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Quantifying the performance improvement potential of Foliated Transportation Networks

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Abstract

The purpose of this paper is to quantify the performance improvement potential of foliated transportation networks (FTN) compared to a traditional direct shipment network (DS) with respect to key performance indicators (KPI). The network models are evaluated through discrete event simulation. Input data and parameters have been drawn from a case company. The concept of FTN is shown to reduce the negative environmental impact of a transportation network through its implementation. This is the first study that quantifies the potential of FTN. Furthermore, the study is based on empirical data.

Keywords: Mixed model transportation; Discrete event simulation; Direct shipment; Hub and spoke; Transportation network performance evaluation.

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1. Introduction

In the context of inter-city general cargo freight transportation networks, there are two predominant network structures, namely, direct shipment (DS) and hub-and-spoke (HS) networks (Woxenius, 2007). A DS network is best utilized when the number of nodes in the network is limited, the demand for transportation in every connection is sufficiently high and the primary optimization parameter is time and transport work. On the other hand, a HS setup is preferred in a network with a vast number of nodes, where aggregation of demand is necessary to attain adequate flows and the primary parameter of optimization is resource utilization and coverage (Crainic, 2003).

Aside from the impact of empty haulage on the resource utilization of a transport network (McKinnon and Ge, 2006), the match between the distribution of transport need and network structure and the discrete property of freight transportation also significantly impact the performance of a transportation system (Lumsden et al., 1999). These technical inefficiencies in the road bound general freight transportation systems have significant negative external effects which make efficient use of the physical

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resources of interest for society as a whole (European Commission, 2003). The negative impacts referred to include pollution (e.g., NO_X, HC, CO_2, particles etc.), noise pollution, congestion and traffic hazards.

A conceptual model that attempts to address these concerns is Foliated Transportation Networks (FTN). FTN is a hybrid model that aims to improve the physical performance of a transportation system by combining the two predominant network structures, i.e., direct shipment (DS) and hub and spoke (HS) (Bjeljac and Lakobrija, 2004, Persson and Lumsden 2006). It is stipulated that by foliating the two structures (i.e., DS and HS), and by dynamically planning, controlling and optimizing the distribution of goods and resources between the two sub structures, strengths of the individual setup will be amplified at the same time as their weaknesses diminish, resulting in better system performance than any single one on its own (Kalantari and Sternberg, 2009; Persson and Lumsden, 2006; Persson and Waidringer, 2006). However, to date, no study has actually quantified this hypothesized potential.

The purpose of this paper is to quantify the performance improvement potential of foliated transportation networks (FTN) compared to a traditional direct shipment network (DS) with respect to selected key performance indicators (KPI) that are identified to express the physical performance of a transportation network. The KPI include fill rate, number of trucks, transport work and traffic work. This research takes the perspective of the transportation service provider and is based on empirical data from the domestic Swedish general cargo freight transportation service provider.

2. Transportation networks

Transportation networks are commonly described in terms of nodes and links (Lumsden, 2006). The transportation network designs can be divided into two principle categories: direct shipment or hub and spoke (Crainic, 2002; Lumsden, 2006). In reality, one only seldom finds any pure systems (Crainic, 2002) and, also in theory, variations of the same two themes exist (Lumsden, 2006; Woxenius, 2007).

2.1 Direct Shipment vs. Hub and Spoke

In a direct shipment network all nodes are interconnected with direct relations. Direct relation means that the transport is dedicated (Crainic, 2003; Lumsden, 2006). The only nodes involved in the coordination of the transport and the consolidation of goods are the origin and destination nodes. Goods are not consolidated along the way and the transportation is independent of other O/D pairs (Woxenius, 2007). The DS network is best utilized when the number of nodes in the network is limited, the demand for transportation in every connection is sufficient and the primary optimization parameter is time and flexibility.

A DS setup by default affords the shortest time in transit since the goods always travel directly, taking the shortest way and without any additional stops, consolidation operations or handling. A DS setup requires a greater number of resources, e.g., trucks in the system, leads to a lower transportation frequency and its performance is dependent on sufficiently large volumes, i.e., the demand in each relation must match the capacity reasonably well in order to achieve acceptable levels of the resource utilization rate.

Conversely, in a HS setup, all the nodes are only interconnected with a hub resulting in an additional coordination and consolidation/deconsolidation step (Crainic, 2002) which means that deliveries seldom run the shortest way. A hub network creates a larger spatial coverage and high transport frequency for the network since the volume that flows between the O/D pairs does not need to be very large to be included (Woxenius, 2007). Other advantages of the HS setup are a high resource utilization rate, both regarding time and capacity, a lower number of resources in the network and more leveled flows (Lumsden et al., 1999). A HS setup is preferred in a network with a vast number of nodes, where aggregation of demand is necessary to attain adequate flow and the primary parameter of optimization is resource utilization and coverage (Bryan and O'Kelly, 1999).

2.2 Foliated Transportation Networks

Bjeljac and Lakobrija (2004) describe FTN as a DS network where only “full” units are sent directly and all units that are not full are consolidated in the HS layer of the system (Figure 1). In this setup, even though they regard the network as consistent of two different layers in its management, the physical network is the same for both layers.

Lumsden et al. (1999) describe a similar approach where the basic structure is a HS setup that can be shortcut with occasional direct relations when possible, i.e., when there is enough demand to fill a whole unit in any O/D pair relation.

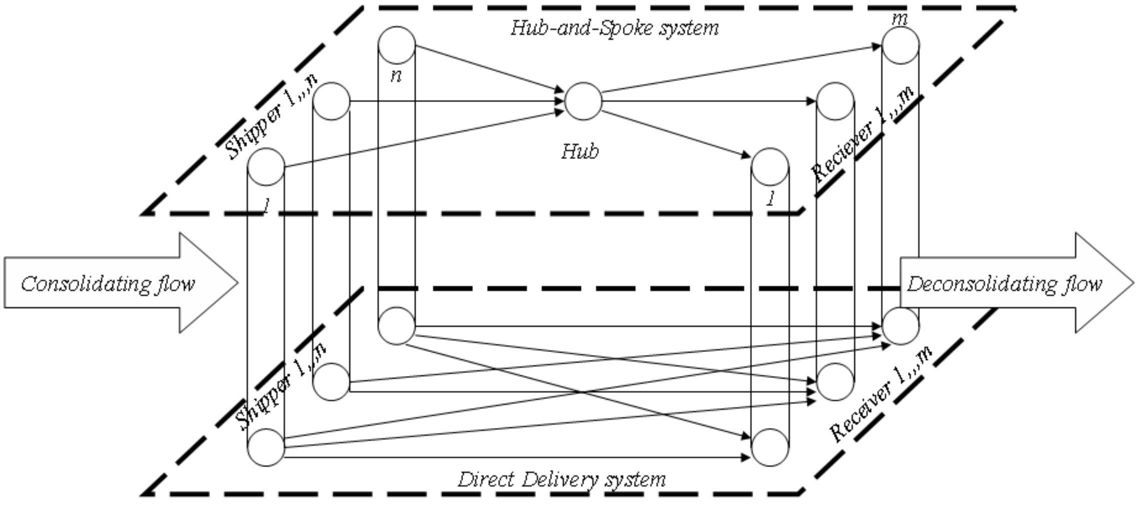

Figure 1: Foliated Transportation Network model.
Source: Persson and Lumsden, 2006.

In the Bjeljac and Lakobrija (2004) model the hub volumes are identified after the departure of all DS trucks, i.e., the decision to send a sub set of the total volume in a O/D pair to the hub is made after it is operationally apparent that the remaining volume is not sufficiently large to fill a whole unit. In contrast, Persson and Lumsden (2006) suggest a setup where the hub volumes are identified in advance and are sent first in order to improve the system’s performance from the perspective of total time in transit. The argument is that because the required transit time through a HS network is inherently longer compared to a DS setup, it would, on a system level, be beneficial to afford that portion of the goods the longest time window by shipping it first. This approach would, however, require an unprecedented level of accuracy regarding operations planning and control when it comes to identifying the hub volumes in advance (Kalantari and Sternberg, 2009).

3. Methodology

This study makes use of empirical data collected from a representative company to serve as input and configuration parameters in an experimental discrete event simulation model. The Swedish general cargo freight market is almost entirely dominated by two major companies, each covering the country with their own network of terminals. This offers support for the argument to use empirical data from one company in a general model, i.e., without actually modeling the specific system of that company. In this study, one of these companies has been chosen based on availability.

The models represent an ideal typical direct shipment network and a foliated transportation network (FTN) in order to experiment and compare the performance of the different network setups. FTN, as described by Bjeljac and Lakobrija (2004), will be modeled and compared with DS in order to quantify its potential. A model of FTN as described by Persson and Lumsden (2006) will also be used in order to investigate the sensitivity of the identified potential with regard to planning and control precision.

The choice of simulation was an obvious one based on the fact that the systems in question are complex and dynamic where experimentation in a real system would be too expensive at the same time that no satisfactory analytical solution could be found (Law and Kelton, 1991). The concept of FTN has not left its conceptual cradle, which means that an implementation of the system cannot yet be found to study. Simulation allows for testing new procedures, policies or methods (Banks *et al.* 2001). In this study a discrete event simulation model is used.

This study relies on both quantitative as well as qualitative empirical data. The qualitative data has been collected by the corresponding author through semi-structured interviews and observations. The data has mainly been used for purposes of system configuration, guidance in the collection of quantitative data, input data analysis and validation of the models. A number of informants have been interviewed, ranging from senior managers, middle managers, internal consultants and senior sales representatives to operative personnel as well as ERP-system designers and maintenance staff.

The quantitative data has been provided by the company on request. In order to improve the reliability of the study, different data sets with different resolutions have been obtained from different sources within the company. The primary sources of data used in the models have been provided by a data management specialist from a special unit in the company. The data set has contained the daily volumes (payload expressed in kg) in each relation of the network. A sample of eight consecutive weeks (40 working days) has been drawn from the provided data. The data has been verified through a comparison with aggregated (i.e., total volume in each relation aggregated for the entire period) data provided by senior management for the same period of time, and historic data provided by middle management at one of the terminals. The data has also been verified through cross check with qualitative data collected in interviews and during on site observation.

The chosen period of time is considered representative and the total flow exhibits signs of high stability. This is in line with the other sources of empirical evidence i.e. interview materials and historical quantitative data aside from the sample. The empirical data in the sample has been used for deciding the physical network setup, i.e., the number and position of terminals, and to create theoretical distributions for the daily volume of goods in each of the relations of the network. The performance of the two different network models under study has been measured through the set of KPI presented in Table 1.

Table 1: Key Performance Indikators (KPI).

KPI	*Description*
Number of trucks	The minimum number of trucks required to fulfill the transportation need of each cycle.
Average system fill rate	The ratio of the total amount of goods and the total loading capacity (C) of the fleet of trucks deployed.
Traffic work	Truck capacity multiplied by the distance traveled.
Transport work	Amount of goods shipped multiplied by the distance traveled.

3.1 Delimitations

The focus of this study is on the long-haul transport portion of the domestic Swedish general cargo freight transportation operation of the reference company. The system limit for this study is drawn at the departing gate of the origin terminal and the receiving gate of the destination terminal. System boundaries are drawn around the overnight guaranteed domestic network of the company. Aspects regarding order reception, goods collection and distribution to end consignee have been excluded. An introduction of the mentioned additional aspects would also be at the cost of the generality of the models because the specific company’s business model, product range and customer profiles would play a major role on the output of the system.

4. The simulation study

The empirical data collected from/provided by the reference company has been used not to simulate the operations of the specific firm in and of itself but rather to provide representative input parameters for the comparison of two general models, i.e., a direct shipment network and a FTN. Also a third model was developed for purposes of sensitivity analysis. The simulation study follows the steps proposed by Law (2001a) and the model is created in Simul8[1] simulation software. The input data analysis, model

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[1] Simul8 version 15.0 © copyright 1993-2008 Simul8 corpration. http://www.simul8.com Free student version.

descriptions and validation aspects of the simulation study will be discussed in detail below.

4.1 Input data analysis

The sample data (8 working weeks of detailed data) was checked for extreme values, autocorrelation, variance and other anomalies that would be in contrast to the other sources of data, i.e., the aggregated data for the same period, historic or qualitative data (Leemis, 2004). None of the tests revealed any reason to doubt the correctness of the data provided. Using the criteria of overnight service guarantee as defined by Bjeljac and Lakobrija (2004), 15 terminals were selected from the network, yielding an O/D matrix of 210 relations.

A randomly selected sample of 10% of the relations were selected and tested for fit for theoretical distributions. These tests for goodness of fit were performed using a statistical software called Stat::Fit[2]® (Law, 2001b). In the same fashion the theoretical distribution that best fit the size of the single shipments was estimated. The tests provided no reasons for rejecting any of the selected distributions.

4.2 Model description

Three different models were developed: a direct shipment model, a FTN model as described by Bjelajc and Lakobrija (2004) and a FTN model as described by Persson and Lumsden (2006). The first two models are used to quantify the potential impact of the FTN on the KPI as compared to DS and the third model is used to quantify the impact of the planning and control error on the identified potential of FTN. This error is the result of attempting to identify the hub volumes first as Persson and Lumsden (2006) prescribe as opposed to the setup used by Bjeljac and Lakrobrija (2004) where the hub volumes are identified and handled last. Prognosis error refers to the variation in fill rate due to the discrepancies between forecasted need for capacity and the actual outcome on a truck-by-truck basis (Kalantari and Sternberg, 2009). The prognosis, i.e., the identification of the hub volumes, created based on placed orders and not projected demand.

In all three cases the network structure, i.e., number of terminals and the distance in between them, has been mirrored from sampled data without revision. Goods in all setups have been modeled as weight measures with direction, i.e., an origin and a final destination. The weight dimension has been used to model the truck capacities. However, the empirical data is a composite measure of weight and volume expressed only in kg, i.e., payload (see 3). This has allowed for the assumption that truck capacity can/should reasonably be utilized up to 100%. This notion is supported by qualitative data and respondent validation.

In all setups, goods are served by the FIFO principle, thus there is no sophisticated selection criteria that would make optimization in grouping different consignments to a particular loading unit possible. This is in contrast to a real world system where some selection, however unsystematic or arbitrary, is bound to be feasible.

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[2] Stat::Fit® version 2 © copyright 1995-2001 Geex mountain software corp. http://www.geerms.com Free student version.

4.3 Direct shipment model specifics

In the DS setup, each run starts with the random generation of total volume per relation and day based on the theoretical distributions extracted from the empirical data. The volume in each relation is subsequently divided in individual consignments according to the distribution of the consignment size.

Trucks are then loaded with consignments according to the FIFO principle and are shipped to their destinations. During the run, total number of trucks, average fill rate of the trucks, average system fill rate, total volume of goods, total transport work and total traffic work are collected.

4.4 FTN Comparison Model Specifics

Bjeljac and Lakobrija's (2004) FTN has been modeled for the main experiment. In the FTN models, there is one terminal designated as the hub. For the decision of which terminal will act as hub, a gravity model (Lumsden, 2006) is used. The process of random generation of goods volumes in every direction and its division to individual consignment is identical in all three setups. The difference between the FTN and DS setup appears first when the goods are to be loaded on trucks and shipped. In every relation before a truck is to be loaded, a test is performed to see whether the remaining amount of goods is more or less than what would fit on one truck. If the amount is more than the capacity of one truck, the goods are loaded and shipped directly, identical to the DS setup.

However, when the remaining amount of goods in one relation, after shipping the amount referred to above, is less than one truck's capacity, the goods are loaded onto trucks that have the hub terminal as the intermediate destination. Also, all the goods destined for the hub terminal as their final destination are loaded on the same trucks without discrimination or separation. The "hub-trucks" depart then after all DS trucks have left their terminals of origin.

The contents of the hub-trucks are upon arrival to the hub terminal unloaded, sorted and then reloaded onto trucks and sent to their final destinations. The goods that have the hub terminal as their final destination are not further handled in the model. The trucks arriving at the hub terminal are also utilized for shipping goods from the hub terminal to the final destinations.

4.5 FTN Model created for sensitivity analysis

In the model that, among others, Persson and Lumsden (2006) present, the hub volumes are to be identified and shipped first, before the DS volumes depart. This sequence is in reverse of the one defined in the model outlined by Bjeljac and Lakobrija (2004) where the DS volumes are shipped first and the hub volumes are identified by default. This reversal created at least two new sources of uncertainty that need handling.

For one, the identification of the hub volumes is done on the basis of a prognosis. The impact of the prognosis error is not known and quantified. In order to investigate the sensitivity of the results of the potential of FTN to these sources of uncertainty, a third model was created in accordance with the model description presented by Persson and Lumsden (2006). Secondly, the load composition on a specific truck, i.e., the order of loading, the mixture of different individual consignment and the physical properties of those consignments create an uncertainty regarding the operational outcome of the utilization rate of the physical capacity. This is true both for the hub volumes as well as, and primarily regarding, the DS volumes. This discrepancy is labeled and modeled as *loading error* in all three simulation models.

In this setup, the hub volumes are identified through calculation on the placed orders, i.e., the generated total volumes in each relation. The hub volumes are picked out based on the FIFO principle, and are consolidated and loaded on trucks and shipped to the hub terminal. The goods are unloaded, sorted and reloaded for further transport to their final destinations. Finally, the remaining volumes are processed and shipped in a fashion identical to the DS model description above.

4.6 Validation

Banks (1998) outlines eight different validation strategies for a simulation model. Some of the strategies are not applicable because they require testing the results in comparison to a historic outcome or a specific existing physical system. The models in this study are to be considered generally and are not a representation of a specific system, and two of the model setups simulate systems that are not yet extant. This limits the validation strategies that are applicable to face validation, sensitivity analysis and validation of conceptual model assumptions.

Face validation is implicitly performed throughout the modeling and execution of the simulation in iterative fashion and is largely due to the different role, expertise and level of involvement in the different aspects of the study on the part of the two authors. In addition, transportation and transportation research professionals have been consulted in the validation process. These experts are primarily not affiliated with the company that has provided the empirical data, because of the fact that the models are meant to be general and not a representation of a specific real world system.

The most extensive validation effort has been invested in the sensitivity analysis presented below (section 5). The results of the sensitivity analysis offer details about the sensitivity of the results to different major factors and conditions. The sensitivity of the results regarding the prognosis error was examined. Based on some counterintuitive results of the original runs, the impact of the fill rate of the last trucks was also explored.

Furthermore, the system input, conceptual model and run-model behavior has been compared to and confirmed by the broad range of qualitative data. The extensive input data analysis also provides support for the validity if the models (Sargent, 2004). The combined effort offers confirmation for the validity of the models. Any validation effort becomes more complicated when it regards system setups or policies that are yet not in effect. The implication of this condition will be discussed in detail in the sensitivity analysis part of this paper.

5. Experiment design

The main experiment designed for determining the potential of FTN via comparison with a DS setup is performed through a paired t-test of the results of 20 runs of the two models i.e. FTN according to Bjeljac and Lakobrija (2004) and a corresponding DS model. 20 replicates were deemed more than sufficient through iteration and with regard to the confidence interval of the results sought. It is likely that a smaller number of runs would also be enough. However, due to the fact that each set of replicates did not take more than one minute, no attempts were made to reduce the number of runs to the bare minimum. The aim of the experiment was to identify differences between the results of the two compared systems at the level of $p<0.01$ and to quantify those differences at the confidence interval of 99%.

5.1 Factorial Design for Sensitivity Analysis

The impact of the factors system setup, the number of terminals, variation of demand, loading error and truck capacity were examined in a two-level five-factor complete factorial design. The five factors were selected based on qualitative reasoning and previous results presented in the literature.

The system setup is introduced as a factor in order to test the validity of the results of the original experiment and to exclude the possible dominating impact of other factors on the results. The number of terminals was selected because the size of a network fit for an implementation of FTN has been discussed in previous research though without any definitive results (Hakimian and Zandi, 2009). The input data analysis revealed stable levels of demand. This has also been corroborated by quantitative historical as well as qualitative data. By including this as a factor, the importance of stable demand for obtaining the results from the original experiment could be considered. This is important in order to explore the validity of the outcome with regard to the stable demand that might be company specific. Because of the simplifying assumption of uniform fleet the truck capacity was deemed to warrant its inclusion in the factorial design (Kalantari and Lumsden, 2007). The factors and their levels are found in Table 2.

Table 2: Factorial design factors.

Factor	*High (1)*	*Low (-1)*
System setup (A)	FTN	DS
No. Of terminals (B)	15	8
Demand (C)	Empirical standard deviation	Empirical standard deviation +50%
Loading error (D)	U[0.95 , 1]	U[0.85 , 1]
Truck capacity (E)	40 ton	25 ton

The low levels for factors B and C are somewhat arbitrary. The values have been decided based on a notion of what is reasonable for the purpose of this experiment. The levels of the other factors all have been decided based on empirical inputs or existing theory. Factor D has been described with a uniform distribution, which Banks et al. (2001) names “the distribution of maximum ignorance”. No quantitative data has been able to be obtained in order to model the distribution. The selected distribution is not unreasonable even though no specific quantitative justification can be found in its support. Uniform distribution is recommended in cases such as these (Law and Kelton, 1991).

The result variables for this experiment are the ratio of total volume and the number of trucks (R1), the average fill rate (R2) and the ratio of total transport work and the total traffic work (R3). The reason for including two ratios is the fact that the number of terminals (factor B) affects the total amount of goods, the number of trucks and total distance traveled, rendering the two levels of that factor incomparable. By introducing a ratio, the relative indirect impact on the number of trucks and the distance traveled could possibly be revealed.

5.2 Last Truck Fill Rate

The FTN setups modeled here are based on the existing cited literature. In these no specific level of fill rate is determined for the decision to send the last truck through the different network layers, i.e., DS or HS. Based on this, any truck that is not 100% filled has been sent through the HS layer, i.e., via the hub terminal. Reviewing the results of the original experiment, this reveals a conceptual gap in the model. In reality, one would probably prefer to send a, e.g., 90% full truck directly instead of shipping it via the hub. The unutilized capacity may not warrant the additional time, distance and terminal handling operations that a hub detour would entail.

Based on this, the sensitivity of the results to the impact of different levels' fill rate would mean a truck's rerouting through the hub terminal has been investigated.

5.3 Prognosis Error Impact

In the model description of FTN presented by Persson and Lumsden (2006), it is required on the basis of prognosis to identify and ship the hub volumes before the direct volumes depart from their origin terminals. This approach inserts an uncertainty in the setup, the effects of which are difficult to foresee. Therefore, this aspect has been included in the sensitivity analysis of the results.

The outcome of the FTN model according to Persson and Lumsden (2006) has been compared to the DS model outcome with an incremental fix prognosis error. The error has been increased by increments of 1% from -4% to +15%. With this approach the impact of just the size of the prognosis error on the results has been clarified. It is, however, unrealistic to assume that a fixed systematic error would be sustained without correction. Therefore, the same sets of tests have been run with a randomly distributed error with an incrementally increasing standard deviation. A triangle distribution has been used for this end where the extremes have been increased in 20 steps to go from trig [0.9525, 0.95, 0.935] to trig [1, 0.95, 0.65]. The result of this analysis is meant to shine a light on the robustness of the results of the FTN with regard to the size and spread of the prognosis error.

6. Results

Throughout the presentation of the results, if nothing else is explicitly expressed, the number of replicates is 20. The results referred to are true at a significance level of $p<0.01$ and are quantified at the confidence interval of 99%. The main experiment shows that in the FTN setup the system level average fill rate of the trucks increased by 14.5% (±0.2), the minimum number of trucks required was reduced by 10.5% (±0.4), the total transport work increased by 15.2% (±0.5) and the total distance traveled was not affected compared to the DS setup.

Table 3: Results of the experiment.

	FTN potential (DS=100%)	*FTN potential (DS>75%)*	*Delta*
Average fill rate	+14.5% ± 0.2	+13.65% ± 0.23	-0.75% ± 0.11
Number of trucks	-10.5% ± 0.4	-9.60% ± 0.41	+0.95% ± 0.08
Transport work	+15.2% ± 0.5	+12.57% ± 0.45	-2.29% ± 0.08
Traffic work	No significant difference	-13.62% ± 0.44	-14.17% ± 0.16

However, when the fill rate of the trucks to be allocated to the DS layer was reduced to more than 75% instead of 100% the results were affected. The improvement potential regarding the number of trucks required and the average fill rate of trucks was marginally diminished at the same time as the total distance traveled was drastically reduced and total transport work was also marginally reduced (Table 3).

Table 4: Results of factorial design experiment.

Factor	*Volume/no. trucks (R1)*	*Average truck fill rate (R2)*	*Transport work/traffic work (R3)*
A	0,103911	0,072164	0,074589
D	0,047858	0,045098	0,045364
AB	0,026314	0,022663	0,020262
± K	0,003436	0,000706	0,000702

In the factorial design experiment factors A, D and AB have the highest impact on all three result variables consecutively. Factor A, i.e., the systems setup has by far the highest impact in all three cases. The system setup has twice the impact of factor D and almost five times the impact of factor AB (Table 4).

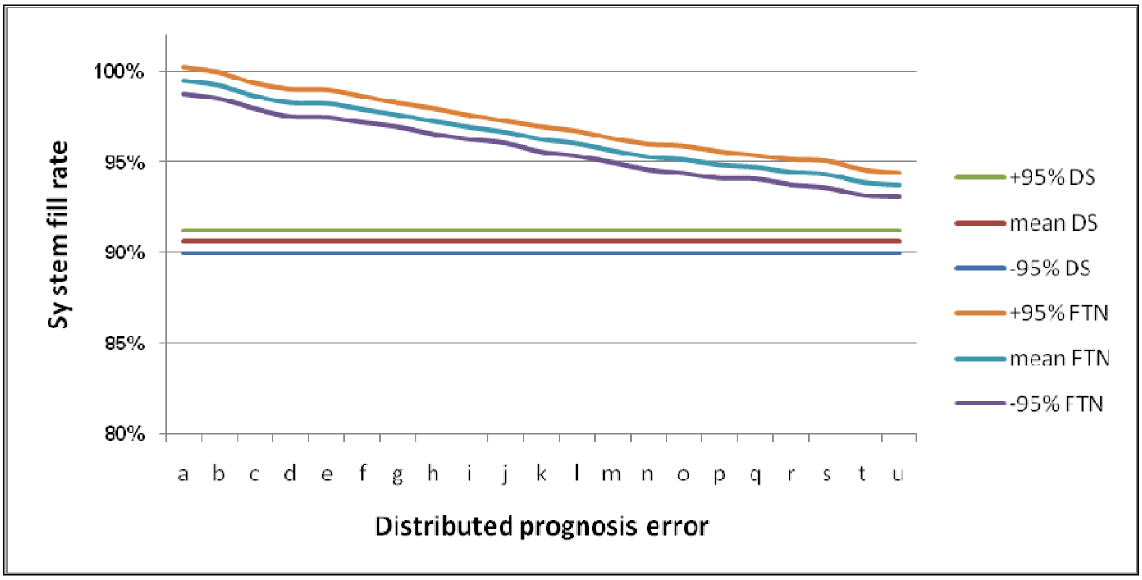

Figure 2: Impact of the distributed prognosis error on the average system fill rate.

The FTN system is shown to be fairly robust regarding the effects of the prognosis error where the error needs to reach unrealistic levels of size and spread before the FTN performance is lowered to the same level as the DS setup (Figure 2). This is true for all KPI except transport work where the FTN performance, in compliance with theory, is actually worse than DS. This robustness is identified even though the relation between prognosis precision and system performance is near linear. The robustness can be explained by the mere size of the improvement potential of FTN. This observation is in line with the main result of the factorial design analysis.

7. Conclusion

It is concluded that the performance improvement potential of FTN compared with DS with regard to the above identified KPI is relatively large. The sensitivity analysis confirms that the observed results are the impact of the introduction of the FTN setup and that this setup is fairly robust with regard to prognosis error. However, because of the relative strength of the impact of factor D, i.e., the loading error, it can be concluded that any setup is sensitive to how well truck capacity can be utilized operationally.

It is further concluded that the governing rules of FTN need to be developed in finer detail as the sensitivity analysis showed that simple manipulation with cut off values results in significant changes in the end results.

8. Discussion and future research

In this section the results are to be put in context as well as for general implications of them to be drawn out. It must be observed that there always exists a trade-off between fill rates and service level. In these experiments, this trade-off has not been addressed by means of ensuring 100% service level i.e. every transport order fulfilled over night. It is likely, and indeed the qualitative data from the reference company concurs, that in reality the transport provider would opt to reduce its service level in order to increase that utilization rates. The approach cannot be said to have biased the results, because the same conditions were set for all three of the models. However, this must still be taken into consideration because for systems were this tradeoff has yielded a better system performance it can be anticipated the introduction of FTN would increase the level of service whilst perhaps the impact would be less pronounced regarding the physical KPI.

Furthermore, cited previous studies as well as the study at hand explain the performance improvement potential of FTN by the load consolidation of the last trucks the cutoff fill rate cannot be achieved in every relation. This indicates that FTN would probably be best suited for systems where the volume of goods handled is neither very low or very high as compared to the size of the load carriers. For systems where the volumes are lower than at least one load carrier in every direction a pure HS system would be more appropriate. Conversely, as the size of the flows start to require a sufficiently large number of load carriers, the impact of consolidation aspect of FTN on the system level would start to dwindle. The upper boundary of this range for the

"Goldilocks system" that would benefit most from FTN is not treated in this study and should get some attention in the future.

On the same note, it was demonstrated that a simple adjustment to the static cut-off value for the fill rate of the last truck, yielded considerable positive dividends for the end results. This indicates that development and implementation of dynamic governing rules such as cut-off values for the last truck or other adapted network optimizing tools would presumably generate an even greater potential for FTN. In the opinion of the authors, this is the premier track for future research.

An incidental observation during the performing of the simulations were that roughly a quarter of the fleet was send to the hub, and subsequently redistributed in the network during the same cycle, in the FTN setups. The implications of this, if any, on the fleet management aspects of the system should generate future research attention.

Finally the reduction of the traffic work coupled with the reduction in the number of trucks in the system should lead to decreased negative environmental impact on the system level. This reduction is supposedly not linear, because of the discrete nature of a transportation system. The ramifications of FTN for a transportation systems environmental footprint ought to be studied in greater detail in future work.

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