers averaged travelling durations based on speed limits of different road types. An optimal graph search procedure seems appropriate since city couriers usually possess very good knowledge of place.

For simulating the Hub and Shuttle strategy another agent type Shuttle is added to the model. On order placement the office determines which main region an order's pickup and delivery position belong to. Orders with those positions in different regions are announced to the couriers as a tour from the pickup position to the hub of the source region first. After delivery to the destination region by the shuttle each order is re-announced as a tour from the destination hub to the delivery position. In the model of the Inside/Outside strategy a new courier type is introduced for processing orders from the outside regions. These couriers are assigned a fixed region and they only receive order requests concerning this region. Tours from the outside region to the central hub (or vice versa) are not delivered immediately but collected during a certain time frame (e.g. 30 minutes) to increase the possibility of bundling.

Simulations of these models show that contrary to our primary expectations, the new logistic concepts cannot or only slightly improve a courier service's ecological quality; measured by the total motorised distance per workday [see Page et al., 2004]. Fig. 1

shows a comparison based on 5 different order profiles[3]. The distances covered in the Hub and Shuttle model are noticeably larger than in the status-quo. The desired bundling rate is not achieved and the balance suffers from additional distances caused by the shuttle service and splitting of consignments into two transport orders. The Inside/Outside strategy displays a marginal improvement compared to the status-quo. This strategy fits the order profile slightly better and does not involve additional motorised traffic.

4 FIXED EXCHANGE POINT MODEL

These simulations of alternative logistic strategies do not justify a change of practice for economic or ecological reasons. A main cause is the large number of empty runs: In the status-quo model, couriers accept orders that force them to leave their principal work area. After delivery, they cannot acquire appropriate succeeding orders and must return to the central area. In the Hub and Shuttle model additional shuttles are introduced that collect consignments for long distance transport. However, the bundling effect is outweighed by the fact that the shuttles consort regularly without regarding utilisation. In the Inside/Outside model, consignments are forced to be transported along some main routes. Here, the bundling effect might be outweighed by the fact that these routes are inflexible and differ from the actual optimal transport routes.

Each logistic strategy contains interesting aspects that can be integrated into a new concept to enhance the couriers' cooperation. In the new model named *Fixed Exchange Points*, the city area is divided into clusters as well. However, the cluster's alignment is not radial (as in the Inside/Outside model) or restricted to the central city area (as in Hub and Shuttle). We rather apply a cluster algorithm that considers the flow of orders in the whole city area. At the cluster borders, we place exchange points similar to the hubs from our previous models. Consignments whose delivery covers multiple clusters are split into distinct orders for each cluster. Roughly speaking, this strategy is an institutionalised variant of order exchanges that city couriers perform to avoid leaving their preferred delivery routes in reality.

4.1 Data Preprocessing

The basic idea of the cluster algorithm is to divide the city area into n clusters with approximately

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[3]i.e. historical data sets of transport orders

Figure 2: UML activity diagram of the basic cluster algorithm

equal volume of orders. Besides we demand that all city districts within a cluster have to be connected. The basis for clustering are historic transport order data and a geographical division of the city area into m districts. For each order we determine the district where the order is picked up and where it is delivered. We then create an $m \times m$ matrix that displays the order flow between each pair of districts. We further define a neighbourhood relation for districts and a rule to divide the value of an order between different districts: When an order is picked up in a district, we allocate a value of a $(0 \leq a \leq 1)$. When it is delivered into a district we allocate a value of $(1 - a)$.

The algorithm is initialised by determining n districts as cluster seeds (see Figure 2). These areas can be chosen randomly or based on geographical or economic aspects (e.g. the districts with the highest order volume). Furthermore, we define an optimal cluster size by dividing the total number of orders by the number of clusters. During the main algorithm, unallocated neighbouring districts are added to the clusters in order to make them grow to the optimal size as fast as possible. In each iteration, a cluster can only grow by a single district which guarantees a certain degree of fairness. When a cluster reaches its optimal size or is not able to add further districts it is passivated; i.e. it is no longer allowed to grow. The algorithm stops after all clusters have become passivated.

The main algorithm cannot guarantee that each district is allocated to a cluster, since it might become surrounded by passive clusters. If such districts were allocated to a remaining active cluster, it

would violate the assumption of connectedness. We therefore add each of these districts to the smallest neighbouring cluster in a post-processing phase. Furthermore, we need to compensate significant differences between cluster sizes. Since it is unlikely that all clusters can reach the same size, we define a rate c $(0 < c < 1)$ by which cluster sizes might differ from the optimum. We then re-activate all clusters and check if the size of the smallest cluster already lies within these bounds.

If it does not, we consider all neighbouring districts; except for those belonging to clusters of size 1 (to prevent clusters from disappearing) and those belonging to passive clusters (to avoid a cyclic exchange of districts beetween clusters). From these, we choose the district whose replacement leads to the lowest deviation of the source and target cluster from the optimal cluster size. We have to make sure that its parent cluster is still strongly connected after removing it, and choose the next best district if this cannot be achieved. This step is repeated until the cluster has reached the optimal size or cannot allocate any more districts. Then the cluster is passivated and we continue with the next smallest cluster. After termination, we re-check if all clusters have reached the optimal size and repeat the compensation step if necessary.

4.2 Model and Implementation

After determination of the clusters, the couriers are divided into groups. Each group is assigned to a cluster and handles all orders within this cluster. In the normal case, couriers are not allowed to leave their cluster during transport. If an order is transported between two different clusters, the order has to be exchanged at the cluster border. The courier then deposits the consignment at an exchange point until a courier from the neighbouring cluster redraws it and continues the transport.

When an order enters the system, the central office first determines the optimal route through the different clusters. If the order's pickup and delivery point are in the same cluster, the order is allocated similar to the status-quo model. Otherwise, it is split into parts where each part is announced as a distinct order. Couriers evaluate these orders by rating all target exchange points and choose the one causing the least detour with respect to their currently accepted orders. This exchange point is cached and set as a destination point, when the order is awarded to the respective courier. The succeeding order parts are not announced before a partial delivery is finished.

A major problem is to share the revenues and the allowed transport durations of order parts between the involved couriers. However, the couriers might be able to compensate potential disadvantages of such orders by having fewer competitors and choosing an optimal exchange point. Furthermore, the number of couriers in each cluster is adjusted flexibly to regulate their utilisation. The couriers can apply for a change of cluster if their utilisation has been too low for a certain time. On the other hand the office can announce a change if the utilisation in a cluster is too high and the quality of service within this cluster can no longer be guaranteed.

Similar to the previous models, the implementation of the Fixed Exchange Points strategy comprises two agent types: couriers and central office. The office is responsible for order allocation and communicates with the couriers via signals. On order arrival, the office applies the Floyd algorithm [see Domschke and Drexel, 2002] to determine the consignment's optimal route through multiple clusters; where a minimum number of exchanges is used as an objective. After splitting the order into parts, it is announced to the couriers in the respective clusters with a multicast signal. The remaining order delivery workflow is implemented similar to the previous models.

4.3 Preliminary Results

The cluster algorithm achieved an appropriate decomposition of the city area. Our data-base contained 103 districts of Hamburg and 2100 orders of a local courier service. The goal was to create 6 clusters from randomly chosen seed districts. The algorithm's parameters were set to $a = 0.5$ and $c = 0.95$. We achieved a rather equal distribution of order volumes with a mean of 320 and a standard deviation of 14 orders per cluster. The clustering quality was confirmed by means of visual validation. However, there are some drawbacks: Firstly, the choice of the seed districts largely influences the clustering results. Secondly, the algorithm only considers those districts where an order is picked up or delivered. It should take into account all districts covered by an order, but this information cannot be extracted from the given data directly. Anyway, the current algorithm provides an adequate heuristic.

The clustering results in an acceptable maximum of two exchanges per order computed with the Floyd algorithm. In pilot simulation runs, we found that only a quarter of the distances covered by the couriers are idle runs. However, these values are subject

to a large variance. Considering orders that cover multiple cluster, only a small number of *first* order parts had to be disposed (about 3 per cent) due to continuing rejection by the couriers. This indicates that the short distances, the improved bundling facilities, and the possibility to freely choose an exchange point make these orders "attractive". In contrary, succeeding order parts are disposed more often, partly due to a suboptimal choice of exchange points. Furthermore, it becomes obvious that orders with a very short distance between pickup and delivery point often cover multiple clusters as well. These orders should be transported directly to avoid unneccessary exchanges that strongly delay an order's delivery. In a further publication we will present more detailed results of the new model focusing on its ecologic quality.

5 CONCLUSIONS AND FUTURE WORK

In this paper, we have summarised our work on multi-agent-based simulation of alternative logistic concepts for city courier services. Since the previously analysed hub-oriented strategies did not show the expected economic and ecologic improvements, we propose a new strategy named Fixed Exchange Points with close relations to city couriers' actual work-sharing mechanisms. We have developed an agent-based model of this strategy, implemented it in our FAMOS framework and conducted first pilot runs. The results of these runs show that a refinement and extension of the model is necessary. The number and placement of fixed exchange points should be calibrated using simulation-based optimisation. To accelerate order processing in a realistic way, the coordination between the simulated couriers should be improved. All couriers involved in the processing of an order should agree upon an appropriate work-sharing *before* the order is awarded to the first courier. Agent-based simulation provides appropriate means to model such negotiations; e.g. by means of interaction protocols and game-theoretic models. Finally, it might be interesting to evaluate the described strategies and models in other logistics domains with larger distances and frequencies of transport orders.

REFERENCES

H. Deecke, N. Knaak, R. Meyer, and B. Page. Nachhaltige Logistikkonzepte für Stadtkurierdienste: Projekt-Endbericht. Technical report, University of Hamburg, 2003.

R. Domschke and R. Drexel. *Eine Einführung in Operations Research*. Springer, Berlin, 2002.

J. Ferber and O. Gutknecht. A meta-model for the analysis and design of organizations in multi-agent systems. In *Third International Conference on Multi-Agent Systems (ICMAS '98) Proceedings*. IEEE Computer Society, 1998.

B. Gehlsen, R. Bachmann, and N. Knaak. Werkzeuggestützte Kalibrierung agentenbasierter Simulationsmodelle. In T. Schulze, S. Schlechtweg, and V. Hinz, editors, *Proceedings Simulation und Visualisierung 2004*, pages 115–126, Magdeburg, March 2004. SCS-Europe.

F. Klügl. *Multiagentensimulation – Konzepte, Werkzeuge, Anwendung*. Agententechnologie. Addison-Wesley, Munich, 2001.

N. Knaak. *Konzepte der agentenbasierten Simulation und ihre Umsetzung im Rahmen des Simulationsframeworks DESMO-J*. Diploma thesis, University of Hamburg, 2002.

R. Meyer. Bewegungsgraphen – Ein Konzept für die räumliche Modellierung der Umgebung in der individuen- und agenten-basierten Simulation. In J. Wittman and L. Bernard, editors, *Simulation in Umwelt- und Geowissenschaften – Workshop Münster*, pages 47–60, Aachen, 2001. Shaker.

N. Minar et al. The Swarm Simulation System: A Toolkit for Building Multi-Agent Simulations. Technical report, Santa Fe Institute, 1996.

B. Page and W. Kreutzer. *The Java Simulation Handbook – Simulating Discrete Event Systems with UML 2 and Java*. Shaker, Aachen, 2005.

B. Page, N. Knaak, and R. Meyer. Logistic strategies for sustainable city courier services – an agent-based simulation approach. In A.G. Bruzzone et al., editors, *Proc. International Workshop on Harbour, Maritime and Multimodal Logistics Modelling and Simulation (HMS 2004)*, pages 139–144, Rio, Brazil, September 2004.

C. Reick. Zur Modellierung von Stadtkurieren. Technical report, University of Hamburg, 1997.

M. Remondino and G. Correndo. Data mining applied to agent based simulation. In Y. Merkuryev, R. Zobel, and E. Kerckhoffs, editors, *Proceedings of the 19th European Conference on Modelling and Simulation*, pages 374–380, Riga, June 2005. SCS-Europe.

R. G. Smith. The contract net protocol: High level communication and control in a distributed problem solver. *IEEE Transactions on Computers*, 29 (12):1104–1113, 1980.