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Towards an agent-based modelling approach for the evaluation of dynamic usage of urban distribution centres

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Abstract

Previous modelling attempts show that theoretically the urban distribution centre appears to be successful in many cases, which is in sharp contrast with the real world showing the fact that only 15 out of 200 urban distribution centres are running after 5 years. It can be concluded that modeling approaches do not seem to predict well with respect to the feasibility of urban distribution centres. The main policy measures that are expected to contribute to the successful functioning of the urban distribution centres are toll (requirements) (road pricing), providing operational subsidies and application of time windows inside the city. The potentially supportive role of these policies will be analysed more detailed by obtaining more insight into the dynamic behavioural interaction between stakeholders in city logistics such as freight carriers, retailers, urban distribution centre and municipality. Policy experiments with a multi-agent model have shown their value for understanding the dynamic behaviour between stakeholders.

Keywords: Urban consolodation center; agent-based modelling; dynamic pricing; evaluation

1. Introduction

In recent decades cities have been getting larger and becoming denser, which put tremendous increase of demand for business deliveries and passenger transport. The increased importance of environmental

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and social impacts of such issues adds additional dimensions to the city's problem. Therefore efforts are made to improve the traffic flow inside the city. Passenger transport is investigated relatively well inside the city (Huschebeck & Allen, 2005)[1], but a gap in knowledge is present on the freight transport inside the city (Van Duin & Quak, 2007)[2]. Freight transport contributes an estimated 10% - 30% of the traffic flow in various cities (Ministry of Land Infrastructure and Transport Japan, 2010)[3] (Crainic *et al.*, 2009)[4], but an estimated 40% in pollution and noise (COST321, 1998)[5]. One of the proposed policy measures, besides toll-roads and time-windows for trucks in the inner city, is the urban distribution center (UDC) (Dablanc, 2007)[6]. The urban distribution center is a promising concept, where the load of entering trucks is transferred to new trucks to increase the load factor and allow for easier time-windowed operation (e.g. by avoiding traffic jams) (Quak & de Koster, 2009)[7].

The main benefits of UDC's are (Huschebeck and Allen, 2005)[1]: reductions in the number of vehicle trips, reductions in the number of vehicle kilometres, and better utilization rates for vehicles. A higher load factor in the city can decrease harmful effects associated with city logistics. The main concern is the financial viability of the centre. In practice the UDC concept has failed due to stakeholder behaviour as freight transport itself is under high pressure with strong competition and Just-In-Time delivery systems (Germain & Droge, 1996)[8]. Unsuccessful business cases behind many UDC's led to unhealthy financial outcomes where the continuity of operations depended on government subsidies or heavy regulatory measures (van Duin *et al.*, 2010)[9]. Despite that many *ex ante* evaluations, indicated that UDC's would be financially feasible (e.g. Marcucci and Danielis, 2008)[10] only 15 out of 200 centres evaluated *ex post* were still running after 5 years (Browne *et al.*, 2005). Additional value added services can potentially boost the income of the UDC, but collaboration between all involved actors is necessary to secure demand, which make operations complex. The main critical success factors for UDC's as known from the literature are presented in Table 1. Business cases behind UDCs, investigated based on Cost Benefit Analysis (van Duin *et al.*, 2008)[11](van Duin *et al.*, 2010)[9], showed all very low financial viability, with a strong need for governmental subsidy.

Table 1. Critical success factors for an UDC (Marcucci and Danielis, 2008) [10], (Browne *et al.*, 2005) [12]

Critical success factors for the UDC
Location in/near the city
Subsidy collection
Collaboration with shipper and freight carriers
Financial viable
Service cost of the UDC
Access permit cost
Delay in delivery time
Distance of the parking bay from the shop

The main policy measures, which contribute to the successful functioning of the urban distribution centre, are tolls, provision of subsidies and time-windows- and access regulations inside the city. The potential supportive role of these policies will be analysed in more detail in this research by obtaining more insight into the dynamic behavioral interaction between freight carriers, retailers, UDC operators and municipalities.

Former research (Holguin-Veras, 2008)[13] (Quak, 2008)[14] has shown its value with respect to the understanding the behavioral reactions between freight carriers and municipalities. For example Holguin-Veras (2008)[15] doubts whether pricing is an effective policy instrument to organize freight transport in such a way that it results in a more balanced use of the limited infrastructure. Holguin-Veras (2008)[15] explains why pricing schemes do not fully affect the parties paying for transport: this is caused by imperfections in the freight transport market due to contractual limitations and poor interaction between different actors. The receiver usually determines the conditions of transport, e.g. time or date (see also Quak, 2008[14]). The carrier in turn only has contacts with the receiver at the delivery, because the receiver sets the conditions at the time it orders at a shipper. Since transport is usually only a very limited part of the price that the receiver pays the shipper for the ordered products, the receiver hardly notices a price signal of the road pricing scheme. Especially for-hire carriers hardly change their behavior due to road pricing (Holguin-Veras, 2008)[15].

Our main research question addressed here is as follows:
"What is the impact on urban distribution center usage of changing traffic conditions, dynamic pricing strategies and/or variations in operating schemes?"

In order to answer this question the following (sub)questions were addressed:

1. Which alternative models exist to evaluate city logistics and UDC processes including the behaviors interactions between the different agents involved?
2. What policy measures contribute to the successful functioning of the UDC and what are their individual impacts?

Section 2 contains a brief literature review on city logistics modelling, which will answer the first (sub) research question and provide practical knowledge on modelling approaches as well as a theoretical framework for the stakeholders. Section 3 specifies the developed multi-agent model, chosen to capture the complexity of individual behaviours from the perspective of societal objectives. Various modelling components like vehicle routing which were already present at Kyoto University were adapted for this model. Section 4 describes the experiments with this model to answer the second (sub) question. Section 5 concludes the paper with the main findings of this research.

2. Extending the modelling paradigms

Before the 1990's urban goods movement, modelling was generally based on costs (transport and facility costs) (Ogden, 1992)[16], but later a shift towards policy oriented modelling took place (Routhier, 2006)[17]. In city logistics models the general approach is to first estimate commodities or trucks origins and destinations. Next, vehicle routing calculates the optimal route for the required goods or destinations. In the next step further influences of traffic conditions can be taken into account in a traffic calculation and finally output parameters are generated. Policy-oriented modeling tries to understand urban truck movement under the influence of various government policies and adds the policy instruments to the city logistics model and completes the model with respect to social impacts. The latest generation of models extends the policy-oriented modeling approach with dynamic interactions or negotiation between agents and allow us to study of the dynamic behaviour of actors, reacting on policies, to observe and analyse effects on sustainability and economic/social aspects.

Fig. 1 shows an outline of the basic city logistics model. We elaborate on the current state-of-the-art in the different model stages in the remainder of this section.

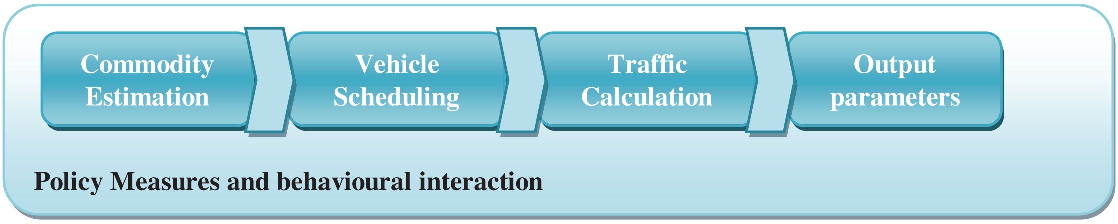


Fig. 1. Framework of model layout in City Logistics modelling

In order to estimate the impact on traffic flow, first commodity or vehicle estimations need to be made as input for the model (Muñuzuri and Cortés, 2009)[18]. Here the transported commodities can be estimated on socio-economic demographic parameters of various sectors, as 81% of total trucks trips inside the city are for distribution and purchases (Russo and Comi, 2004)[19]. With the vehicle calculation the amount of trucks is estimated based on the delivery information of the various store types present in the sector as for example a pharmacy has different delivery characteristics as a supermarket with fresh products (Muñuzuri and Cortés, 2009)[18].

With this information vehicle routing is performed to estimate truck movements. This can be done with various algorithms (Wang and Holguín-Veras, 2008)[20]. The grid and time windows have to be taken into account to include effects of rush hour (Woudsma, 2001)[21]. Here a representation of an actual city can serve as the basis of the grid or a virtual grid can be used to investigate effects and modelling behaviour (Nakamura *et al.*, 2008)[22].

The results from vehicle routing can directly serve as the impact on traffic flow or as input for large traffic simulators. Currently, Intelligent Transport Systems to contribute to real-time enhanced trip planning are investigated with these simulators (Taylor, 2004)[23], (Tseng *et al.*, 2008)[24], (Taniguchi and Shimamoto, 2004)[25]. The output parameters of the model are generally represented with social, environmental and economic scale by most authors (Taniguchi *et al.*, 2001)[26], (Patier and Browne, 2009)[27]. Social output is for example the reaction of the urban inhabitants in complaints about noise or traffic jams or the behavioral reaction of truck drivers to road pricing (Holguin-Veras, 2008)[15]. For environmental output harmful emissions like CO_2 or noise are taken as indicators (Figliozzi, 2011)[28]. For economic output the profit or turnover of freight carriers are used or financial output of other actors. This information can then be used for cost/benefit analysis as in van Duin *et al*. (2008)[11]. With these output parameters the impact of various policies can be investigated. In most of these models the individual stakeholders' perspectives were not taken into account and a general society perspective was adapted (in contrast to Wisetjindawat *et al*. (2007)[29] and Zargayouna *et al*. (2008)[30]). In these static situations (constant cost/demand/traffic flow) a global optimum is sought, but not the actual impact on routing is estimated for various agents. Therefore there is a desire to use a multi-agent model and find out if (and under what dynamic conditions) this promising concept of the urban distribution centre can contribute to enhanced city logistics.

Policy measures & behavioral interaction.

Policy measures aimed at, for example, reduction of environmental impacts can be evaluated by comparing various scenarios (including a reference case). Recent evaluation studies concerned the presence of an urban distribution centre and toll roads (Russo and Comi, 2010)[31], (Browne *et al.*, 2005)[12]. These measures influence the total model and are therefore represented as a separate shell around the model. An evaluation of different policies is given by Russo and Comi (2010)[31].

Our problem focus shows some similarity with the Integrative Freight Market Simulation approach by Holguin-Veras (2002)[32]. This approach intends to provide an approximation to the processes that take place in real life through different agents, in which: *producers* create or transform the commodities that are demanded elsewhere; *consumers* utilize products and raw materials created by the producers, for either personal use or as input to production processes; *shippers* arrange for carriers to transport the commodities from places of origin to their destinations; while the government is divided into a *regulatory body* and a *traffic management center (TMC)* that provides real time traffic information and exercises traffic control. However the modelling part differs completely because Holguin-Veras[32] estimates the provision of transport services assuming and solving a Cournot-Nash market equilibrium model and estimates the routing patterns with heuristics that ensure satisfaction of the Cournot condition and the other system constraints (which is similar to our approach despite the Cournot condition).

In our research the behavioral interaction is implemented in a multi-agent model. With a multi-agent model individual stakeholder behavior and actions are explicitly modeled, which in turn has impact on the overall outcome of the model. More information on multi-agent systems can be found in Weiss (1999)[33] and Wooldridge (2009)[34]. With these models for example the effect of price settings by freight carriers on the global outcome can be estimated (Tamagawa *et al*., 2010)[35], (Roorda *et al*., 2010)[36]. Another example is the implementation of residents complaining after experiencing high noise levels. With a multi-agent modelling these individual choices and reactions are included in the model. Also learning behavior and reaction time can be included (Watkins and Dayan, 1992)[37]. Further development of specific stakeholder modelling had led to the auction concept in (van Duin *et al*. 2008)[38], but also game theory and other negotiation techniques can be included to imitate human behavior (Anand *et al*., 2010)[39].

3. Specification of the multi-agent model

There are 5 types of agents, namely freight carriers, a UDC, trucks, retailers and roads. The municipality is considered as an agent specifying its policies and collecting the feedback information from the road network. There are also two types of dummy agents, namely the streets and nodes, which are needed to perform calculations at this model scale/size. The multi-agent model is described schematically in Fig. 2, where agents and flows are represented. The trucks, roads and retailers are purely reactive agents (i.e. these agents have no goal and just reply when they are asked). The UDC and freight carriers are objective function agents (i.e. they strive for a goal). In the model the collaboration between shippers and freight carriers is assumed to be perfect as they act as one agent. The agents in the model behave purely rational to financial and/or added value motives determined per specific stakeholder.

As shown by the legend in Fig. 2 interaction among the agents is based on:

- Goods, which have
  - a place of demand (x and y coordinate) ;
  - a volume (in the unit size of 100 parcels);
- Information, which can be
  - travel speed information from roads (or other patches) to trucks;
  - UDC fee (in Yen);
  - Travel costs and time between two nodes in order to calculate the optimal route of the Freight Carriers and the UDC (in Yen, respectively hours);
- Money, which has
  - An amount in units of Yen paid for the logistics service;
- NOx emission, which has
  - An amount in units.

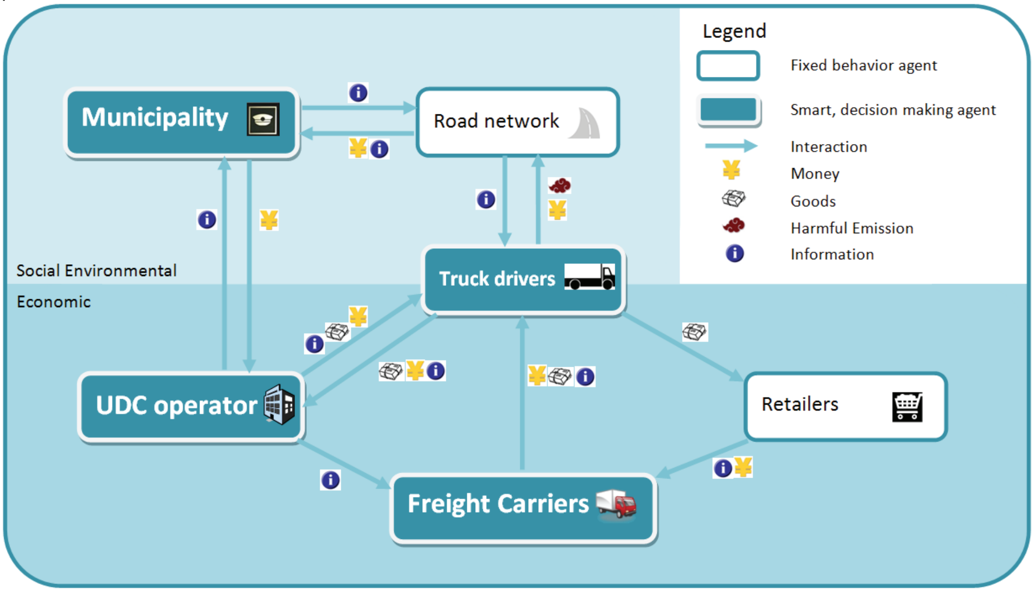


Fig. 2. Schematic representation of the agent interaction

Goods are transferred between trucks and Freight-Carrier (FC) terminals, UDC terminal or retailers. Information is transferred between roads and the following agents: streets, FC terminals, UDC terminal and trucks. Nodes transfer information to or from FC terminals, UDC terminal and streets. Trucks exchange information with FC terminals, UDC terminal and roads. Lastly roads present information to the FC terminals. Money travels between trucks and FC terminals or UDC terminal and between trucks and roads. Also money flows between FC terminals and the UDC. NOx emission is emitted by trucks and collected by the roads.

3.1. Agent description

Freight carrier. Besides demand information, which contains the number of goods demanded and the location, the freight carrier collects the UDC fee information and network travel conditions. With this demand information the freight carriers perform the vehicle routing. The vehicle routing is a VRPTW-F solved with a genetic algorithm. After performing the vehicle routing the freight carriers have generated a best route for all their trucks. In this route the departure times of the trucks and the order of the destinations are contained. At the time of departure, the truck is generated and send out by the freight carrier. After the trip execution the empty trucks return to the freight carrier terminal reporting their toll costs and km count.

The decision to use the services of the UDC is based on a (route) cost based choice mechanism in which is calculated whether it is cheaper to deliver the goods themselves or to drop all the goods at the UDC. The idea is that individual trucks represent small companies offering freight service to a certain area of the city. These small companies compete fiercely on price, and do not have the facilities to combine efficient deliveries themselves and therefore accept many times small load-factors. Therefore the hypothesis is formulated that within this competitive market segment the usage of a UDC can add to economic and environmental benefits.

Terminal agent. At the start of the program the UDC fee is set by the user. During the day trucks arrive with goods for specific destinations at the UDC (demand). Vehicle routing on the current demand is performed based on an early delivery scheme, a fixed time delivery scheme or just when a truck is full. This vehicle routing problem is also a VRPTW-F solved with the genetic algorithm (similar to the Freight Carrier). After their trip execution the empty trucks return back to the UDC terminal reporting their toll costs and km count.

Trucks. Trucks are generated by either one of the freight carriers or by the UDC. The trucks stay on the road and on crossings decisions for directions are made based on destination and traffic congestion. The truck sets its speed every 2.5 minutes with information from the road it is driving on. The truck keeps on the road (and crossings) by checking where it is heading. When it is heading for something, which is not a road (or crossing) it will change direction. The truck can drive either to the UDC, where it will drop all its goods, or it can drive to several retailers where the truck delivers the appropriate goods. After delivery (of 1 tick) it continues to its next destination. The final destination is always the original terminal. During driving the truck emits NOx at every time step. When the truck enters the city, it can be requested to pay toll to the road. Trucks keep track of their traveled distance. The truck receives a route from his freight carrier or UDC. It has to follow the customer order, but it is free to choose the route in between (fixed order variable route).

*Streets and nodes.*The nodes are present at the crossing of the roads and the streets link these nodes. The streets request travel time and cost information from the road segments. The nodes use the Dijkstra algorithm to calculate the cheapest paths to all other nodes in the system. At the start of the day the roads reset their NOx. At the end of the day, the average speed per time phase from today is taken as the current average speed per time phase for the next day. During the day the roads collect NOx from the trucks and reduce their speed when more rucks are present on their road segment.

Retailers &Municipality. At the start of a day 10 randomly selected retailers place an order. During the day the retailers will receive their orders by trucks straight from the freight carrier or the UDC. At the beginning of the day the municipality sets the average congestion rate and toll rate. At the end of the day the municipality collects the NOx emission from all the roads per time phase.

Fig. 3 shows the input and output parameters of the model. The service cost of the UDC and subsidy are under investigation with the model. The fee setting for the UDC can be dynamic or fixed at certain levels. The congestion rate can have three levels (low, medium or high (corresponding with an average speed of 18 km/hour, 15 km/hour and 13 km/hour respectively). Access costs in the form of toll to the city centre will be a policy measure to investigate. The toll can be set to 0 Yen, 400 Yen and 800 Yen. The UDC delivery scheme can be early delivery scheme, fixed time delivery or full truck delivery scheme. The first delivery scheme is that the freight carriers drop their goods at the UDC early in the morning (before 9:00), thereby giving the UDC the time for the whole day to deliver. This allows optimal routing for the UDC as it can be done for the whole set of goods of that specific day. The second delivery scheme allows freight carriers to drop the goods at the UDC before 14:30, narrowing the time for UDC delivery and requiring vehicle routing before all the goods are present. The latest scheme is more realistic and more complex from the UDC point of view, while providing additional benefit for the freight carriers of flexible drop-off. Per delivery scheme 360 runs are performed. Subsidy can ranges from 0% subsidy on the fee price up to 50%.

The multi-agent model contains a genetic algorithm for solving the truck routing (truck drivers) and variable demand locations (the retailers). Both elements cause variability in the output. The output is recorded in the number of UDC deliveries, delivery costs for freight carriers and the UDC, KM count, NOx emission and the UDC financial performance. In Table 2 the assumptions to the model are described.

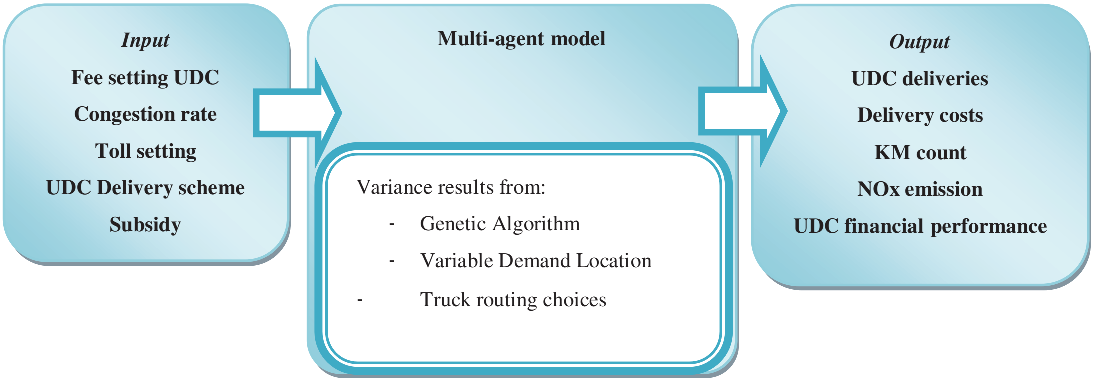


Fig. 3. Schematic representation of the multi-agent model

Table 2. Modelling assumptions

Modelling assumptions
Model parameters
Time scales in the model are 2.5 minute per tick and 1 hour per phase.
Active hours are between 6.00 am and 7.00 pm.
The model represents an inner city with diameter 5 km and per patch the size is 1/3 km.
General assumptions
There is only one type of truck.
There is only one type of good.
Model represents an artificial city.
Freight Carriers
Freight carriers travel with an average load factor of 42%.
Artificial high overload penalties exist.
Artificial high delay penalties exist.
The freight carrier uses the quick decision maker choice model to choose for the UDC.
UDC
Location of UDC is near entry of the city for freight carriers.
Artificial high overload penalties exist.
Artificial high delay penalties exist.
The UDC can have an early delivery, fixed time deliveries or full truck delivery scheme.
Trucks
Per 2.5 minute 1 unit of NOx is generated per truck.
Fixed truck costs are 15624 Yen per truck per day.
Variable truck costs are 1175 Yen per 10 minutes per truck.
Individual trucks from the terminals in the model represent small truck companies.
Trucks can choose the least congested road at a crossing.
Trucks use a (fixed retailer order) variable route scheme.
Road Network
Each road has an average speed profile during a day to include congestion
Retailers
Per retailer unit on average 100 parcels are delivered.
Municipality
There can be three different congestion levels in the city.
There are three states for toll.

The policy experiments with the dynamic UDC are modelled as the described agents and programmed in Netlogo (authored by Uri Wilensky in 1999). The model holds 3 freight carriers, an UDC, a municipality, variable trucks, 240 retailers and a road network of 300 individual road segments, where the inner-city also holds dummy agents in the form of 60 nodes and 114 streets.

3.2. Validation and verification

In the multi-agent testing a timeline sanity check is performed to see if the steps are performed in the correct order. Timelines for individual agents were checked with their expected behavior and the time line of the total model was verified. Parameters were changed for the UDC fees, for the congestion levels, and toll rates over a period of 1 day and 10 days.

4. Policy measures experimented

In our first experiment it was to be checked if an increasing UDC usage will lead to a decrease of both NOx emission and km count. The variance originates from the variable demand location, fee setting, solvation by the Genetic Algorithm and truck decision making. In this experiment there was no toll requirement, normal traffic congestion and no subsidy was given and the fixed time delivery scheme was used. This total data set consists of 2318 model runs.

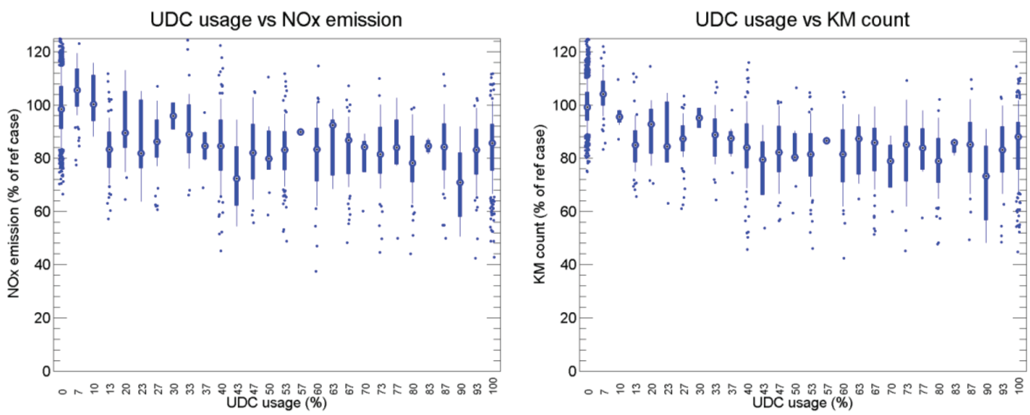


Fig. 4. (a) Correlationship between percentage of usage vs. NOx emission compared to the reference case (without UDC) (*left*) and (b) correlationship between percentage of usage vs. km count compared to the reference case (without UDC) (*right*).

The negative correlation for increasing UDC usage percentage with both NOx emission and km count is visible in the boxplot. Though the correlationship is not as strong as expected from literature, compared to the reference case without UDC deliveries, the NOx emission decreases with 19.0% and a standard deviation of 13.7 %, and the km count decreases with 18.8% with standard deviation of 12.9%. These results have been determined for the interval between 70% and 90% UDC usage. The fact that this is less than found literature is possible caused by the fact that the same truck size was assumed for both the freight carriers and UDC. Normally the UDC often has larger truck sizes (as indicated in an interview by Kim Hassal).

In the Table 3 all the policy experiments are shown for specific delivery schemes, congestions rates and various toll rates on the impact of the NOx emission and km count. Each presented input settings consists of 360 model day runs. From Table 3 it becomes evident that different delivery schemes or toll rates do not have a significant impact on NOx emission decrease or km count reduction. However, there is a significant difference between the low and high congestion rate for NOx emission both in mean and standard deviation. This could be expected however it is good to see the model represents the emission behavior of the trucks quite well.

Table 4 shows the impact on four UDC financial parameters. These parameters present the fee with the highest UDC income per day, the highest UDC income and the fee at the 80% and 20% UDC usage boundaries.

Table 3. NOx emission and km count information for various input settings

Delivery scheme	Mean difference NOx emission	Standard deviation NOx emission	Mean difference km count	Standard deviation km count
Various Delivery Schemes				
Early Morining	21.2%	10.6%	17.0%	9.1%
Fixed time Delivery	24.8%	11.3%	19.8%	10.5%
Full truck Delivery	24.2%	8.2%	18.5%	7.5%
Various Congestion Rates				
Fast	12.0%	15.7%	15.4%	13.4%
Normal	25.2%	15.0%	19.8%	14.4%
Slow	27.5%	9.5%	21.2%	9.2%
Various Toll Rates				
Null	25.2%	15.0%	19.8%	14.4%
Low	24.3%	11.7%	19.8%	10.9%
High	22.3%	12.5%	17.7%	12.3%

Table 4. Financial impact of various input parameters on 4 UDC parameters

	Optimal fee (Yen)	Maximum income per day (Yen)	80% usage boundary (Yen)	20% usage boundary (Yen)
Various Delivery Schemes				
Early Morning	70	-370.000	50	100
Fixed time Delivery	60	-300.000	55	105
Full truck Delivery	70	-320.000	40	100
Various Congestion Rates				
Fast	50	-430.000	40	80
Normal	60	-300.000	50	105
Slow	70	-200.000	80	110
Various Toll Rates				
Null	60	-300.000	55	105
Low	70	-300.000	55	105
High	70	-260.000	55	105
Various Subsidy Rates				
None	60	-300.000	50	105
25%	75	-150.000	65	130
33%	90	-3.400	80	160
50%	120	300.000	105	210

Similar to earlier research experiences (Van Duin & Quak, 2008)[11] it will be hard to find a positive business case for a UDC. In the experiments the only positive business case for the UDC, which could be found, is based on a subsidy rate of 50%. For the optimal fee the fee with the highest average income per day was chosen. The fees are lower than prices indicated in literature (Ieda, 2005)[40]. Like Holguin-Veras (2008)[15] it can be observed that the freight carriers are insensitive for different toll rates.

4.1. Dynamic fees for urban distribution centre usage

In order to improve the financial model of a UDC it is interesting to investigate a dynamic fee for UDC usage. The experiments have been tested with model for five different fee scenarios shown in Fig. 5. During the day the fee increases due to the fact the opportunity to combine new loads efficiently into new routes decreases. The fee lines during the morning period from 8.00 am until 11.00 am remain flat since this is the best and most realistic moment of the day to collect the loads and plan efficient routes. After that period the chance of sending extra trucks into the town is more likely to happen. At the end of day, from 5.00 pm until 7 pm the price cannot increase anymore because it will not be competitive anymore compared to straight delivery.

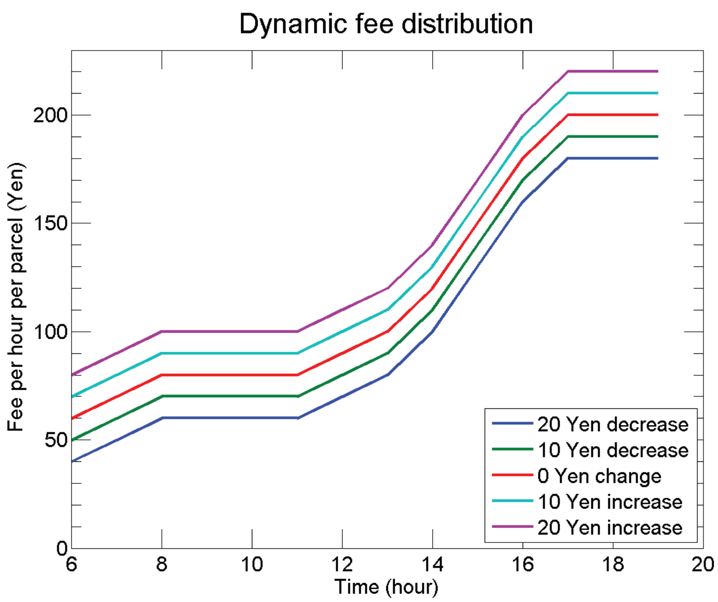


Fig. 5. Dynamic UDC fee profiles

For these scenarios the impact of NOx emission and km count reduction correspond to the reference case with no toll, no subsidy, fixed time UDC delivery scheme and normal congestion. The average UDC usage percentage is presented per fee setting. The mean and corresponding standard deviation for the UDC financial parameters are presented in Table5 per different fee setting.

The differences in mean of the UDC usage percentage are around or more than one standard deviation for the -20, 0, 10 and 20 dynamic fee settings. The 20 setting is not significantly different from any other fee setting due to the high standard deviation for the UDC income. In total 50 runs were performed.

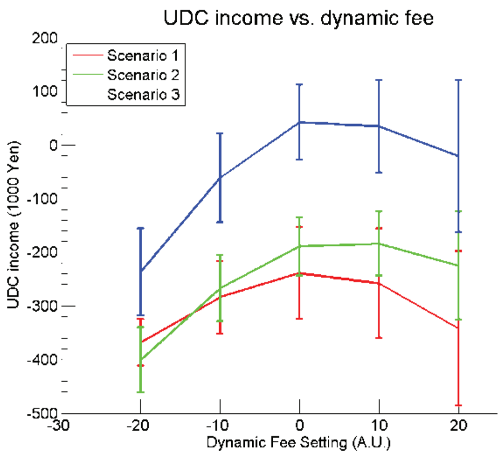
Table 5. Mean and standard deviation of the UDC parameters per dynamic fee setting

Fee setting	Mean of UDC usage (%)	Standard deviation of UDC usage (%)	Mean of UDC Income (Yen)	Standard deviation of Income (Yen)
-20	90	11	-368.000	43.700
-10	83	13	-284.000	67.400
0	79	12	-239.000	86.100
10	58	14	-258.000	102.000
20	46	7.6	-342.000	144.000

Our first experiments with dynamic fee profiles seem to provide promising results for the (-10/0/10)-profiles since the fact that the UDC income is almost significantly higher than the -300.000 Yen per day in the similar situation for fixed fee. However further and full evaluation of all possible dynamic fee settings is desired to find potential better dynamic fee settings.

4.2. Dynamic fees for urban distribution centre usage: Changing conditions

As a last research activity it is interesting to know whether dynamic fee setting for UDC usage would provide even better results in case of high congestion in the inner city. In the reference case (scenario 1) the congestion rate is normal, but the other scenarios have a high congestion rate. In all scenarios the toll rate is zero and the delivery scheme is fixed time delivery. In the last scenario (3) there is involvement of the municipality scenario by providing a subsidy of 33% of the paid fee. Fig. 6(a) shows the impact on the UDC income and Fig. 6(b) shows the UDC usage percentage displayed for different dynamic fees and for the various scenarios.



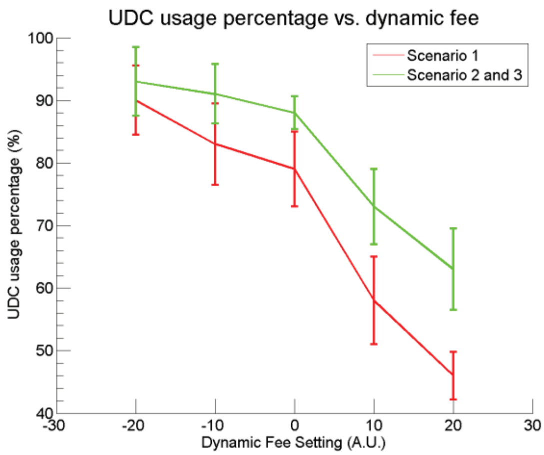


Fig. 6. (a) Income of the UDC vs. dynamic fee (*left*) and (b) UDC usage percentage vs. dynamic fee (*right*)

The UDC usage rate is the same for scenario 2 and 3 as the difference lies in the additional subsidy from the municipality. As expected the third scenario differs significantly from the first two scenarios with respect to the UDC income. The UDC income is the highest for the dynamic fee rates of 0 and 10.

Differences in UDC usage for the various fee rates are only significantly high at the dynamic fee setting 10 and 20.

Comparing the three scenarios there is no significant difference between the NOx emission or km count reduction and the freight carriers costs. For the UDC income there is a significant increase in the third scenario with respect to the scenarios. Also for the municipality there is a significant increase in costs in the third scenario. Since there is no significant decrease in NOx emission or km count between the second and third scenario, the municipality will need other incentives like social or corporate well-being associated with the UDC, before the municipality will participate in providing such high and long term subsidies.

5. Conclusions

In this paper we have addressed a modelling approach based on multi-agent modelling combined with vehicle routing and incorporating a dynamic usage of UDC and responsive behaviour of the involved carriers. Former studies (Browne *et al.*, 2005)[12] already have shown low financial viability of the UDC concept. However, we still believe that the UDC is a promising concept to reduce congestion and emission inside the city centre, but main concerns are the financial viability of the centre. The UDC can increase the load factor and allow for easier time-windowed operation (avoid traffic jams) (Quak & de Koster, 2009)[7]. A higher load factor in the city can decrease harmful effects associated with city logistics. In practice the concept has failed due to stakeholder behavior as freight transport itself is under high pressure with Just-In-Time delivery system (Germain & Droge, 1996)[8] and inadequate price setting. The unsuccessful implementation of any urban distribution centre makes self-sufficient operation impossible (van Duin *et al.*, 2008)[11]. In theoretical business case analysis the urban distribution centre appeared to be successful in many cases (Marcucci and Danielis, 2008)[10]. This difference between theory and practice could be caused by the fact that static representations use average values for calculation and thereby do not take statistical effects and individual choices into account. More precise understanding of the dynamics of local conditions in the inner cities and the interactive dynamics in the behavioral attitudes between the freight carriers, urban distribution center and the municipality is needed. The introduction of more dynamic mechanisms in this study encompasses variable traffic conditions and dynamic demand locations. Dynamic UDC usage was tested by various delivery schemes and dynamic fee settings during the day.

As first attempt to introduce and understand the dynamics a multi-agent model with vehicle routing (solvation based on the genetic algorithms) was developed. Simulation-experiments were setup with 3 freight carrier terminals, 1 UDC centre, 12 - 18 trucks, 240 retailers and a road network (including 300 roads, 114 streets and 60 node agents). Conclusions are based on these experiments.

An increase of a UDC usage corresponds to decrease of NOx emissions and kilometers in the inner-city. The NOx emission decreases with 19.0% with standard deviation of 13.7 % and the km count decreases with 18.8% with standard deviation of 12.9% in comparison without a UDC. This seems not in line with the 60% reduction of vehicle kilometers in Kassel (Kohler, 2004)[41], however the outcomes seems to be realistic considering a maximum average load factor of 42%. Different delivery schemes or toll rates do not have a significant impact on NOx emission decrease or km count reduction. There is however a significant difference between the low and high congestion rate of 1 standard deviation for NOx emission. Subsidy providence doesn't impact NOx emission or km count, only for UDC financial viability. The only positive business case for the UDC is with a subsidy rate of 50%, which indicates the complexity of generating a positive business case for an UDC and in line with the research findings (Browne *et al.*, 2005)[12](van Duin *et al.*, 2008)[11]. To enhance UDC financial performance the dynamic UDC fee was tested. The fee varies during the different hours of the day. Five cases were tested by increasing the general dynamic fee curve with -20, -10, 0, 10 or 20 Yen per parcel. Significant differences between various dynamic fee settings are present. The fact that the UDC income is almost significantly higher than the -300.000 Yen per day in the similar situation for fixed fee is encouraging. Still further evaluation of all possible dynamic fee settings is desired to find potential better dynamic fee settings and/or experiments with dynamic auctions (van Duin *et al.*, 2007) [38]since the financial viability fails.

As a last experiment the traffic conditions have changed to highly congested. Comparing the scenarios there is no significant difference between the NOx emission or km count reduction and the freight carriers' costs. For the UDC income there is a significant increase when the municipality subsidies 33% of the UDC delivery price. Since no significant decreases in NOx emission or km count have been identified between the scenarios, the municipality will need to seek for other incentives like social or corporate well-being associated with the UDC, before the municipality will participate in providing such high and long term subsidies.

From this research it becomes that generating a positive business for a UDC is highly challenging. For a UDC to be profitable, it seems to be necessary to receive subsidy permanently or/and to find other value added activities like for example pre-retail activities to increase profitability. When collaboration in the form of subsidy is needed, other incentives are required for the municipality to participate.

To our opinion multi-agent modelling has shown its value for understanding the dynamic multi-stakeholder behavior, i.e. the stakeholder interactions between freight carrier, shopkeeper, urban distribution center and municipality. Further development of multi-agent modelling will be continued in several city logistics case studies in order to develop an ontology to formalise city logistics problems and to setup a laboratory in which policy experiments can be executed (Anand *et al.*, 2010)[39].

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