Environmental Informatics for Sustainable Logistics

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Abstract. In the first part we provide a review of the rather young field of Environmental Informatics. We argue that Environmental Informatics methods and tools are powerful means in environmental information processing for supporting sustainable development. In the second part we introduce a case study dealing with sustainable logistic systems for city courier services based on agent-based simulation methodology. New logistic strategies together with an increased employment of bicycle couriers and bundling of consignments seem to be appropriate for reducing costs, transportation distances, and emissions. By means of this simulation model ecological, economic as well as social implications of two alternative logistic strategies have been analysed and evaluated. Promising results have been found in the study by introducing inner city interchange stations for bundling deliveries for the suburban areas. It turns out that agent-based simulation methodology is a powerful tool for modelling sustainable logistic systems in Environmental Informatics.

1 Introduction: The Role of Machine Environmental Information Processing

The protection of our environment remains one of the greatest challenges in our industrialized societies. This challenge is addressing politics, economy as well as technology and research. It is clear that the various problems in environmental protection, environmental planning, research and engineering can be only solved on the ground of a comprehensive and reliable information basis. State and dynamics of the environment are described by biological, physical, chemical, geological, meteorological, or social-economic data. This data is *time* and *space dependent* and addresses past or current states. The processing of this data and the production of meaningful *information* on the environment, on its stress factors and mutual influence mechanisms are fundamental for any kind of environmental planning and preventive measures. Therefore environmental problem solving is mainly an *information processing activity* handling a wide range of environmental data. Solutions to our environmental problems are strongly dependent on the quality of accessible information sources. Certainly, qualified information is a very critical factor in making decisive political actions and in changing peoples attitudes on the environment. This information on environmental aspects is just as important for decisions on actions in environmental protection as for gaining knowledge in environmental research.

Meanwhile the application of information technology has become vital in the environmental domain in industry, in public administration as well as environmental research for providing the required environmental information on the appropriate level of detail, completeness, accuracy and speed. However, in this context a straightforward data storage for environmental mass data is not at all sufficient. Rather the filtering of meaningful and up to date environmental information on the state of the environment from this data storage is required to support administrative and planning tasks in environmental protection. In this way one of the main goals of environmental information systems is addressed, namely to prepare the mass of collected environmental data in such a way that they can be used for routine operational environmental administration tasks as well as for political-strategic decision making.

Environmental information processing has recently focused on the following trends:

- *environmental monitoring* by means of remote sensing and the combination of data streams from all over the world,
- a policy for sharing and *integrating environmental information* across political, technical and organizational boundaries making wide use of internet technology,
- advanced *model-based data analysis techniques*, shifting the focus from data to dynamic system structure, industrial applications of environmental information processing, aiming at higher ecological efficiency of the economic system.

It is obvious that advanced computing technologies play an important role in these developments. Information processing in the environmental domain has been lacking a sound conceptual and scientific basis, since there has not been a significant research in this special domain for a long time. This is certainly not only a matter of Applied Informatics or Applied Computer Science, respectively, but an interdisciplinary task where many scientific disciplines should be involved (e.g. geo- and bio-sciences, environmental engineering, economics and law, management sciences, etc.). On the other hand, the growing field of environmental information processing is a great challenge to Informatics methodologies and their applications. From this process of mutual stimulation, some 15 years ago a new discipline has emerged, named as *Environmental Informatics*.

2 Review of Environmental Informatics: Background and Main Issues

The rather new discipline of *Environmental Informatics* has been emerging in central Europe some 15 years ago with the claim of contributing to the development of a sound conceptual basis for environmental information processing on scientific grounds. However, *Environmental Informatics* does not see itself as a pure supportive discipline providing environmental sciences with computer tools. Much more it has to offer a wide range of powerful proven methods from Informatics or Computer Science, respectively, for complexity reduction and problem solving which can be also useful in the various environmental domains. We can define *Environmental Informatics* as follows:

> *Environmental Informatics is a special subdiscipline of Applied Informatics dealing with methods, techniques and tools of Computer Science for analyzing, supporting and setting up those information processing procedures which are contributing to the investigation, removal, avoidance and minimization of environmental burden and damages.(translated from Page and Hilty in [19]).*

Environmental Informatics is holding a mediation role. On one hand, it analyses real-world problems in a given environmental domain and defines requirements on information processing. On the other hand, it introduces the problem solving potential of Informatics methodology and tools into the environmental field (see Fig.1).

In environmental information processing we typically deal with many different, rather *heterogeneous data structures and information sources* such as text data on environmental laws or research projects, measurement data from monitoring networks, structural data on chemical substances, formatted engineering data on environmental technology, just to name a few. In particular, environmental data is often *geographically coded*, i.e. information is attached to a particular point or region in space. The represented data objects are often *multidimensional* and have to be described by means of complex *geometric objects* (e.g. polygons or curves). In addition we usually have a *temporal aspect* in our environmental data sets. Also processing of *empirical data* with *statistical methods* as well as of *vague, uncertain* and *incomplete information* is a major concern in Environmental Informatics. A comfortable user access on *heterogeneous and distributed environmental data bases and information systems* via computer networks has to be supported. In this context *meta data* access is crucial for user orientation. *Environmental modeling* is well established in the environmental field. And finally, environmental data must be presented and evaluated in a *domain overlapping, multidisciplinary context*. As a requirement, this information has to be often deducted from a number of domain specific primary data bases beforehand.

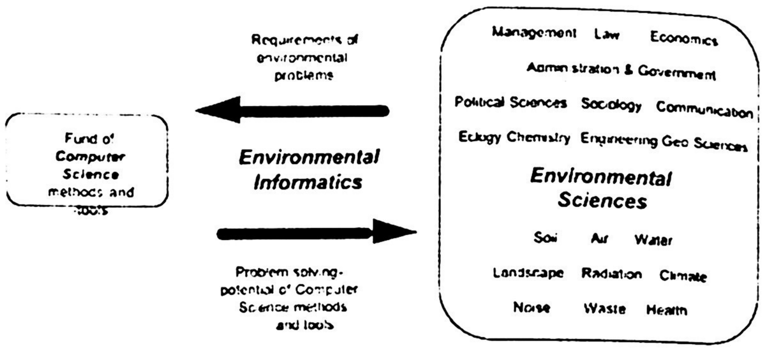

Fig. 1. Environmental Informatics bridges the gap between Informatics' methodology and the environmental application domain

On this background Environmental Informatics has to focus on a number of main issues. Thus, complexly *structured heterogeneous data bases and distributed, Web-based information systems* are investigated. *Meta data or special meta information systems*, respectively, as well as all kinds of user assistance are required for the very heterogeneous user groups in large scale environmental information systems. For spatial information processing aspects of *geometric data structures and algorithms* as well as of modern *open and distributed Geographical Information Systems* (GIS) have to be considered. *Knowledge-based and qualitative concepts* are of relevance in dealing with uncertain, vague and incomplete environmental knowledge and information. Complex environmental data has to be visualized by means of powerful scientific *visualization* approaches. Concepts and architectures for *mathematical analysis and modeling software* are required for computerized statistical analyses as well as for *environmental modeling and simulation.* Beyond that there is the key issue in Environmental Informatics of *integration of data, information, models and knowledge* from various distributed sources in the environmental sector.

During the last 15 years a scientific community has been formed in central Europe dealing with environmental information processing on a scientific level originally organized by the Special Interest Group "Computer Science in Environmental Protection" in the German Computer Society (Gesellschaft fuer Informatik - GI, see http://www.iai.fzk.de/Fachgruppe/GI/welcome.eng.html.). Yearly conferences and workshops with a considerable number of participants and publications have been held ever since (in 2004 already the 18th yearly conference of the special interest group has taken place, see [29]) . Quite some time ago the contributions to these conferences as well as the conference locations became more and more international (Strassbourg in 1997, Zurich in 2001, Vienna in 2002, Geneva in 2004 and Bruno scheduled for 2005) and new thematically related international workshops have been introduced (e.g. International Symposium on Environmental Software Systems – ISSES, see [18] and [12] or ECO-INFORMA, see [25]). Meanwhile *Environmental*

Informatics has emerged as a truly international and widely interdisciplinary research campaign.

3 Requirements on Environmental Informatics for Sustainable Development

Even if Environmental Informatics is a rather young field a critical assessment of the early work, achievements and directions should be appropriate. It seems that the early work had its main focus on system developments for monitoring the status quo of the environment. Although diagnosis is indispensable, it is no solution if no therapy follows. Applying sophisticated computing methodologies just to cure at symptoms of our environmental problems should certainly not satisfy us. Since the Rio Summit has claimed "*sustainable development*", there seems to be now a rewarding framework and direction for the future work in Environmental Informatics at hand. Here, sustainable development means a way of living and a form of using resources that does not discriminate against future generations. Although it is certainly difficult to implement sustainable development in real world practice, it is clear that *information* will be a very critical resource in changing attitudes and making decisive political actions into that direction possible. In [10] Hilty from the University of Hamburg has proposed new principles for Environmental Informatics already as early as 1997 which are more compatible with requirements from sustainable development:

Structure orientation:
The emphasis should be on structure related view of environmental information, rather than on state related. It is more relevant to recognize system structure and dynamics than a precise documentation of current state of the environment.

Cause orientation:
Environmental information systems should not be restricted to ecological data, but also provide economical as well as social data, since most environmental problems are caused by human economic activities. In this way the ecological-economic system context provides a framework for information processing promoting a higher resource productivity.

Discourse orientation:
Environmental problems are usually leading to political and economical interest conflicts. Using information technology for problem solving in consensus means new mediating capabilities of the software tools applied.

Thus, Environmental Informatics has to accept the challenge of playing an active role in the local and global transformations that will be necessary to approach sustainability by providing the high quality information processing concepts and solutions required.

A promising application domain for sustainable Environmental Informatics, which has been come into focus more recently (see [11]-[17]), are *traffic and logistic systems* where economic, social as well as ecological aspects play an important role.

To demonstrate how modern methods and tools from Computer Science, i.e. agent-based technology, can be applied in Environmental Informatics to design sustainable system structures in logistics we refer to a case study which has been developed in a 3-year research project at the University of Hamburg funded by a local research program on sustainable development.

3 Methods and Tools of Environmental Informatics for Sustainable Logistics – A Case Study[1]

3.1 Problem Definition: Sustainable City Logistics

In this chapter we introduce a case study in Environmental Informatics dealing with an agent-based simulation model of logistic strategies for sustainable city courier services

Courier services form an important sector of urban freight traffic in many large cities. Compared to express services, the individual delivery of consignments by couriers increases speed and flexibility of service and thereby customer satisfaction. However, present forms of organization lead to a daily volume of traffic that is problematic in economic and ecologic respects. After rapid growth during the 1990's, many courier firms currently undergo a phase of stagnation that is mainly caused by aggravation of urban traffic conditions and reduced order volume due to increasing use of digital communication in media and commerce [16]. New logistic concepts for reducing costs, distances and emissions could possibly 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 with respect to the high acceptance of present courier service structures. Due to the decentralised organisation of courier services, detailed agent-based simulation models seem to be an adequate means for analysing and balancing those conflicting objectives. At the University of Hamburg a simulation study as part of a research project has been conducted in co-operation with two local city courier services.

[1] This section of the paper is an updated version of an earlier publication by the author and his coworkers Nick Knaak and Ruth Meyer [15] and based on the final project report [16].

3.2 Organisation of Courier Services

Presently most courier services are organized as agencies providing services of order acceptance, mediation and accounting to the self-employed couriers. Orders are placed at a central office and announced to the courier service's fleet by radio. The courier fleet consists of motorized couriers with passenger cars, station wagons and vans and fewer bicycle couriers moving in the city area. Couriers compete for interesting orders and autonomously plan their own 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. Constraining the number of orders a courier might execute in parallel enforces adherence to the courier service's guaranteed delivery time. If an unpopular order is eventually not accepted, the radio operator applies increasing pressure on appropriate couriers. Due to being self-employed, couriers are nevertheless allowed to reject an order.

This simple decentralized mediation scheme – "based on unwritten rules" – balances the couriers' utilisations and revenues, the efficiency of tour planning and the courier firm's service quality (speed and reliability) quite well [13]. For optimization purposes it should only be modified with care. Most courier services in Hamburg are organized the way described above whereas one of the cooperating courier services applies a simple disposition policy allocating each order to the inactive courier closest to its pickup position.

3.3 Logistic Strategies

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* [4] some main regions with high order volumes are identified in the central city area and a hub is installed in each region (Fig. 2, left). 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.

This strategy might display an ecologic advantage since it promotes the application of bicycle couriers in the main regions and shortens the motorised distances covered individually by increased bundling of consignments. While the courier service's decentralized organisation remains untouched additional effort is also required: Hubs must be established and consignments have to be split into two different transport orders.

Another variant of hub logistics is a strategy named *Inside/Outside* ([4], pp. 16) that relies on a single central hub (Fig. 2). 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 bicycle couriers preferably take on deliveries in the central area.

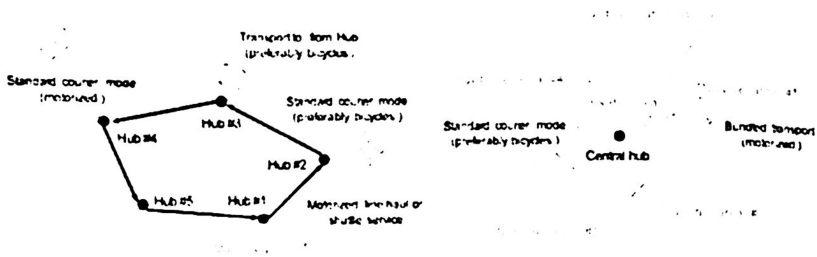

Fig. 2. Alternative logistic concepts for courier services: Hub and Shuttle (left) and Inside/Outside (right)

3.4 Courier Services as Multi-agent Systems

Due to the couriers' mobility and autonomous decision-making in order evaluation and tour planning courier services share numerous properties with multi-agent systems [5]. It is therefore straightforward to analyse the impact of new logistic policies using agent-based simulation models [14], i.e. models based on the metaphor of autonomous, self-interested actors with flexible behaviour. In our model the couriers and the central office are represented as autonomous agents communicating via a mediation scheme that closely resembles the well-known contract-net protocol [23]. Changes in individual behaviour required by new logistic strategies can be represented more intuitively than using traditional simulation techniques like event scheduling or process interaction [20].

Based on a system analysis of the courier firms and an earlier simulation study [13] a conceptual model of the "status quo" was built using different UML diagram types. Couriers and office are modelled as state charts communicating via the contract-net like mediation protocol shown in Fig. 3. When an order is placed (*Allocate*), the office announces the request to all potential couriers in order of their priority (*Request*). 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 described below. After a duration inversely proportional to the rating value (*Interest*) they send a proposal for transportation (*Propose*) to the office who awards the order to the first applicant (*Award*). If the rating stays below a certain threshold, couriers do not answer at all and the office re-announces the order later if necessary.

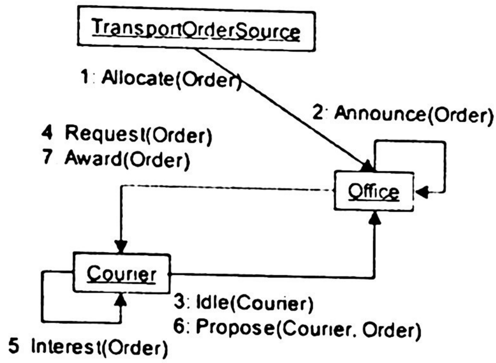

Fig. 3. UML collaboration diagram showing the contract-net like mediation protocol of the agent-based courier service model ([14], p. 151)

From their accepted orders the courier agents plan a delivery tour using a suboptimal strategy based on 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 that additionally considers speed limits of different road types. An optimal graph search procedure seems appropriate since city couriers usually possess very good knowledge of an area.

A courier's interest in taking on an order is evaluated with a rating function introduced in [14]. The function considers criteria of individual *order quality*, *need for orders* and *utilization*. Order quality Q(o) is quantified as:

$$Q(o) = revenues(o) / detour(o) - cost(c) \cdot v_{avg}(c),$$

where revenues(o) are the courier's revenues[2] gained by order o, detour(o) is the detour necessary to deliver o relative to the existing tour, cost(c) and $v_{avg}(c)$ are operating expenses per kilometre and average speed of the courier's conveyance. A courier c's need for orders is computed from his current "order situation":

$$S(c) = T(c) / T_{max},$$

where T(c) is the estimate time necessary to process the existing tour and T_{max} is the maximum delivery time guaranteed by the courier service. If T(c) exceeds T_{max} the courier cannot take on another order without endangering the guaranteed delivery

[2] For delivering an order couriers receive a flat rate of 3 € and 1 € per kilometre. The flat rate is halved for hub orders in the *Hub and Shuttle* and *Inside/Outside* model.

period, i.e. his need for orders N(c) = 0. Otherwise N(c) takes on a value decreasing exponentially from 1 to 0 with tour duration:

$$N(c) = (\exp(-q \cdot S(c)) - \exp(-q)) / (1 - \exp(-q))$$

The parameter -q determines the steepness of the exponential function. If the product Q(o) · N(c) exceeds a threshold w · util(c) increasing proportionally with the courier's previous utilisation, a proposal is issued after a deliberation period

$$t_{delib} = \delta \cdot (1 - N(c)),$$

where δ is a time interval in the range of a minute.

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 our model of the *Inside/Outside* strategy a new courier type is introduced for processing orders from the outside regions. These "outside" 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. Orders from the outside regions are not allocated according to the above rating function, which did not display satisfying results. Instead each order is assigned to the courier with the least detour and inactive couriers are prioritised.

The three models were implemented making use of the Java-based discrete-event simulation framework DESMO-J (see [21] and www.desmoj.de) and its agent-based extension FAMOS [14] both developed at the University of Hamburg. FAMOS offers the possibility of graph-based spatial modelling as well as behaviour modelling with executable state charts. The simulations are driven by empirical order profiles of the participating courier firms totalling 5 days. Since these data include information on order allocation, profiles of respective courier fleets could also be extracted.

3.5 Parameter Fitting

The parameters of the rating function – especially the factor w for weighing the utilisation dependent threshold – are crucial for valid courier behaviour. Due to the availability of information on order allocation those parameters were carefully calibrated. For this purpose simulations were run with each order being assigned to the courier who delivered it in reality. The results were compared to further simulations using the rating function for order allocation. Exemplary results of this compari son concerning diverse output measurements are shown in Figure 4.

	Daily distance (km)	Revenues (€/km)	Utilisation (%)	Order delivery time (min)
Bikers				
Empirical order allocation	47.7 (25.4)	1.80 (0.43)	68.0 (17.0)	46.7 (32.5)
Allocation by rating function	46.1 (16.9)	1.65 (0.34)	65.4 (6.1)	47.9 (28.2)
Motorised couriers				
Empirical order allocation	91.4 (44.6)	1.12 (0.45)	64.4 (18.3)	
Allocation by rating function	91.3 (32.1)	1.15 (0.28)	59.1 (14.7)	

Fig. 4. Comparison of empirical and simulated order allocation in 4 simulation runs. The first three measurements are averaged over the courier fleet, the order delivery period over the set of orders. Standard deviations are stated in brackets ([16] p. 40)

As expected, the best approximation was obtained by weighting the bikers' utilisation (w_{Bike}) stronger than that of motorized couriers (w_{Car}), whose decision-making is less influenced by physical fatigue.

We complemented the manual calibration procedure with automated calibration runs using the DISMO system [6] for distributed simulation-based optimisation, again an extension of the DESMO-J framework mentioned above. Starting from random values a genetic algorithm varied the parameters w_{Bike} and w_{Car} with respect to an objective minimizing the difference between several output measures[3] of the empirical and simulated order allocation. The simulation runs for the automatic calibration were performed during one night on a cluster of about 20 SUN workstations in parallel and led to similar results as the more time-consuming manual calibration [2].

The new logistic concepts also contain degrees of freedom that are critical to the functioning of the system. The effect of different hub numbers and locations as well as region sizes and organisation of shuttle service should be investigated in future simulations. The results of the *Hub and Shuttle* model presented below are based on a "common sense" placement of hubs dividing the central city area into three main regions. Two shuttles consort in line haul starting from the same hub in opposite direction. In the *Inside/Outside* model the city area is divided into a central "inside" region and six adjacent "outside" regions with reasonably uniform distribution of orders. The hub is placed at a prominent location downtown. Depending on order volume, 4 to 7 motorised couriers are assigned to each outside region.

3.6 Experimental Results of the Agent-based Simulation Study

The analysis of the different logistic strategies' economic, ecologic and social impact concentrates on three measurements in the first instance. The total motorised distance is considered as an indicator of ecologic quality and the mean order delivery time as a measurement for economic benefit. The distribution of the couriers' revenues provides an indication of a policy's expected social acceptance.

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[3] The objective considered sum and standard deviation of total distances covered by the couriers as well as mean and standard deviation of order delivery times.

Fig. 5 (left) shows a comparison of the total motorised distance with order profiles from 5 different workdays. Contrary to our primary expectations the distances covered in the *Hub and Shuttle* model are noticeably larger than in the status quo. This might be due to the fact that the investigated order profiles do not fit the selected regions and hub positions well since only about 25 percent of orders meet the conditions for transport via the hub system. Therefore 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. In contrast 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. Possibly a more detailed dimensioning of region layout and courier assignment could improve the effect.

From Fig. 5 (right) showing a comparison of mean order delivery times averaged over 5 workdays it becomes obvious that both new policies display extended durations for consignments processed via the hub. Since only 30 percent of the consignments are concerned and the remaining deliveries are even accelerated in the *Inside/Outside* model the trade-off might be acceptable. In both new strategies the couriers' average revenues per kilometre are raised by about 0.3 € due to the new accounting scheme and increased bundling ([16], p. 46).

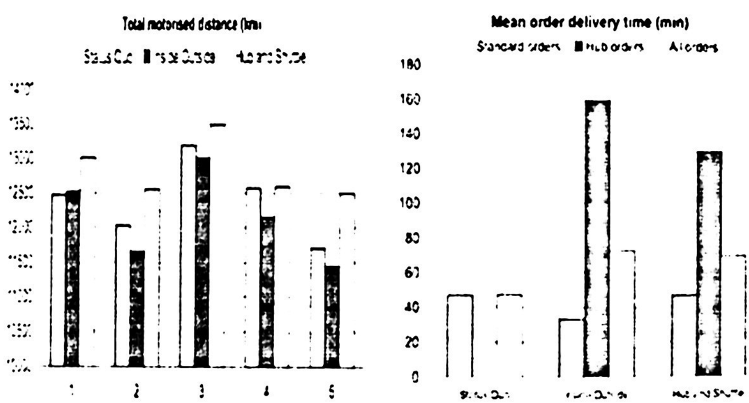

Fig. 5. Comparison of ecologic and economic benefits of the new logistic policies ([16], p. 45)

7 Conclusions

In this contribution in the context of sustainable Environmental Informatics we introduced an agent-based model of city courier services as a tool for analysing alternative logistic concepts which meet requirements of sustainable development. Simulations were run to compare the existent organisation of typical courier services with two new logistic concepts based on hubs. Concerning ecological measures like the total motorised distance the *Inside/Outside* strategy shows a reasonable improvement compared to the status quo. More detailed dimensioning of the policy's degrees of freedom might further enhance the effect. This will be accomplished in future experiments making use of the distributed system DISMO [6] based on the DESMO-J simulation framework in Java.

It turns out that agent-based simulation methodology is a powerful tool for modelling sustainable logistic systems in Environmental Informatics.

References

1. Avouris, N., Page, B. (eds.). Environmental Informatics – Methodology and Applications of Environmental Information Processing. Kluwer Academic Publishers, Dordrecht, Netherlands (1995).
2. Bachmann, R., Gehlsen, B., Knaak, N.: Werkzeuggestützte Kalibrierung agentenbasierter Simulationsmodelle. In: Schulze, T., Schlechtweg, S., Hinz, V. (eds.): Proceedings of the 2004 Conference on Simulation and Visualisation, Magdeburg (2004) 115-126.
3. Bossel, H.: Modeling and Simulation. A. K. Peters, Wellesley Publ. (1994).
4. Deecke, H.: Stadtkuriere – Unterschiedliche Simulationsszenarien in MOBILE. Internal report, Technical University of Hamburg-Harburg, Hamburg (1997).
5. Ferber, J.: Multi-Agent Systems: An Introduction to Distributed Artificial Intelligence. Addison-Wesley, Harlow (1999).
6. Gehlsen, B., Page, B.: A Framework for Distributed Simulation Optimization. In: Peters, B.A., Smith, J.S., Medeiros D.J., Rohrer, M. W. (eds.): Proceedings of the 2001 Winter Simulation Conference, Arlington, VA, USA (2001) 508-514.
7. Gnauck, A., Heinrich, R. (eds.): EnviroInfo 2003 - 17th. International Conference Informatics for Environmental Protection (Cottbus, September 24-26, 2003), Metropolis Publ., Marburg (2003).
8. Guariso, G., Page, B. (eds.): Computer Support for Environmental Impact Assessment. IFIP Transactions B-16. North-Holland, Amsterdam (1994).
9. Hilty, L..M.., Page, B., Radermacher, F.J., Riekert, W.F.: Environmental Informatics as a new Discipline of Applied Computer Science. In Avouris, N., Page, B. (eds.). Environmental Informatics – Methodology and Applications of Environmental Information Processing. Kluwer Academic Publishers, Dordrecht, Netherlands (1995) 1-11.
10. Hilty, L.M. : Umweltbezogene Informationsverarbeitung – Beiträge der Informatik zu einer nachhaltigen Entwicklung. Habilitation thesis. University of Hamburg, Hamburg (1997)
11. Hilty, L.M., Martinssen, D., Page, B. : Designing a Simulation Tool for the Environmental Assessment of Logistical Systems and Strategies. In: Guariso, G.; Page, B. (eds.): Computer Support for Environmental Impact Assessment. IFIP Transactions B-16. North-Holland, Amsterdam (1994) 187-198.
12. Hilty, L.M., Page, B., et al.: Object-oriented Specification of Models and Experiments in Traffic Simulation. In: Denzer, R. et al. (eds.): Environmental Software Systems, Vol. 2., IFIP 2nd International Symposium on Environmental Software Systems (ISESS '97), British Columbia, Canada, Chapman & Hall, London (1997) 335-342.
13. Hilty, L.M., Meyer R., Ruddy, T.F.: A General Modelling and Simulation System for Sustainability Impact Assessment in the Field of Traffic and Logistics. In: Rautenstrauch,

C., Patig, S.: Environmental Information Systems in Industry and Public Administration. Idea Group Publishing, Hershey, PA (2001).
14. Knaak N., Meyer, R. Page, B.: Agentenbasierte Simulation mit einem objektorientierten Framework in Java. In: Tavangarian, D. Grützner, R. (Hrsg.): Simulationstechnik – 16. Symposium in Rostock, September 2002. Erlangen, SCS European Publishing House (2002) 247-252.
15. Knaak, N., Meyer, R., Page, B.: Agent Based Simulation of Sustainable Logistic Concepts for Large City Courier Services. In: Gnauck, A. R. Heinrich, R. (eds.): EnviroInfo 2003 - 17th International Conference Informatics for Environmental Protection (Cottbus, 24.-26. September 2003), Vol. 1, Metropolis Verlag, Marburg (2003) 318-325.
16. Knaak, N.., Meyer, R., Page, B., Deecke, H.: Agentenbasierte Simulation nachhaltiger Logistikkonzepte für Stadtkurierdienste". Department for Computer Science Report 260, University of Hamburg, Hamburg (2004).
17. Page, B.: Environmental Protection as a Challenge to Applied Informatics. A Workshop Introduction. In: Aiken, R. (ed.), Information Processing 92 – Proc. 12th World Computer Congress, Madrid, Spain, 7-11 Sept. 1992, Vol. II. Elsevier Sc. Publ.(1992) 595-604.
18. Page, B.: Environmental Informatics – Towards a new Discipline in Applied Computer Science for Environmental Protection and Research. Inv. Paper , International Symposium on Environmental Software Systems – ISSES 1995. Penn State University, Malvern, June 1995. Chapman&Hall (1995) 3-22.
19. Page, B., Hilty, L.M.: Umweltinformatik als Teildisziplin der Angewandten Informatik. In: Page, B., Hilty, L.M.: (eds.), Umweltinformatik, Handbuch der Informatik, Vol 13.3., Oldenbourg Verlag, München-Wien, 2nd Edition .(1995) 15-31.
20. Page, B., et al.: Computer-based Support for LCA's and Company Ecobalances Using Material Flow Networks. In: Alef, K. et al. (eds.): Information and Communication in Environmental and Health Issues. ECO-INFORMA '97, Vol . 12 (1997) 179-191.
21. Page, B., Lechler, T., Claassen, C., Objektorientierte Simulation in Java mit dem Framework DESMO-J. Libri Publ., Hamburg (2000).
22. Page, B., Neufeld, E.: Extending an object oriented Discrete Event Simulation Framework in Java for Habour Logistics. International Workshop on Habour, Maritime & Multimodal Logistics Modelling and Simulation – HMS 2003, Riga, Latvia, Sept. 2003, Riga Technical University (2003) 79-85.
23 Radermacher, F.J., Riekert, W.F., Page, B., Hilty, L. M.: Trends in Enviromental Information Processing. In: Brunnstein, K.; Raubold, E. (eds.): Applications and Impacts. IFIP Transactions A-52. North-Holland, Amsterdam (1994) 597-604.
24. Smith, R.G.: The Contract Net Protocol: High Level Communication and Control in a Distributed Problem Solver. IEEE Transactions on Computers 29, 12 (1980) 1104-1113.
25. Page, B., Mack, J., Monitoring the Development of Environmental Information Systems on the Federal and State Level in Germany – A Documentation on the WWW. In: Proc. ECO-INFORMA '96 – Global Networks for Environmental Information. Nov. 1996, Lake Buena Vista, Florida (1996) 689-694.
26. Page B., Rautenstrauch, C.: Environmental Informatics – Methods, Tools and Applications in Environmental Information Processing. In: C. Rautenstrauch; S. Patig (Eds.) Environmental Information Systems in Industry und Public Administration. Hershey, PA USA (2001), 2-11.
27. Möller, A., Rolf, A., Page, B., Wohlgemuth, V.: Foundations and Applications of Computer Based Material Flow Networks for Environmental Management. In: C. Rautenstrauch, C.; Patig, S. (eds.) Environmental Information Systems in Industry und Public Administration. Hershey, PA USA (2001) 379-396.
28. Page, B., Voigt, K.: Recent History and Development of Environmental Information Systems and Databases in Germany, Online Information Review, Vol. 27, No. 1 (2003) 37-50.

29. CERN (ed.): Sharing. Proc. EnviroInfo 2004 - 18th International Conference Informatics for Environmental Informatics (Geneva, Oct. 21-23, 2004), editions du Tricorne, Geneva (2004).