Lecture Notes in Logistics
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Uwe Clausen
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Efficiency and Innovation in Logistics

Proceedings of the International Logistics Science Conference (ILSC) 2013

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Preface

The importance of logistics in all its variations is still increasing. New technologies emerge, new planning methods and algorithms are developed, only to face a market with a growing complexity and the need for weighting monetary costs against ecological impact. Mastering these challenges requires a scientific viewpoint on logistics, but always with applications in mind.

This volume presents up-to-date logistics research in all its diversity and interconnectedness. It grew out of the "International Logistics Science Conference" (ILSC) held in Dortmund in September 2013, which brings together leading scientists and young academics from nine different countries. The conference was jointly organized by the "Efficiency Cluster Logistics" and the "Fraunhofer Institute for Material Flow and Logistics". The Program Committee used a double blind review process to choose the 12 strongest contributions. The respective papers were then grouped in the four areas of *Sustainability Logistics*, *Intralogistics*, *Transport Logistics* and *Logistics Facilities*.

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International Logistics Science Conference 2013

The International Logistics Science Conference was held on September 4th, 2013 in the Westfalenhallen Dortmund, organized by the "Efficiency Cluster Logistics" and the "Fraunhofer Institute for Material Flow and Logistics." Information about this conference and follow-up events can be found on http://www.ilsc.eu/

Contents

Part I
Sustainability Logistics

Electric Mobility in Last Mile Distribution

Matthias Klumpp

Abstract Electric mobility is a major development trend and future expectation for transport and logistics, especially in the first and last mile context of modern city logistics concepts. Nevertheless, logistics research has been dominantly engineering research in this field and aspects of cost and resource efficiency have been neglected so far. This contribution outlines a concept for a cost and sustainability evaluation regarding the use of electric vehicles in last mile distribution schemes and therefore provides a first insight into the application business value of electric mobility concepts for logistics. The results show that electric vehicles will provide no "one-size-fits-all" solution but are reasonable only in specific segments due to their maximum payload and range restrictions as well as still very high purchase price levels. Moreover, especially small and medium sized logistics companies will refrain from this trend due to high risks and fixed system costs within overall logistics processes as well as regarding training requirements.

Keywords Electric mobility · City logistics · Sustainable logistics · Cost and sustainability evaluation

1 Introduction

Electric vehicles are expected to play an important role in future mobility and transport concepts [1, 2]—due to long-term resource shortages as well as the negative effects of traffic greenhouse gas emissions such as carbon dioxide and methane. Because the expected effects of climate change and the global threat to ecosystems are in particular attributable to the emission sources like "private transport, transport processes" [3, p. 13] the caused harmful environmental

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processes must be reduced at least in their impact. Common rethinking in terms of developing environmental awareness and the realization that sustainable development only works with the conservation of ecosystems have already begun [4]. The focus on sustainable development motivates companies to integrate the increasing ecological demand in their service and product cycles. In particular the logistics industry, as a major issuer of greenhouse gas emissions in large quantities, has understood the requirements of "practical implementation guidelines of green business strategies" [5, pp. 41, 42] and hence satisfies the demands of their industry and retail customers. In the logistics industry environmentally friendly and resource-efficient business activities are increasingly gaining in importance [6]. One feasible measure implementing this sustainability strategy in logistics could be the commercial use of electric vehicles.

But today research regarding electric vehicles is mainly addressing engineering questions. Only a minority of publications addresses information, infrastructure and logistics questions related to the introduction of electric vehicles [7–12]. This research suggests an evaluation of the use of electric vehicles in last mile distribution concepts in terms of two important perspectives—sustainability and cost efficiency:

1. *Cost efficiency*: Recent research suggests that there are many areas in logistics companies and processes with heavy adaption requirements when electric vehicles shall be used in last mile distribution [13].
2. *Sustainability*: The major question if especially the carbon dioxide emissions are reduced with electric vehicles instead of diesel-engined trucks is hard to answer as the current electricity production mix has to be taken into account. This mixture is differing heavily from country to country (even among the different German states) and also will be undergoing heavy changes due to the exit in nuclear electricity production in Germany in the next years. This perspective has to calculate the bottom line of CO_2 emissions per ton-kilometer in last mile distribution of electric vehicles compared to diesel-engined vehicles.

In order to combine these two perspectives, a field study deploying last mile transportation systems is used to evaluate these perspectives with extensive process mapping and process cost evaluation efforts. As a result structure the matrix in Fig. 1 is suggested in order to enable further research and transfer options for these results.

The EU and NRW funded research project 'E-Route' evaluates the *practical implications of electric vehicles* in last mile distribution processes with the project partners FOM Hochschule, University of Duisburg-Essen, Deutsche Post Bonn and NOWEDA Essen.

In this research setup Sect. 2 describes the necessary and expected changes in logistics processes, using i.e. an AHP evaluation among logistics experts. Section 3 described a draft calculation regarding the subsequent cost implications of these changes towards electric mobility in logistics. Section 4 outlines the sustainability implications and Sect. 5 combines these evaluation perspectives in the proposed evaluation scheme. The conclusion in Sect. 6 provides some further research implications and an outlook.

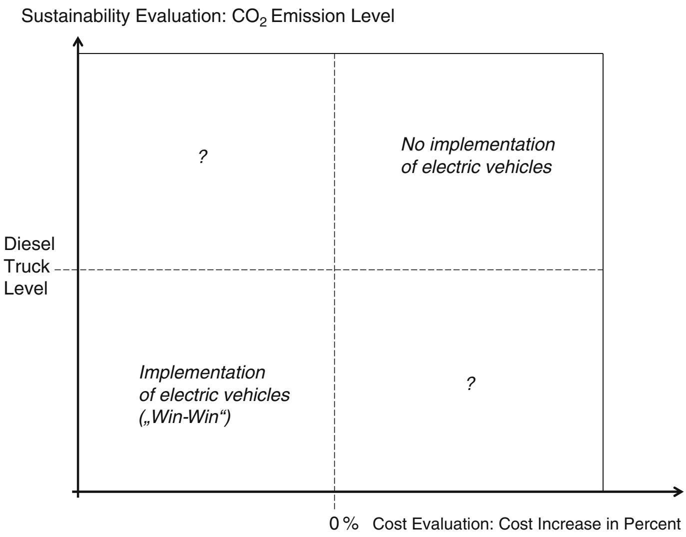

Fig. 1 Evaluation matrix for electric vehicles in last mile distribution

2 Logistics Process Changes

Currently logistics companies modernize their vehicle fleet. For example, the logistics service provider Deutsche Post DHL has expanded 10 % of its worldwide car pool to vehicles with innovative propulsion technologies. With regard to this, the use of electric vehicles (EV) plays a significant role [14].

A large number of challenges prevent a widespread use of EV in logistics today. For example the limited maximum range constrains the application fields, so that currently EV are only to be used for urban delivery trips. Especially in urban areas EV show a high potential in terms of an acceptable implementation of electric mobility [15]. According to this, the advantages of the EV are especially the noise-reduced and low emission transport. From today's perspective the use of EV, in particular when used in last mile traffic is reasonable and shall be scrutinized and implemented further.

To increase the use of EV, research efforts are driven in many ways, especially in engineering. In this field research is focused for example on the improvement of the battery technology for improving energy supply and increasing the range of the EV. From a business perspective the commercial launch and the use of the EV are prohibited by a lack of knowledge. Because of "limited resources" [16, p. 15] it is a challenge—particularly for small and medium-sized enterprises—to calculate the important operational adjustments and business investments necessary for electric mobility.

The objective is to investigate only the changes in costs and operational processes caused by the use of EV in last mile-distribution of logistic and trading companies.

The accomplishment is based on a simple-designed and practical investment analysis in terms of a comparative vehicle cost calculation. In the first step of this research the fundamental effects, concerning changes in costs, are shown by a comparison of a conventional diesel-engined vehicle versus EV. The second step indicates the specific cost changes for an exemplarily selected operational change area by using EV. This knowledge increases the transparency of costs for practitioners who seek an extension or conversion of the own fleet with EV.

In the course of first research activities operational change areas were identified and queried in an expert survey, using the method of Analytic Hierarchy Process (AHP). The analysis of the results showed that in particularly the core logistics processes like transportation and scheduling as well as transport goods and fleet management are relevant operational change areas by using EV. The high weighting of the operational change areas transportation and scheduling is caused by the restricted range of EV which requires an adjustment of the route and tour planning. The reason for the significance of transport goods is the limited payload of EV (Fig. 2).

Due to the different drive concepts arise, in the comparison of the two types of vehicles, significant differences in the payload. The EV is able to load 510 kg less than a comparable diesel-engined vehicle. To verify and extend the results of the expert survey, the processes of participating project partners were evaluated

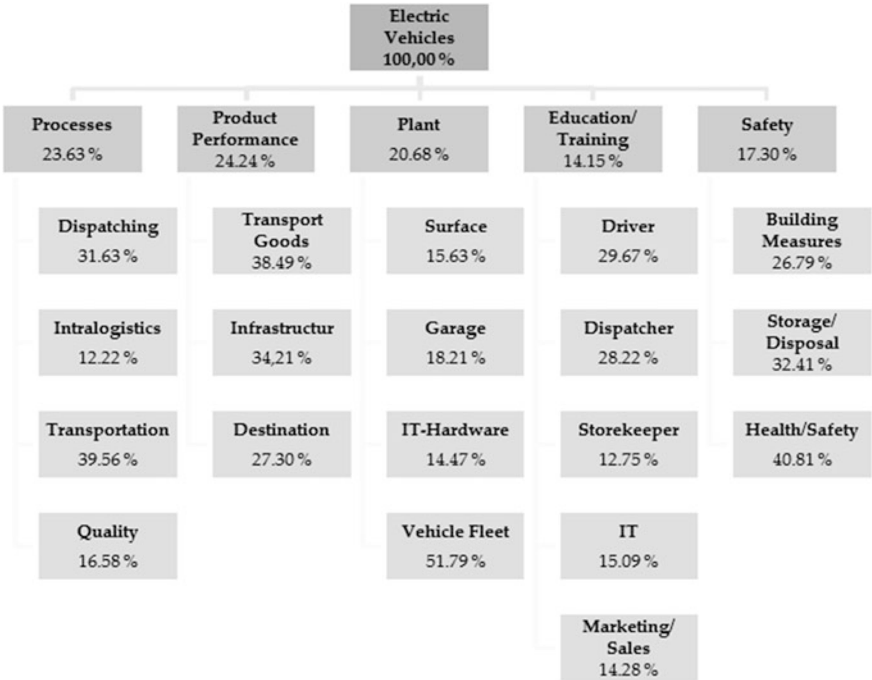

Fig. 2 Operational change areas: local weighting

further, with the goal to identify company-specific operational change areas by using EV. The findings of the affiliating processes complement the results of the expert survey with the AHP method.

3 Cost Implications

With regard to short-distance traffic in particular last mile-traffic, it is difficult to assign the costs to individual orders or shipments. The reason for this is the large number of different loading and unloading places. The transport costs for the forwarding services are therefore calculated at average costs based on a weight of 100 kg. Insofar the average costs for the price calculation per vehicle depend on the following facts:

- kilometre rate,
- daily rate,
- annual running performance,
- transported goods per account period [17].

The kilometre rate and the daily rate are due to the vehicle cost calculation. To calculate the kilometre rate different types of costs such as costs for fuel, tires or repair are used. These are costs that depend on usage. To determine the kilometre rate, the costs are divided by the annual running performance. The daily rate is calculated from the fixed costs, such as costs for drivers, vehicles and overhead, divided by the time. These costs arise in subject to the particular account period and are thus time-dependent [17]. To evaluate the cost effect of payload differences between diesel-engined-vehicles and EV, following assumptions were made in context of an exemplary calculation (Table 1).

For the diesel-engined-vehicles the assumptions in Table 1 base on technical data of a IVECO Daily and for the EV on technical data of the IVECO Daily Electric. The detailed calculation of the kilometre rate for both vehicles can be found in Table 2.

The purchase price of the vehicle as part of the depreciation is part of the annual vehicle cost accounting and is consulted to calculate the use- and time-dependent vehicle costs. With depreciation of light transport vehicles usually a high proportion of the time-dependent costs are applied. In this exemplary calculation

Table 1 Data for an exemplary vehicle cost calculation

	Diesel-engined vehicle	Electric vehicle
Purchase price	35,170 €	100,000 €
Running performance/day	80 km	80 km
Transported goods/day	800 kg	800 kg
Payload of the vehicle	Maximum 1.310 kg	Maximum 800 kg
Utilization/day	59 %	100 %

Table 2 Kilometre rate diesel-engined vehicle versus EV

	Diesel-engined vehicle Ct/km	EV Ct/km	Cost benefit (+) or cost disadvantage (−) for EV Ct/km
Depreciation	5.86	16.67	−10.81
Fuel costs	17.02	7.43	−9.59
Lubricant costs	0.17	0.00	−0.17
Tire costs	2.67	2.67	0.00
Maintenance costs	10.00	5.00	−5.00
Miscellaneous costs	0.50	0.50	0.00
Kilometre rate	**36.22**	**32.26**	**−3.95**

therefore 30 % of the annual depreciation amount is attributed to the usage-based vehicle costs and 70 % were assigned to the time-dependent vehicle costs. The usage-based vehicle costs are included in the calculation of the kilometre rate, the time-dependent vehicle costs are part of the daily rate.

To calculate the fuel costs, the expenses for diesel and electricity base on the specific average values of the year 2012. At that time the price for diesel was 147.8 Cent per litre and for electricity 14.02 Cent per kilowatt-hour [18, 19]. The costs for lubricants of diesel-engined-vehicles are recognized with 1 % of fuel the costs. Costs for lubricants will not be charged for EV, because this type of vehicle does not use lubricants [20, pp. 29–33]. The tire costs are taken into account with 400 € per tire and an annual running performance of 60,000 km for both vehicle types. In the example 20,000 km annual running performance is used as a basis for the exemplary calculation.

Hence one-third of the tire costs are recognized. For repair and maintenance for the diesel-engined vehicles 10 cents per kilometre are estimated. An electric engine consists of about 200 engine parts and has significantly fewer components than an internal combustion engine with more than 1,400 parts. Therefore, the EV is considerably less maintenance. For repair and maintenance 5 cents per kilometre are recognized for the EV. The miscellaneous costs are equal for both vehicles.

The higher daily rate for EV is based in particular on the higher purchase price. In addition to this it is believed that the use of EV needs higher qualified personnel, especially for driving activities as well as for planning and scheduling. So for EV higher costs for drivers and commercial personnel will be accepted. To calculate the cost effects of the payload differences, the vehicle costs per 100 kg of a diesel-engined-vehicle and an EV is first calculated (Tables 3 and 4).

At a touring range of 80 km and a shipping weight of 800 kg, a cost difference stems from the previous exemplary calculations, compared between a diesel-engined vehicle and an EV. In comparison the EV is per tour 3.11 € more expensive than the diesel-engined vehicle (Table 5). The utilization of the EV here is 100 %. The utilization of the diesel-engined vehicle is 59 %. With a full utilization of diesel-engined vehicle is resulted in a cost difference of 12.89 € per tour.

With regard to the expert survey of operational changes the criterion transport goods, as a subcriterion of product performance has been identified as particularly

Table 3 Costs per tour per 100 kg of a diesel-engined vehicle

Vehicle costs	Calculation	Vehicle costs/tour/100 kg
Kilometre-based costs	80 km/tour × 0,3622 €/km = 28,98 €/tour	(28,98 €/tour: 1.310 kg) × 100 kg = 2,21 €/100 kg
Time-based costs	172 €	(172 € × 1.310 kg): 100 = 13,13 €/100 kg

Table 4 Costs per tour per 100 kg of an EV

Vehicle costs	Calculation	Vehicle costs/tour/100 kg
Kilometre-based costs	80 km/tour × 0,3226 €/km = 25,81 €/tour	25,81 €/tour: 800 kg) × 100 kg = 3,23 €/100 kg
Time-based costs	200 €	(200 € × 800 kg): 100 = 25,00 €/100 kg

Table 5 Comparison of costs between EV and diesel-engined vehicle

	EV	Diesel-engined vehicle	
	Transport weights per tour		
	800 kg	1.310 kg	**800 kg**
Kilometre-based costs per tour	3.23 €	2.21 €	3.62 €
Time-based costs per tour	25.00 €	13.13 €	21.50 €
Total costs per tour	**28.23 €**	15.34 €	**25.12 €**
Utilization	**100 %**	100 %	**~59 %**

relevant for use of EV. Due to the limited payload of the EV for these vehicles a potential cost disadvantage is resulted. Firstly there is a risk of a constraint service due to the limited payload. Thus, transport goods with a high specific weight are less suitable for transportation by EV. Secondly, the higher transport costs have a negative impact on operating profit.

In the exemplary cost account the largest identified cost factor is the depreciation which base on the purchase price and which are used to calculate the kilometre rate. Half of the purchase price of the EV consists of costs for the batteries. In addition to that EV are produced in small series. With increasing mass production, as well as product and process innovations plus economies of scale, there is the possibility of reducing costs of the EV [21]. In terms of decreasing purchasing costs, the costs for depreciation will be reduced. In this way, the negative effect of the limited payload of EV is alleviated and the cost gap between diesel-engined vehicles and EV is smaller.

For further evaluation of cost implications the following distribution of last mile delivery tours compiled by logistics experts from the research project E-Route will be used, dividing the tours into distinctive distance and weight classes (distribution matrix in percent, Fig. 3). This is highly relevant as EV have only limited payload and rang capabilities—with major impacts on the logistics cost structures as shown above.

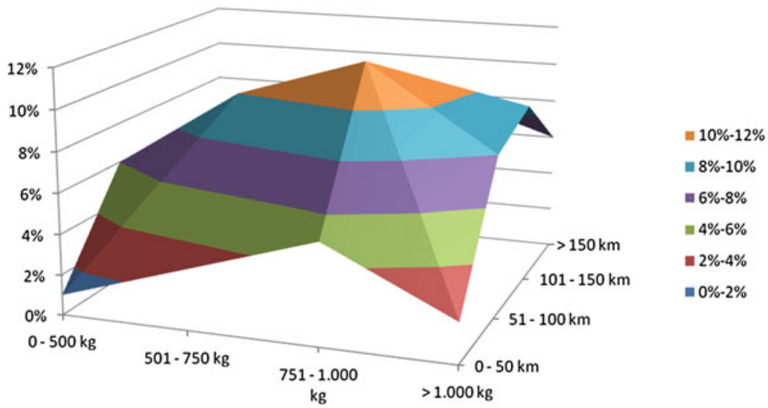

Fig. 3 Expert estimate distance-weight-matrix classification for last mile tours

4 Sustainability Implications

Measuring carbon dioxide emissions for electric vehicles is extremely difficult and has so far only achieved in research for cars (in comparison to diesel an hybrid cars for example, leaving electric vehicles with a slightly better sustainability balance sheet based on the current electricity production mix in Germany). The major problems regarding this evaluation are:

- The electricity production mix based on different energy sources (renewable, gas, oil, nuclear) is highly influencing the overall sustainability evaluation of electric mobility—whereas in countries with "clean" energy sources as for example Norway with 100 % water-based electricity production also electric cars and trucks are a green mode of transport, in countries with an electricity production scheme based on gas or coal the carbon dioxide emissions caused finally also by EV are higher multiple times;
- The inclusion of infrastructure implications on the sustainability evaluation are still an open research question—with the major assumption in question the probability of electric supply infrastructures to be additional or replacing the existing diesel and gasoline supply infrastructure;
- Due to restricted payloads and ranges, EV may induce more traffic and require a larger number of trucks to be used to transport the same amount of goods—where it is still unclear how to include this into CO_2 and sustainability evaluations.

Therefore it has to be assumed in line with previous publications that a comprehensive sustainability evaluation for electric mobility in last mile distribution can only be reached through a comprehensive evaluation in combination with the overall electricity production and distribution system, depending heavily on national and regional power and utility policies [22].

5 Comprehensive Evaluation

Figure 4 provides the overall comprehensive evaluation of application fields of electric vehicles in last mile logistics concepts.

The results outlined above show cost as well as sustainability evaluations regarding electric mobility in last mile distribution to be heavily dependent on the questions of average tour payload as well as average tour length: For higher payloads and longer tours, electric vehicles are up to 90 % more cost-intensive and even not feasible for tour lengths above 100 km on average (box A).

Two further insights have been (1) the facts of a hard (i.e. variable) sustainability evaluation due to the dependency of electric vehicles of the factual electricity production mix—which varies strongly in different regions and with different suppliers. If a completely green electricity production from renewable sources is assumed, EV may reach better sustainability evaluations. But as for example coal-fired plants are used in electricity production, EV may even have higher CO_2 emissions than existing diesel-engined vehicles in a comprehensive well-to-wheel-calculation (box B). (2) Second it has also become obvious in the process evaluations of the research project, that energy-intensive last mile transport tasks as e.g. temperature-controlled environments (pharmaceuticals, food) are unfeasible for electric transport as the additional energy for heating or cooling cannot be taken from the electric power system due to battery restrictions. This implies that secondary systems (also for cabin heating in winter times) are necessary today, inducing further cost burdens on EV for such applications (box C).

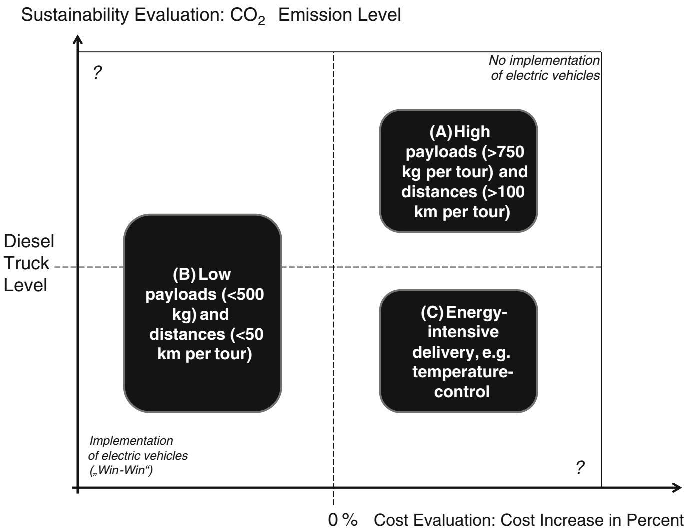

Fig. 4 Comprehensive evaluation scheme for last mile distribution

6 Conclusions

This research evaluation scheme for electric mobility in last mile distribution has shown the general feasibility as well as the necessary process changes in logistics for the changeover to electric vehicles. Besides the detailed cost implications mainly caused on a long-term basis by the still lower payload and the higher purchase price levels, cost increases have to be expected in general, varying strongly depending on product weights to be carried on last mile tours.

Furthermore, it is already obvious that electric vehicles will provide only niche solutions even in the narrow field of city and last mile distribution logistics as for example for energy-intensive areas such as temperature-controlled transports electric vehicles are not feasible.

Finally, further research is necessary especially on the question of sustainability as the overly evaluation in this regard depends on the applied electricity mix (production scheme), which is varying heavily depending on region and electricity provider, a general evaluation of electric mobility is hardly possible with the information and research methods of today.

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Green Technologies and Smart ICT for Sustainable Freight Transport

Chara Georgopoulou, Nikolaos M. P. Kakalis, Harilaos N. P. Psaraftis, Valerio Recagno, Sara Fozza, Panagiotis Zacharioudakis and Agnes Eiband

Abstract Sustainable freight transportation is high on the European and international agenda. The EC White paper of Transport 2012 denotes technological innovation as a key part of the future strategy "to achieve a faster transition to a more efficient and sustainable European transport system". In the context of the 60 % GHG emission reduction target for the EC transport sector, deployment of sustainable fuels, energy-efficient propulsion systems and smart information systems will be needed. Green corridors, a new EU concept for long-distance and perhaps large-flow transport networks, is planned to serve as platform for demonstration and later adoption of environmental-friendly, innovative transport solutions and intelligent transport systems. The EU project SuperGreen (1/2010–1/2013), 'Supporting EU's Freight Transport Logistics Action Plan on Green Corridors Issues', aimed to support the definition and benchmarking of green freight

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corridors through Europe with respect to environmental, technical, economic, social, and spatial planning aspects. In this framework, a set of representative EC freight corridors has been assessed and comparatively evaluated against the potential use of advanced technologies and intelligent information/communication technologies. This paper presents the methodology developed and applied for the assessment and benchmarking of corridors with advanced technologies. A set of more than 200 technologies has been assessed against their possible impact on the corridor performance. Advanced technologies for engine and propulsion systems, fuels and energy sources, navigation technologies, cargo handling systems, heating and cooling technologies, vehicles (road and rail vehicles, and waterborne vessels), best practices, and innovative units were analysed. Also smart Information and Communication Technologies (ICT) such as single window systems, expert charging systems, centralised and decentralised transport systems and others could achieve tangible benefits in terms of improving the corridor Key Performance Indicators (KPIs). Case studies and examples are presented.

Keywords Green corridors · Benchmarking · Green technologies · ICT

1 Introduction

In 2007, the European Commission (EC) introduced the green corridor concept for long distance transport networks, to promote environmental sustainability and energy efficiency in the transport industry [1]. Green corridors could serve as a platform to demonstrate the use of environmentally-friendly technologies, advanced information systems and logistic solutions towards sustainable transportation [2].

The objective of the SuperGreen project (1/2010–1/2013) was to support the EC in defining and benchmarking European corridors against their sustainability footprint and greening potential. The project targets were:

- To develop a corridor benchmarking methodology against key performance indicators (KPIs) on the environment, economy and service quality;
- To analyse the role of advanced technical measures, the so-called green technologies, and Information and Communication Technologies (ICT) towards the goal of greener corridors;
- To provide the EC with recommendations on green corridor, stemming from the experience of public and private transport stakeholders;
- To recommend policy strategies and future Research and Development (R&D) on green corridor development.

The purpose of this paper is to present the SuperGreen approach on the impact assessment of green technologies and ICTs on existing EC corridors. The current corridor performance, the so-called baseline, is compared to the case that green technologies and ICTs are implemented on the corridors.

The paper is structured as follows. Section 2 presents the SuperGreen project outline. In Sect. 3, the benchmarking of corridors with green technologies is described. Section 4 presents the benchmarking of corridors with ICTs. Section 5 summarises the conclusions of this work.

2 The SuperGreen Project

SuperGreen[1] is a 3 year Coordination and Support Action research project co-funded by the 7th EC Framework Program and the project partners. It was kicked-off in January 2010 and finished in January 2013. The project consortium consisted of 22 partners from 13 EU countries, including shippers, transport operators, academia, research and development institutions, consultancy bodies, and social and spatial planning authorities. The main project phases were:

- Identification of European corridors;
- Definition of corridor KPIs;
- Evaluation of baseline corridor KPIs;
- Collection of data on green technologies and smart ICT systems, suitable to be applied on the corridors to improve performance and solve bottlenecks;
- Benchmarking of green corridors with green technologies and smart ICT;
- Recommendations for R&D calls;
- Policy implications;
- Dissemination of results.

2.1 EU Corridor Baseline

The first project activity was to define a set of representative European corridors to test the project methodology. After a series of consolidation rounds, 9 corridors were screened out of 60 candidate ones, based on the TEN-T priority projects,[2] the Pan European Transport Network[3] and project partner's proposals. Particular attention was paid to the coverage of long distance routes serving large freight volumes by all transport modes apart from air. The SuperGreen corridors are shown in Fig. 1 [2, 3].

1 http://www.supergreenproject.eu/.

2 http://ec.europa.eu/transport/themes/infrastructure/index_en.htm.

3 http://ec.europa.eu/transport/themes/infrastructure/ten-t-implementation/extending/pan-european_corridors_en.htm.

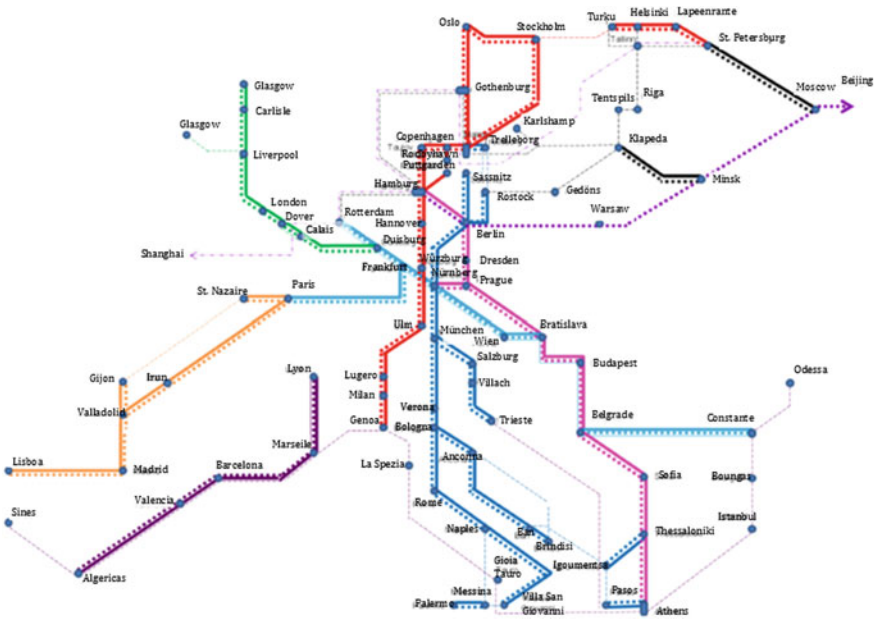

Fig. 1 The SuperGreen corridor network [2]

Then, a methodology was developed to evaluate the baseline performance against sustainability KPIs and reveal areas for future improvement. Since no corridor benchmarking study was found in the literature, the methodology was drawn upon past experience on transport chains [2, 4, 5]. In this respect, the SuperGreen methodology examines a corridor by decomposing it into transport chains, calculating their KPIs, and, finally, aggregating the results at the corridor level. After a series of dedicated workshops, the following KPIs were identified [2]:

- Relative cost (€/tn.km);
- Average speed (km/h) (or transport time, in hours);
- Reliability (% of shipments delivered within acceptable time window);
- Service frequency (no of trips per year);
- CO_2 (gr/tn.km);
- SO_x (gr/tn.km).

Some extra KPIs were also identified, such as congestion, land use, traffic safety and noise. A quantitative definition of these KPIs was not considered and few data about them were collected. Thus, these extra KPIs were excluded from the baseline evaluation, although they were considered in the qualitative benchmarking of ICTs, as discussed in Sect. 4.

Table 1 presents the corridor baseline. Information about the transport chains was collected by means of a survey on transport operators over the corridors. The

Table 1 Baseline corridor benchmark [2]

Corridor	Mode	Cost (€/tn.km)	Av. speed (km/h)	Reliability (%)	Service frequency (no/year)	CO_2 (gr/tn.km)	SO_x (gr/tn.km)
Brenner	Inter-modal	0.03–0.09	9–41	95–99	26–624	10.62–42.11	0.02–0.14
	Road	0.05–0.07	19–40	50–99	104–2600	46.51–71.86	0.05–0.08
	Rail	0.05–0.80	44–98	50–100	208–572	9.49–17.61	0.04–0.09
	SSS*	0.04	23	100	52	16.99	0.19
Clover-leaf	Road	0.06	40–60	80–90	4.68	68.81	0.09
	Rail	0.05–0.09	45–65	90–98	156–364	13.14–18.46	0.01–0.02
Nureyev	Inter-modal	0.10–0.18	13–42	80–90	156–360	13.43–33.36	0.03–0.15
	SSS	0.05–0.06	15–28	90–99	52–360	5.65–15.60	0.07–0.14
Strauss	IWW**	0.02–0.44	–	–	–	9.86–22.80	0.01–0.03
Mare nostrum	SSS	0.003–0.2	17	90–95	52–416	6.44–27.26	0.09–0.4
	DSS***	–	–	–	–	15.22	0.22
Silk way	Rail	0.05	26	–	–	41	–
	DSS	0.004	20–23	–	–	12.5	–

*Short sea shipping
**Inland waterways
***Deep Sea Shipping

transport chain performance was evaluated using: (1) the survey results, (2) a literature review on baseline technologies and (3) the Ecotransit[4] tool, to calculate the vehicle emissions. The results are expressed as ranges of values that correspond to the minimum and maximum values of the transport chain KPIs [2, 3, 6].

2.2 Benchmark Objective

The next project milestone was two-fold:

- First, to assess the potential impact of green technologies to be applied on the corridors, in order to improve the KPIs and solve bottlenecks.
- Second, to define and exploit the role of ICT flows towards the goal of greener transport.

The next sections present the SuperGreen approach and the results for the benchmarking of corridors with green technologies and ICTs.

[4] http://www.ecotransit.org/.

3 Benchmarking of Green Corridors with Green Technologies

To develop a green corridor benchmark with green technologies, the steps below were followed:

Step 1: Survey on green technologies for all transport modes apart from air, on the basis of past and current research projects at national, European and international level.
Step 2: Screening of the technologies that could significantly improve the corridors KPIs and solve bottlenecks. This activity included a non-corridor specific assessment of the technology effects on the KPIs.
Step 3: Identification of green technology application areas over the corridors.
Step 4: Technology impact assessment on the corridor baseline (corridor-specific analysis) and development of a green corridor benchmark. This process required:

(a) Quantitative data on the technology impact, validated against real-life performance; and
(b) Detailed data about corridor transport routes, such as traffic volumes, frequency of service, delivery time and vehicle features.

Since such data were not available for all corridors, a limited set of benchmark scenarios was produced based on the baseline transport chains (Sect. 2) and the green technology review.

3.1 Green Technology Survey and Qualitative Assessment

A survey on green technologies was conducted, collecting data from manufacturers, research and academic works, and the project consortium. The survey resulted in a list of 200 representative technologies of the following categories: engine and propulsion systems, fuels and sources of energy, navigation technologies, cargo handling systems, heating and cooling technologies, vehicles and vessels, best practices, and innovative units with their treatment [7].

By applying a 6-level qualitative ranking scheme, the initial technology list was reduced to a smaller set of 58 technologies that could significantly improve the corridor KPIs, according to project expert judgment. The top and bottom ranks denoted mature technologies with positive potential and technologies with low impact to the KPIs, respectively [7].

Then, a matrix was created showing possible application areas for the 58 green technologies over the corridors. The matrix was populated based on expert judgement from both inside and outside SuperGreen. The results are publicly available through a web-based repository (http://88.32.124.84/SuperGreen/Login.aspx).

3.2 Benchmark Scenarios

After an extended review on industry and academic works [8–11], the impact of the 58 green technologies on the KPIs was quantified. The analysis was technology-specific and it was based on publicly available manufacturer data, technology success stories and research project results. To facilitate this assessment, the KPIs were further decomposed into factors and mapped to technology performance data [12]. For instance, a green technology that reduces fuel consumption can potentially help to reduce fuel cost, which is an important factor of the operating cost. It has to be noted that the selected factors reflect the size of available information and the targeted resolution of the analysis. Figure 2 presents an overview of the green technology impact on the KPI factors. The impact is expressed as the percentage of green technologies with positive, negative or neutral influence on the factors.

The development of the green corridor benchmark was based on the technology-specific analysis. The benchmark consisted of 20 scenarios; each scenario corresponded to a baseline transport route, combined with a green technology that would improve the route performance. Then, using simple algebraic calculations, the potential impact in route KPIs was estimated [12].

Tables 2 and 3 present the green corridor benchmark. Uncertainty regarding the baseline calculations and the technology impact may have affected the results. Due to lack of data about capital costs for some of the green technologies, the return of investment and its impact on the operating cost were not considered. This reduced the resolution of the analysis, to include only the effects on fuel consumption.

Compared to the baseline KPIs for road transport routes, an improvement of up to 7 % in operating cost and 26 % in CO_2 emissions can be achieved by aerodynamic truck design improvements and hybrid power systems. The picture would change if the return of investment is included in the analysis. For the maritime

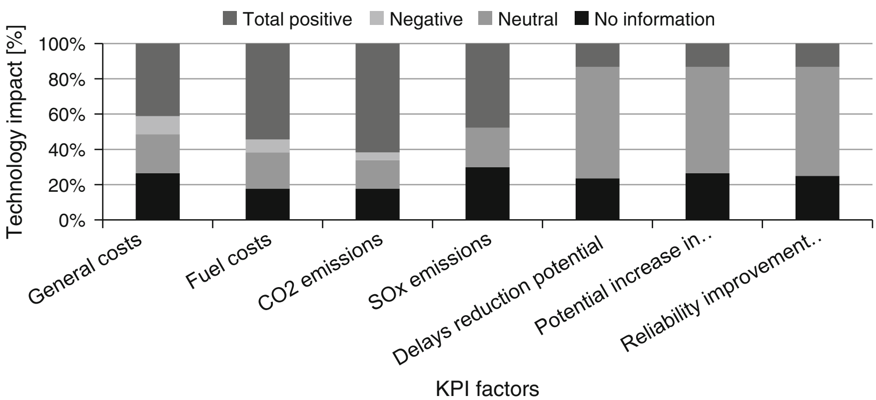

Fig. 2 Estimated impact of the green technologies on a set of KPI factors (horizontal axis). The vertical axis shows the percentage of technologies (number of technologies per total technology number)

Table 2 Green technology benchmark scenarios: Mare Nostrum, Nureyev, Strauss and silk way corridors

Scenario	Technology	KPI	Impact (%)
Mare Nostrum—SSS: container liner service between mediterranean ports	Waste heat recovery systems	Rel. cost (€/tn.km)	1–5
		CO_2 (gr/tn.km)	2–5
		SO_x (gr/tn.km)	1–5
	Exhaust abatement systems	Rel. cost (€/tn.km)	−4 to −1
		CO_2 (gr/tn.km)	−4 to −1
		SO_x (gr/tn.km)	90–96
	Integrated SS transport	Av. speed (km/hr)	5–8
Nureyev—SSS: container vessel serving a port-to-port connection linking Rotterdam and Helsinki	Contra rotating propeller	CO_2 (gr/tn.km)	5–15
		SO_x (gr/tn.km)	4–16
	Mechanical azimuth thrusters	CO_2 (gr/tn.km)	0–20
		SO_x (gr/tn.km)	0–21
	Wind propulsion–sails*	CO_2 (gr/tn.km)	0–15
		SO_x (gr/tn.km)	0–14
	LNG	CO_2 (gr/tn.km)	10–20
		SO_x (gr/tn.km)	98–100
	Cargo cassette trans lifter	Av. speed (km/hr)	0–38
		Serv. Freq.(no/year)	0–6
		Reliability (%)	0–6

(continued)

Table 2 (continued)

Scenario	Technology	KPI	Impact (%)
Strauss—IWW: JOWI class container vessel, serving Rotterdam-Duisburg segment	Exhaust abatement systems	Rel. cost (€/tn.km)	0–1
		CO_2 (gr/tn.km)	−5–8
	Route optimisation systems	Rel. cost (€/tn.km)	1
		CO_2 (gr/tn.km)	10
		SO_x (gr/tn.km)	10
	LNG	CO_2 (gr/tn.km)	10–19
		SO_x (gr/tn.km)	95–100
Silk way—rail: connection between China and Poland	Braking energy recovery and on-board energy storage	CO_2 (gr/tn.km)	30–40
	Intelligent temperature unit	Reliability (%)	Positive

The benchmark scenarios and the green technologies are described in columns 1 and 2, respectively. The technology effect on the baseline KPIs is shown in columns 3 and 4

Table 3 Green technology benchmark scenarios: Brenner and Cloverleaf corridors

Scenario	Technology	KPI	Impact (%)
Brenner corridor–road: route between Verona and Berlin operated by heavy duty EURO V type refrigerated trucks	Hybrid trucks	Rel. cost (€/tn.km)	6–7
		CO_2 (gr/tn.km)	25
	Aerodynamic drag improvements	Rel. cost (€/tn.km)	3–4
		CO_2 (gr/tn.km)	10–26
		SO_x (gr/tn.km)	13–25
	Low rolling resistance tires	Rel. cost (€/tn.km)	0–1
		CO_2 (gr/tn.km)	2–4
	Card-board pallets	Rel. cost (€/tn.km)	Positive impact
		CO_2 (gr/tn.km)	
Cloverleaf–road: fleet of Euro IV trucks of 24–40 t capacity case study, serving the link between London and Duisburg	Aerodynamic drag improvements	Rel. cost (€/tn.km)	2–8
		CO_2 (gr/tn.km)	10–26
		SO_x (gr/tn.km)	10–26
	Hybrid trucks	Rel. cost (€/tn.km)	13–23
		CO_2 (gr/tn.km)	25
		SO_x (gr/tn.km)	10–26
Cloverleaf–rail: electrified long train operating between Midlands and Duisburg	Energy settlement systems	Rel. cost (€/tn.km)	1

The benchmark scenarios and the green technologies are described in columns 1 and 2, respectively. The technology effect on the baseline KPI is shown in columns 3 and 4 cases, the introduction of energy efficiency measures can bring up to 20 % reduction of CO_2 emissions. An improvement of about 38 % on the average speed could be possibly achieved if better cargo handling systems were used. SO_x after treatment systems can reduce the total transport chain SO_x emissions by more than 73 %. Fuels like liquefied natural gas (LNG) and compressed natural gas (CNG) are among the cleanest fossil fuels that can serve the shipping and road industries. The energy settlement systems in railways could provide with energy savings. Finally, the optimal design of waste heat recovery systems can provide with economic benefits in large deep sea shipping cargo flows. It is worth to mention that the results are case-dependent and cannot be generalised for any other transport route. Also, the benchmark does not imply any endorsement on the routes and/or the green technologies, by the SuperGreen consortium, or the EU Commission.

3.3 Implementation of Exhaust Gas Abatement Systems in the Mare Nostrum Corridor

In this paper, the benchmark scenario for exhaust gas abatement systems on the Mare Nostrum corridor is presented; any other scenario of Table 2 could be shown instead. The Mare Nostrum corridor includes Mediterranean and Black sea trade routes, with rail and road connections linking the ports to inland networks. The scenario is about a container liner service amongst the ports of Barcelona, Valencia, Gioia Tauro, Piraeus and Istanbul, operated once a week by feeder vessels of about 2,000 TEUs.

To estimate the green technology impact, a typical operating vessel profile must be considered. An average engine load of 75 % during the trip and 50 % at port was assumed. The mean distance sailed was 1,425 km, with a delivery time of 55 h and a speed of 14 knots. The time at port was 17 h. A typical freight loading factor of 70 % was considered.

3.3.1 Green Technology Description

Under the International Maritime Organisation (IMO) air pollution regulations [13], exhaust gas cleaning systems, like scrubbers, are one technical option to mitigate sulphur emissions, with alternative fuels like LNG or low-sulphur marine diesel oil being the other technically known options. Scrubbers can remove sulphur from the engine exhaust gas up to 99 % by using chemicals, seawater, or dry scrubbing technology. Due to the scrubber power needs, the overall fuel consumption increases, thereby increasing the CO_2 emissions [14]. The scrubber installation may require on-board vessel alterations, like additional tanks, pipes, pumps, effluent water treatment system. Extra operational costs may occur, if chemicals solvents are in use.

Currently, scrubbers are not widely used in the Mare Nostrum corridor. Such technologies have been installed in vessels sailing in the Baltic Sea, due to the regulatory regime in that region.

3.3.2 Benchmarking of Scrubbers on the Mare Nostrum Corridor

According to the literature [15], scrubber operation may increase fuel consumption by 2–3 %. This would influence fuel costs and CO_2 emissions. SO_x cleaning efficiency could be as high as 99 %. SO_x emissions reduction would depend on the engine loading and the operating profile of the scrubber.

For the Mare Nostrum scenario, the green technology impact was estimated:

- Relative cost: Assuming a range of values for the fuel consumption rate and the bunker oil price, the negative technology effect on fuel costs was estimated at about −1 to −4 %.
- CO_2 emissions: The negative effect on baseline CO_2 emissions was at the range of −1 to −4 %.
- SO_x emissions: For continuous scrubber operation, the SO_x emissions reduction could reach 96 %. In case that the scrubber is not operated below 50 % engine load, the reduction of emissions would be about 75 %.

4 Benchmarking of Green Corridors with Smart ICT

To develop a green corridor benchmark with ICTs, the steps below were followed:

Step 1: Conduction of a specialised expert ICT workshop (held in Genoa, Italy).
Step 2: Assessment of the results of the above ICT workshop.
Step 3: Non-corridor specific description of the ICT systems under investigation, including data about basic functionalities, cost, funding mechanisms, and other technical performance characteristics.
Step 4: Corridor-specific investigation on the existence of ICTs on the corridors and future implementation plans for ICTs, if any. Other relevant data could be also collected.
Step 5: Based on step 4, inter alia, investigation of potential impact of ICT on the KPIs of a corridor.
Step 6: Synthesis and interpretation of the results.

The above sequence of steps may look easier than it really is. As mentioned in Step 5, ideally one would like to obtain a precise quantification of the potential impact of a specific ICT on the corridor KPIs. However, our experience revealed that in many cases such a goal turned out very difficult or sometimes impossible to achieve, due to the following reasons:

(a) Data necessary to quantitatively compute the ICT impact on corridors generally proved to be difficult or elusive to obtain. This is due to reasons such as general unavailability or lack of information, unwillingness of operators or other sources to reveal such data (if any), and non-homogeneity in data quality. The problem of data availability (such as cargo flows) is recognised in the EU. In some cases, estimates of such data can be produced based on mathematical models. A fortiori, any linkage of such data with particular ICTs is even more complicated.
(b) In contrast to the green technologies (Sect. 3) that can have a direct and tangible impact on the corridor KPIs, the impact of ICTs on the greening of a corridor is of a different nature. For instance, an innovative propulsion system consumes less fuel, resulting in less CO_2 and SO_x emissions. On the other hand, a broadcasting ICT can result in no CO_2 emission reductions in and of itself, but it could do so, if it is appropriately used by the operator. Similarly, a ship may reduce speed, if it is known that there is congestion at the next port of call, a truck may use a different route, if an expert toll system is used, and so on. The same is true for most of the KPIs. The way such information is used (if actually used at all) is at the discretion of the human operator and as such does not lend itself to ease of measurement. The same is true for systems such as the European Railway Traffic Management Systems (ERTMS), expert charging systems, single-window systems and other ICTs examined. Actually, some of these ICTs (for instance, platooning) have not yet reached the implementation phase. Either way, the potential performance of these systems depends more on the way these systems are used and less on the systems themselves.

In that sense, it was proven difficult to connect all ICTs with the KPIs in a precise quantitative way and a qualitative evaluation was followed. Still, for some ICTs we managed to get some quantitative results, but as these are only indicative and case-specific, caution should be exercised in any attempt to generalise them. If anything, they can only be considered as clues as regards the validity of postulated conclusions.

Below we only give a summary of the results. Full details can be found by visiting the SuperGreen web site.

4.1 Qualitative Assessment

In the workshop held in Genoa, a dedicated questionnaire was constructed in order to collect data and evaluate the importance of a set of proposed ICTs:

- Adaptive speed control;
- Congestion charging;

- ERTMS;
- Freight transport information technology solutions (Fretis) or compatible system;
- Installation of sensors on-board vehicles;
- Single window systems;
- Platooning;
- River information systems;
- River tolls;
- Tracking units.

The ICTs were clustered in the following functional groups:

- Expert charging systems;
- Centralised transportation management systems;
- Decentralised transportation management systems;
- Broadcasting, monitoring and communication systems;
- Safety systems;
- E-administrative systems;
- Emissions footprint calculator systems.

Also, a first qualitative assessment of the ICTs impact on the corridors was performed. As expected, there was a large variation on the results, because of the different application areas and ICTs considered. For example, the Congestion Charging ICT seems to have an important effect on the congestion KPI and rather unimportant on the KPIs of Cargo Security and Safety.

4.2 Benchmark Scenarios

The next target was to develop the green corridor benchmark with ICTs. A set of 15 benchmark scenarios was constructed (Table 4), aiming to reveal the importance of ICT implementation on the corridors. The importance level had 5 grades, plus the ability to characterise the importance as "unknown". The benchmark scenarios were compiled by individual experts or subgroups of experts, during the Genoa workshop. The material was collected and processed, resulting in a corridor-specific ICT benchmark with respect to the KPIs. An example (only one among several) for the mean importance of the Congestion Charging ICT on the KPIs is shown in Fig. 3.

Table 4 ICT benchmark scenarios

Scenario no	Corridor	Mode	ICT
1	Mare nostrum	SCM	Tracking units
2	Brenner	Road	Expert charging
3	Brenner	Rail	ERTMS
4	Two seas	Road	Broadcasting
5	Silk way	Maritime	Emissions calc
6	Silk way	Rail	ERTMS
7	Edelweiss	Road	Emissions calc
8	Finis terrae	Maritime	JUP
9	Finis terrae	Rail	ERTMS
10	Strauss	IWT	RIS
11	Strauss	IWT	Expert tolls
12	Nureyev	Maritime	E-admin
13	Nureyev	Maritime	Icebreaker assignment/IBnet
14	Cloverleaf	Road	Platooning
15	Cloverleaf	Road	Safety-speed control

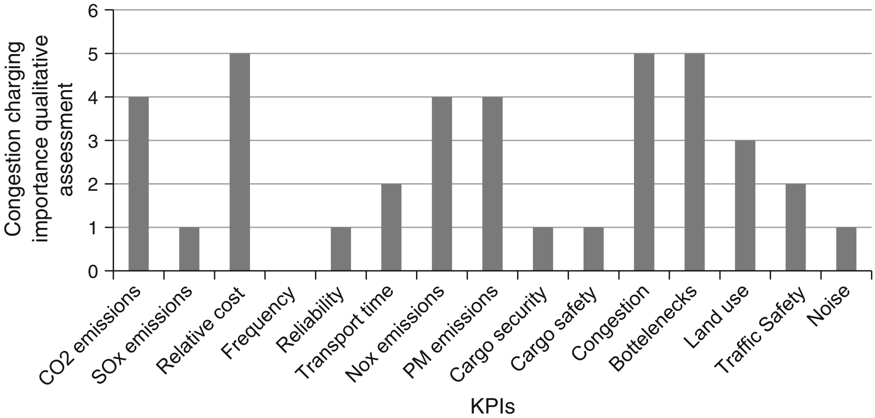

Fig. 3 Mean importance of Congestion Charging ICT on the corridor KPIs

4.3 Implementation of Expert Charging ICT in the Brenner Corridor

We have selected to present one example among the scenarios of Table 4, on the Expert Charging ICT over the Brenner corridor. This corridor concerns freight transport from Berlin, Germany to Palermo, Italy and Athens, Greece through the Italian peninsula. It involves crossing of the Alps through the Brenner Pass,[5] as

[5] Important route for road freight transport crossing the Alps.

well as crossing of the Ionian and Adriatic seas. It also includes the Tauern axis (Salzburg-Trieste).

4.3.1 General Description of Expert Charging ICT

EC countries are implementing various ICT regarding nationwide road pricing schemes, due to rising levels of traffic congestion and emissions. Some examples are:

- The road tax on vehicles (vignette) used in Central European countries, such as the German highway truck toll system, or the Swiss performance-related heavy vehicle fee (HVF), where the toll amount depends on the route, and the truck pollutant category, class (e.g. Eurocode), weight and number of axles.
- The Congestion Charging ICT, such as the Stockholm congestion tax, introduced in 2006 to reduce traffic congestion in Stockholm during peak hours, and the London congestion tolls. These systems surcharge the users of a transport network in periods of peak demand, to reduce traffic congestion.
- The "Pay as you drive" (PAYD) ICT, where the Automobile Insurance is determined by how much and for what purpose the vehicle is used.

Since congestion charging ICTs are designed mainly for urban applications and the PAYD ICT is used for insurance purposes, our analysis focuses in ICT systems similar to the German highway truck toll system.

4.3.2 Expert Charging ICT Status on Corridor

There are four countries involved in the corridor: Germany, Austria, Italy and Greece. In Germany, an expert charging system for trucks is already implemented, the so-called LKW-Maut. In January 2004, Austria introduced an electronic toll collection system for trucks over 3.5 t, using the Dedicated Short-Range Communication (DSRC) technology. In Italy, the toll price is proportional only to the distance travelled. In order to calculate the toll, the truck driver has to withdraw a ticket from an automatic dealer before entering the highway, returning it at the toll gate on exit. In case that the truck is equipped with a Telepass OBU (an automatic toll collection device), the ticket is not necessary. In the Greek segments of Brenner corridor, there is a toll for every specific highway, but not always based on distance travelled. This case by case charging is based on truck weight and emissions class. Greek e-toll systems use Radio-Frequency Identification (RFID) sensors and tags, in order to automatically detect passages from gateways. The process is also performed manually due tellers. The main anticipated benefit of such systems is the extent to which they can be used, to internalise the external costs of transport.

4.3.3 Benchmarking of Expert Charging ICT

As a result of the truck tolling program implementation in Brenner Corridor, freight companies will have an incentive to purchase vehicles with lower emission rates and shippers to use eco-friendlier transportation modes. The UK Commission for Integrated Transport cites [16]:

- 6 % decrease in the number of empty runs and
- 6 % modal shift to rail from road freight mode as a result of implementing the truck toll system.

We expect similar results for the Brenner corridor, including the segments in Italy, where it has not yet been introduced. Also, these factors are likely to decrease CO_2 emissions and other pollutants.

A negative consequence of the freight toll system is the shift of some trucks off the highways and onto other non-central roads, resulting in additional emissions, noise and congestion on these routes.

Last but not least, an indirect but potentially significant effect of expert charging ICTs can be that revenues generated by them can be used as 'offsets', that is, to invest in green technologies that can reduce emissions, either on the specific corridor, or elsewhere. Such 'out of sector' emissions reductions can be as significant as 'in sector' reductions.

Similar analyses were performed for the benchmark scenarios of Table 4, but are not reported here due to space limitations.

5 Conclusions

In this paper, the results of the SuperGreen project on the benchmarking of green corridors with advanced technologies and ICTs were presented. The main objective was to estimate the technology impact on the baseline performance of representative European corridors with respect to energy efficiency, environmental footprint, reliability and service quality. The benchmark also shows the technology potential benefits and drawbacks compared to conventional practices.

5.1 Green Technologies and Corridors

It was shown that there is wide potential for improving the performance of the European corridors. Green technologies are expected to have positive impact in corridor sustainability. Using the SuperGreen KPIs, that positive effect was estimated up to 35 %, a percentage of 39 % of which was described in a quantitative manner. The green technology effects on baseline performance were shown on 20 benchmark scenarios, for which there was sufficient availability of data.

This work revealed the need for adequate and consistent statistical information on transport corridor flows that would allow a precise quantification of the European corridor baseline. Future research on the benchmarking of the green corridors should consider the adoption capacity of green technologies on an aggregated level (fleet basis), including their return of investment. To facilitate the adoption of green technologies, future analyses should examine large-volume transport paradigms, considering indices related to regulatory barriers, benefits on national or community level and infrastructure capacity. Detailed investigation of green technology applications on the European corridors will shed light on their sustainability potential and contribute to a solid understanding of the most promising greening solutions.

5.2 *Smart ICTs and Corridors*

The introduction of ICTs in the SuperGreen corridors will generally have a positive effect in terms of cost, time, safety, security, environmental sustainability and reliability.

It is our belief that the results of this work support the general conclusion that the proposed ICTs have the potential to make logistics greener and constitute a "win–win" option for logistics stakeholders. The benefits would affect fuel economy, operation time variables, safety and reliability. At the same time, it was also seen that there are cases in which deployment of ICTs may have adverse impacts on some KPIs. Caution is necessary in these cases.

There was no clear forerunner in the benchmarking analysis, since there are multiple evaluation criteria. These KPIs are societal or private criteria affecting profitability, environmental impact and social safety and security. What is clear is that all the examined ICTs can provide vital benefits to all the stakeholders involved in the transport process. Another critical point apart from the installation of the systems is the integration with existing systems. Integration and smooth information flows are key points to maximise the positive effect of these systems.

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Corporate Social Responsibility Management of Small and Medium Sized Logistics Service Providers

Nora Meyer and Imke Schmidt

Abstract Logistics, as the connecting link in global value-creation processes, are confronted with the demands of corporate social responsibility (CSR) in a particular fashion. This paper analyses the specific challenges, which small and medium sized logistics service providers have to face when dealing with CSR by presenting the findings of two explorative case studies and comparing these with the results of previous CSR management research. The aim is to point out logistics specific CSR management strategies that respond to the challenges identified and that build on stronger collaboration between business partners.

Keywords Small and medium sized logistics service providers · Corporate social responsibility · Cooperative network management

1 Introduction

The urge to consider sustainability aspects is rising in analogy to the increasing understanding of the causations of climate change and the enhanced transparency of both environmental and social (wrong) doings of organizations [1, p. 46]. Logistics, as the connecting link in global value creation processes, are confronted with the social, ecological and economic demands of corporate social responsibility (CSR) in a particular fashion [2, 3]. On the one hand, rapidly rising oil prices, increasing transparency and consumer awareness of where and how products are manufactured, as well as a growing demand of CSR-reporting, clearly

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show that sustainability is an aspect of the logistics supply chain and affects its economic bottom line [4]. Demands expressed by customers, regulatory bodies, non-governmental organizations (NGOs) and especially employees to address and manage the environmental and social consequences of logistics operations are on the rise [1]. On account of their ecological and social repercussion, logistics processes are increasingly coming to the attention of stakeholders and public criticism. Thus, being in the middle of the sustainability debate, the customer oriented logistics industry has to find solutions to the growing CSR requirements that producing companies are facing, while at the same time price and performance is expected to remain constant. On the other hand, logistics companies and "[s]upply chain managers are in a particularly advantageous position to impact—positively or negatively—the environmental and social performance, through for example supplier selection and supplier development, modal and carrier selection, vehicle routing, location decisions, and packing choices" [1, p. 47].

Therefore, in this paper, we above all strive to achieve the following: Firstly, we want to underline the very specific challenges the logistics sector faces when tackling CSR activities. Secondly, we want to point out management strategies that support the (supply chain) manager in his or her responsible role of impacting positively the corporation's CSR strategy.

With this in mind, we will, in the second section, review the literature on CSR and sustainable supply chain management. In the third section we introduce the methodology of the so-called CSR inventory analysis that we conducted within two firms as a case study. We will then, in the fourth section, describe our main findings, which we will discuss with reference to previous research in the fifth section. In the final sixth section we draw a conclusion.

2 Summary of the Literature

As Carter and Jennings [5] pointed out, the challenge that comes along with research on corporate social responsibility (CSR) lies in the fact that it is a concept that requires a holistic consideration of a variety of aspects. CSR refers to the "[r]esponsibility of an organization for the impacts of its decisions and activities on society and the environment through transparent and ethical behaviour that

- Contributes to sustainable development, including health and the welfare of society
- Takes into account the expectations of stakeholders
- Is in compliance with applicable law and consistent with international norms of behaviour; and
- Is integrated throughout the organization and practiced in its relationship" [6].

In line with this definition, a holistic approach requires the successful integration of the following aspects: Firstly, the sustainability-oriented topics of particular relevance or alarm (1st bullet point) have to be managed. Secondly, those corresponding groups and actors have to be identified and regarded, which are concerned by particular issues in the company and/ or who formulate these issues as requirements (2nd bullet point). Thirdly, the corporate culture with corporate values and their embedding in the sector-specific culture of logistics industries (4th bullet point) is crucial. We consider the law aspect (3rd bullet point) as part of the other dimensions, since they form the minimum standard of societal rules that should be respected by a company [1]. [1]

So far, research that claims to be part of CSR and sustainability has very often neglected the interrelationships among these topics and rather has considered "hot spots", such as environment, diversity, human rights, philanthropy or safety in a standalone fashion without referring to the overarching concept of CSR [5]. Similarly, managers have managed projects case by case, without regarding a more strategic understanding "of how these pieces of the puzzle fit together to create their organization's overall sustainability position" [1, p. 47]. In addition, sustainable supply chain management has rather focused on environmental issues than on social issues: "[t]ransportation carriers have been chosen by researchers […] because they have a large carbon footprint that is more obvious to many of their stakeholders" [1, p. 55]. Thus, what has been neglected is an integrated approach that considers every aspect of CSR. In our research we have the above described understanding of CSR in mind and therefore we do not want to look at the logistics sector by paying attention to single issues such as security or carbon footprint only. Rather, we want to develop an integrated view on the logistics sector and pay attention to the social aspects of CSR, also. But taking such an integrative view, what are the eminent challenges for the logistics sector?

3 Methodology

Apart from the theoretical implications mentioned above, the following practical incidents are crucial to be taken into account: The logistics sector is primarily made up of small and medium-level companies (SME). According to the German Logistics Federation (DSLV), German freight transportation companies, for example, do not have more than 11 employees in average [7]. There are two very particular challenges that go along with that:

1. Firstly, goal-oriented management of the initiatives and the engagement of individual logistics service providers [5] prove to be a challenge, as resources are rare and firms are working to full capacity. Thus, a focus will be put on an analysis of the conditions for the implementation of CSR management, e.g. existing CSR

[1] Although this is not always the case as corruption issues and other illegal practices in daily business demonstrate. Our research has shown that in some cases, also in the logistics sector, corruption and actions within a grey zone are a tolerated part of the daily business instead of a non-tolerated exception.

instruments and structures that the firm already has implemented and that can be built upon, such as a CSR reporting, a CSR or sustainability department, etc.

2. Secondly, the logistics sector is typically characterized by highly interdependent international network structures, which are structured and organized to greater and lesser degrees [8]. Successful CSR strategies therefore demand collaborative structures at the interfaces of economic exchange.

To find out how these specific structural challenges can be managed, two explorative case studies were conducted within a three-year research project called "Integrated Corporate Social Responsibility-Management in logistics networks" (CoReLo). We focused on two case studies in one industry to be able "to take deeper dives into individual industries as sampling frames" [1, p. 57]. With our study, we wanted to analyze more closely the antecedents of CSR particularly for the logistics sector and thus focus on the individual as the unit of analysis. Research has shown that the majority of existing studies on environmental or CSR management implementation focus on the level of the organization, although the role of the individual managers' acceptance and commitment has proven to be of great relevance [1, 9, 10]. To be able to capture the antecedents of CSR, a micro-perspective has been taken, and the employees of the companies, as one very important stakeholder group, were considered. It was the goal of the analysis to gain knowledge on how individual managers can influence the success of CSR management strategies and where potential biases can be detected [1, p. 57]. The aim was to therewith generate more information about the requirements of CSR management in small and medium-level corporations of logistics service provider industries on the one hand and about the conditions of a stronger engagement within the logistics network on the other.

To generate data, we conducted 42 qualitative interviews[2] concerning amongst others CSR commitment, structure and management initiatives (see Table 1) in order to indirectly comprise the existing CSR culture, structures and processes in the two observed companies. Furthermore, elements of network analysis were amended in the interviews in order to grasp an idea of the structure and branch culture of the logistics sector as well as the challenges these provide to the implementation of CSR with partner companies of the logistics network. The aim was to get an idea of the interplay between the firm's CSR values and activities and the external conditions, which the companies' strategies depend on.

For the analysis of the data we refer to a research project entitled "Understanding and responding to societal demands on corporate responsibility" (RESPONSE) [11], which surveyed the "cognitive alignment" as an indicator for the social performance of the 19 companies that were investigated.[3] The cognitive alignment describes the degree to which companies and their stakeholders align on

[2] We conducted 23 interviews in the first half and 19 interviews in the second half of the project. The results presented in this study rely mainly on the 23 interviews of the first phase.

[3] The three-year research project RESPONSE, created and funded by the EU Commission's D.G. conducted 427 interviews in 19 companies in 8 sectors [11, p. 6].

Table 1 CSR analysis scheme inventory (own illustration, on the basis of RESPONSE)

Focus of analysis	Examples
CSR requirements	External influences that support, encourage or substantiate CSR engagement
Motivation for CSR	Commitment to CSR and how this is validated, for example by: • the "business case" • personal or organizational values • expectations of the industry
CSR processes	
1. CSR commitment	Commitments and obligations with reference to CSR, for example: • support of high-level management for CSR themes • the extent to which themes are integrated into strategic corporate decisions and processes
2. CSR structures	Findings concerning the developments of CSR in companies, for example: • whether, where and how CSR is situated • how intensive, for example, the exchange between high-level management and CSR designates is
3. CSR management initiatives	Specific programs, strategies and projects, for example: • CSR training programs, employee evaluations according to CSR criteria • integration of CSR in central business processes • manner and means of communication, like stakeholder dialogue, target agreements, reporting, monitoring, investment, etc

their view on CSR within their particular context [11, p. 6]. The study works at the level of the individual manager's behaviour and the perception of the stakeholders, as "[t]he individuals' understanding and sensitivity towards the social implications of their decisions and actions is deemed in fact to be crucial to enhancing the capacity of business organisations to respond to and bridge the 'cognitive gaps' that separate them from their stakeholders and from society at large" [11, p. 6].

Table 1 shows the scheme of analysis and illuminates how data collected in the interviews were structured with reference to the RESPONSE study.

4 Main Findings

Tables 2 and 3 summarize the findings of the CSR inventory analysis according to the RESPONSE model. A very diverse understanding about what CSR actually means can be seen in the "CSR commitment" category. Since the companies recognized this problem also, they expressed a clear wish to develop a broad, common understanding of CSR. Regarding the "CSR structures" category, our

Table 2 Findings of the CSR inventory analysis

Focus of analysis	Examples
CSR requirements	*The price dictates what we do*; demand of high flexibility within the supply chain, fast changing partners; short-term contracts and orders
Motivation for CSR	*We do nothing, if we are not forced to do it or when it does not pay off.*; *What is our responsibility, anyway? […] it seems to be important, though*
CSR processes	
1. CSR commitment	Aspects of CSR are actually tradition, e.g. the firm philosophy: *People are at the center of everything we do.* But: How to engage people? How to be taken seriously?
2. CSR structures	CSR is a cross-cutting issue; everyone needs to participate; managers have a special obligation to bring CSR forward
3. CSR management initiatives	Many initiatives could be found; design and use of mission statement and internal and external communication methods unclear

Table 3 Internal and external challenges for the implementation of CSR in SME in the logistics sector

Internal challenges (examples)	External challenges (examples)
CSR motivation: rather reactive than proactive because of efficiency pressure	Customer: lack of cost-acceptance of CSR strategies; lack of consistency and reliability
Commitment: lack of a common understanding of what CSR actually means	Supply chain partners: time and costs dominate daily collaboration and don't give room for individual CSR strategies
Structures: lack of integration of CSR strategies into the organization and organizational culture	Relationship with other, non-business stakeholders: company has to learn to speak a non-business language and to take into account non-business factors
Initiatives: lack of structured documentation and evaluation and of a communication strategy	

findings show that executives of the companies analyzed support them strongly. The question remains how this engagement can be integrated better into the organization, its culture and its business practices. Despite this internal structural challenge, several "CSR management initiatives" existed in the companies. However, these were hardly documented, prioritized or evaluated. In addition, interviewees mentioned the difficulty of developing a particular CSR communication strategy. Here the companies are reluctant. The reasons for this lie in the fact that authenticity is very important to the companies analyzed. They are cautious of communicating something that does not reflect the actual activities and practices in the company and do not want to face accusations of "greenwashing". All in all, the CSR inventory analysis conducted within the two companies exposed many challenges that logistics service providers are facing from an internal as well as from an external perspective.

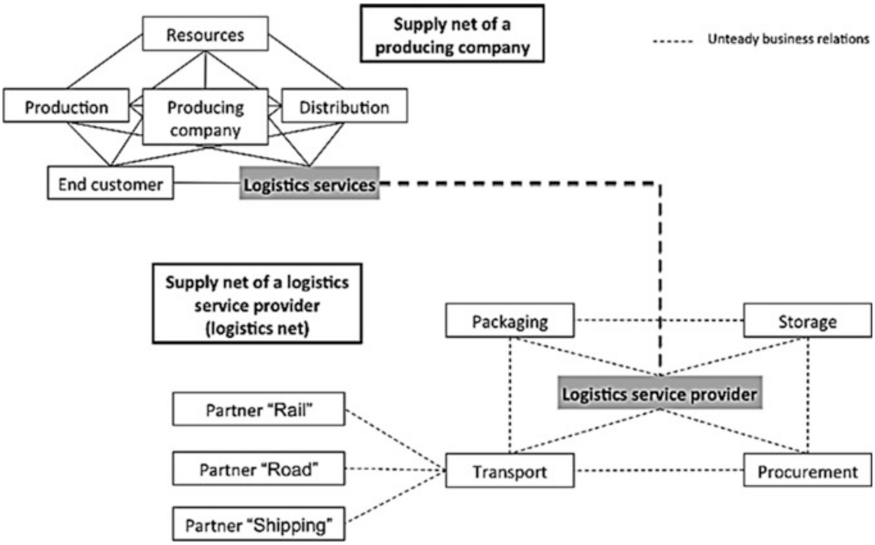

Fig. 1 Multilayer logistics service net (own illustration on the basis of [8])

5 Discussion of Findings

We compared the results of our study to the results of the RESPONSE study to work out specifics for the logistics sector as this sector was not considered in the study.[4] By doing so, we aimed especially at deepening our findings regarding the *external* challenges.

The RESPONSE study tried to find out how cognitive alignment differs across industries. The question was whether rapid changes in the environment of companies triggers or impedes learning, e.g. alignment to CSR. The RESPONSE study submits two potential explanations for the variance in cognitive gaps across industry boundaries to empirical validation, of which the first is:

> Firms in industries characterised by rapid change are likely to show greater cognitive alignment between executives and stakeholders than firms in industries characterized by slower rates of change. [11, p. 48]

A typical logistics network is a multilayer, rather unsteady and loosely interconnected net than an organized and structured network as illustrated in Fig. 1.

Business partners change as rapidly as prices and costs change, and daily business relies heavily on mouth-to-mouth, rather spontaneous agreements. Thus, especially for the small and medium sized logistics service providers, competition is fierce, due to the fact that in general services of different providers are

[4] Eight sectors were represented in the study: food, pharmaceutical, natural resources, energy, banking, chemical, industrial products and information technology [11, p. 25].

exchangeable easily. Environmental complexity is high: the net-structure of the logistics branch features a high level of market dynamism since, although customer requirements do not change rapidly with regard to the service as such, they do so with regard to how well the services are customized to the clients' individual needs.

This leads to the second hypothesis of RESPONSE, which says:

> Firms in industries characterised by higher levels of customisation of products and services offered are likely to show greater cognitive alignment between executives and stakeholders than firms in industries characterised by higher levels of standardisation. [11, p. 48]

The companies see themselves torn between the high expectations of their customers and the hard competition, as the results of the CoReLo research underline. The companies that participate in the CoReLo project offer customized, complete logistics solutions to their clients. The aim is to provide the client with fully integrated, hybrid logistics systems that correspond to the individual requirements of each client and that, in general, go beyond the classical logistics services such as transportation of goods, packaging, handling and warehousing. Within the network of a logistics company, the customer is the leading actor and all activities are in response to his or her expectations and demands. In effect, the service provider organizes the whole process for the customer and customization level is high.

At first sight, the results of CoReLo seem to approve the hypotheses and the preliminary estimation above and might lead to the conclusion that CSR management is very likely to be successfully applied by logistics service providers. But the short-term, open and informal logistics net in its loose coupling rather complicates CSR engagement for individual companies. According to those interviewed in our study, sustainable services require consistency and reliability. Having in mind that CoReLo questioned employees of the companies only and not also various stakeholders, the antagonism of the results between the RESPONSE study and CoReLo calls for a careful reflection of the cognitive gap that presumably exists between what companies think their services should look like and the "true" demands of the clients (and also other stakeholders). Having in mind that the customer is the leading actor and all activities are in response to his or her expectations and demands, the same applies presumably to CSR strategies that in most of the cases only have become relevant due to customer expectations. For example, this was the case with the EURO 5-truck which is until now the most fossil-fuel saving truck on the market and which became accepted due to customer demand. But then, following this logic, the customer may also be a "hindering" factor of individual CSR strategies of a logistics company if he does not support the efforts (financially).

Therefore, we suggest to refine the RESPONSE hypotheses by (1) integrating a differentiated view of the customer as a stakeholder on the one hand and as a crucial strategic business partner on the other hand (although both overlap) and (2) applying a network stakeholder approach that considers the interdependencies between logistics service providers, strategic business partners and their respective stakeholders. By adapting such a perspective, the logistics company and their customers, at least partly, *share* their responsibilities towards the different groups of stakeholders [12, p.62].

Parting from such a view, the logistics service provider can implement an integrated view on the different external challenges and stakeholder relationships *including* the crucial role of the customer. Furthermore, he can consider various ways of cooperation as an important means to intensify the dialogue between the different actors within the logistics net in order to increase cognitive alignment.

This is especially important if one considers the following aspects:

1. Firstly, although a changing environment may trigger cognitive alignment effectively, the true implementation of a CSR strategy within a firm is a long-term and challenging process. Therefore, as time and price pressure remains and will remain constant—a fact that most of the interviewees underlined—cooperation is required to find solutions beyond that. Customers can not demand sustainable logistics solutions and be at the same time not willing to reward the efforts financially. Customer expectations and orders cannot change extremely rapidly with every customer having different, sometimes even opposite requirements, when CSR activities shall take place. To really implement sustainable processes would require a more stable environment, which at the moment does not seem to exist. Regarding the relationship with the customer, one can state that stable and long-term perspectives are missing. In sum, logistics firms are missing an innovation-friendly environment that gives them time and space for new, more sustainable logistics solutions. Therefore, finding cooperative solutions together with the customer is crucial.
2. Secondly, not only are stakeholders and customers important, but rather the very structure of the logistics sector. As we have already stated, logistics service providers do not only depend on the customer and his expectations, but also on the collaboration along the supply chain. A truck driver has to deliver a good in a certain, in general a short time period. Although wages are not high, he has to balance time losses. Therefore, he must be able to rely on the people he has to deal with at each stage. This leads to situations in which bottles of wine have to be offered to achieve that one's truck will be handled first. In other situations, the truck driver has to help out at the lorry platform and unload the goods in his leisure time in order to be able to fulfil the order most rapidly and cheaply as possible. This is why trucks are also being called "sweatshops on wheels". If the situation of the drivers and the informal dealings that sometimes are not far from corruption shall be minimized, CSR rules and standards have to be implemented branch wide. If only one company changes its rules and others do not, the company might get severe competitive disadvantages.
3. Thirdly, our case studies show that there is an increasing stakeholder view establishing in the sector, as fostered dialogue with the public especially in the nearer surroundings of the company increases. NGOs (e.g. environmental groups) or citizens and their representatives are examples for stakeholders

whose interests have to be considered and taken seriously if a company really wants to tackle its social responsibility. Logistics service providers have to learn to manage these non-business relationships and to communicate with these stakeholders in order to maintain their license to operate [3] in the region. The acceptance of the communities located close to the logistics facility has proven to be of high (cost-) relevance for the firm. The hypothesis of the RESPONSE study, which says that "[g]reater pressure from external stakeholders results in greater cognitive alignment" [11, p. 45] is in line with our findings. Here, external "pressure serves as a stimulus for managers to engage with stakeholders in order to gauge their expectations" [11, p. 45]. A cooperative network approach not only helps to handle the communication with the stakeholders successfully, but also to learn from each other and to share a common source of knowledge.

6 Conclusion

The study presented in this article relies on two explorative case studies that allowed us to take an intensive look at CSR motivations, structures and strategies within two logistics companies and their networks. Anyhow, further research is necessary to include more logistics companies and their respective logistics nets in order to be able to get broader insights into logistics-specific CSR challenges and opportunities. Considering our final remarks, a focus of future research on cooperative opportunities within logistics nets might be promising.

We found some interesting forms of cooperation between customers and logistics service providers in the context of CSR strategies. One example is a Research and Development cooperation in which the customer agreed to test new fuel saving trucks. This example shows that there is a chance for stronger long-term business partnerships in CSR and that maybe structure and culture of the logistics sector have already started to change towards a more cooperative one. If CSR is taken seriously on both sides, it might even provide a win–win situation for the customer as well as for the logistics service provider.

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Part II
Intralogistics

Collaborative Detection of Autonomous Transport Vehicles

Andreas Kamagaew and Michael ten Hompel

Abstract To master changing performance demands, autonomous transport vehicles are deployed to make in-house material flow applications more flexible. The so-called cellular transport system consists of a multitude of small scale transport vehicles which shall be able to form a swarm. Therefore, the vehicles need to detect each other, exchange information amongst each other and sense their environment. By provision of peripherally acquired information of other transport entities, more convenient decisions can be made in terms of navigation and collision avoidance. This paper is a contribution to collective utilization of sensor data in the swarm of cellular transport vehicles.

Keywords Cellular transport vehicles · Internet-of-things · Logistics · Computer vision · Wireless sensor network synchronization · Sensor models

1 Introduction and Motivation

To master changing performance demands in facility logistics, autonomous transport vehicles are deployed to make in-house material flow applications more flexible. The so-called cellular transport system consists of a multitude of small scale transport vehicles which shall be able to form as a swarm. Therefore, the vehicles need to detect each other, exchange information amongst each other and sense their environment. By provision of peripherally acquired information of

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other transport entities, more convenient decisions can be made in terms of navigation and collision avoidance. This contribution to collective utilization of sensor data in the swarm of cellular transport vehicles is based upon three founding pillars: synchronization of sensor data, modeling of distance sensors, probabilistic computer vision algorithms for vehicle detection and network based sensor fusion. Finally, this detection methodology was empirically evaluated at the LivingLab Cellular Transport Systems at the Fraunhofer Institute for Material Flow and Logistics in Dortmund.

Methodically, this work follows the visualized approach in Fig. 1. Fundamentally information about the visible cellular transport vehicles of a sensor network is extracted from a set of data, in this case sensor data of a laser scanner. During the processing along the toolchain in Fig. 1 the information content increases steadily whereas the amount of data reduces. The pipeline starts with the synchronization of sensor data which is reflected in Sect. 2.1. This step is the basis of the data processing. For the interaction of the vehicles and the collective utilization of the acquired sensor data a common time base is needed. In the second step of the toolchain the sensor data acquisition takes place which is explained in the context of sensor models in Sect. 2.2. Besides the utilization of the vehicles own sensors, data from other vehicles can be acquired. During the next step the acquired data have to be transformed into the coordinate system of the vehicle. In the next process of the toolchain, the clustering, the amount of data reduces drastically. The acquired and transformed sensor data are segmented and clusters can be build. Those are important for the object extraction. Based on geometric probabilities of the clusters objects can be extracted. In the object extraction step some clusters like noise are rejected so that the amount of data decreases whereas the information content increases. During the classification process the extracted objects are classified into a list of vehicle candidates and a list of other objects. Section 3 deals with the methods of segmentation, object extraction and classification. Finally, the vehicle detection is described in Sect. 4. The list of candidates is used to verify the real vehicles and to calculate their poses.

2 Key Technologies

This chapter is deals with the key technologies which shall be considered for an optimal detection of the used vehicles by the utilization of laser scanners.

2.1 Wireless Sensor Network Synchronization

The topic of sensor data synchronization plays a major role and represents a challenge in the interaction of the used technologies. Without a common time base, sensor data cannot be assigned to a defined point time. Due to the use of

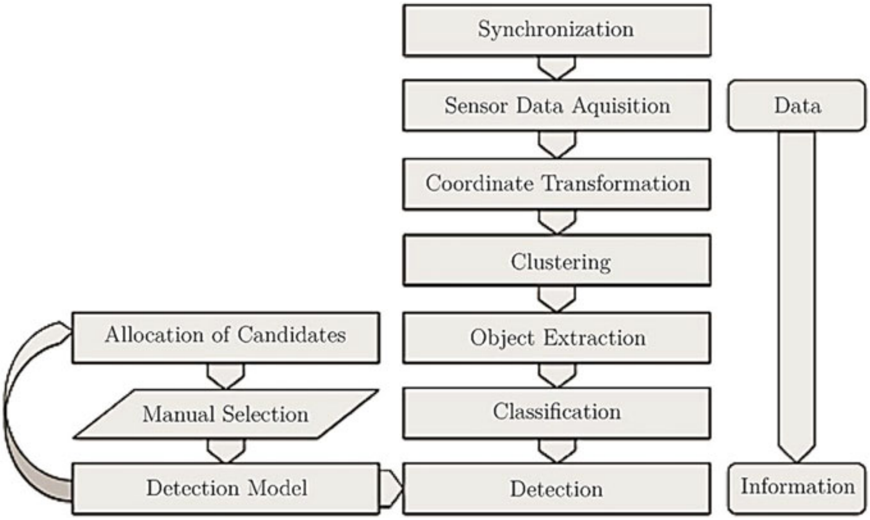

Fig. 1 Toolchain for collaborative detection of autonomous transport vehicles

WLAN as a communication medium, no time deterministic transmission behavior can be mapped. On that account it is necessary to determine the point of time of the data acquisition as precise as possible. Otherwise, no reliable data analysis of merged data is possible.

Therefore, the clocks of all cellular transport vehicles have to be synchronized in order to get a common time base. A synchronization accuracy of at least 10 ms was aimed at. During the next two paragraphs two standards for synchronization are introduced.

2.1.1 Precision Time Protocol Synchronization

The Precision Time Protocol (PTP) is a time synchronization protocol based on the IEEE-1588-Standard [1] with which, according to the master–slave principle, different clocks can be synchronized throughout a wired (Ethernet) network. Figure 2 provides an overview of the process. Theoretically, the PTP protocol is able to completely eliminate the delay times of a deterministic transport medium with symmetric connections. In case of asynchronous connections, for example different routes on a round-trip of a package, the synchronization accuracy is decreased. In Ethernet networks with conventional topologies the deviation is usually in the range of nanoseconds. As a part of the Cellular Transport System the radio protocol IEEE 802.11 (WLAN) is used. Due to the non-deterministic characteristics of this transport medium a larger loss of synchronization accuracy, which will be examined in the following, has to be expected. For this purpose the following experiment has been implemented:

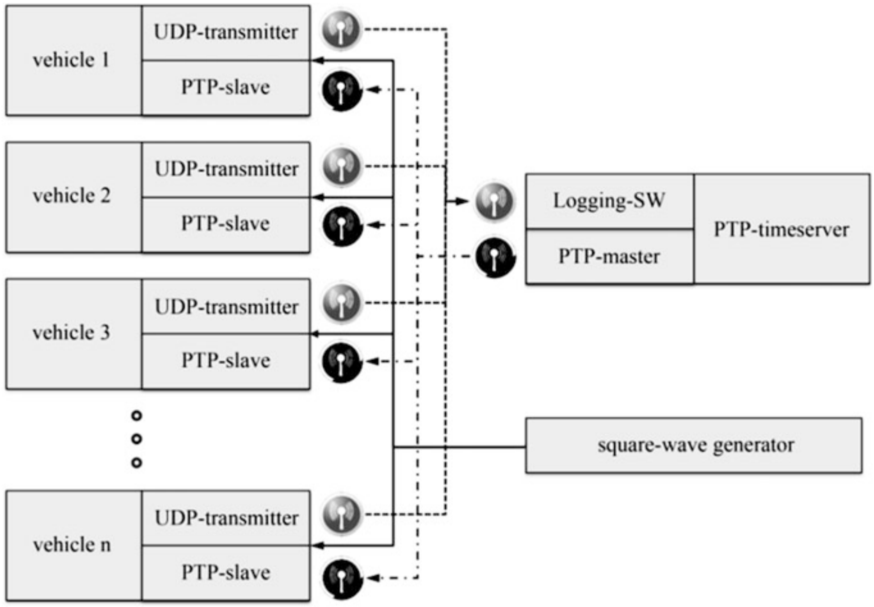

Fig. 2 Setup for the PTP series of measurements

The cellular transport vehicles of the Fraunhofer IML were physically supplied with a square wave with 4 Hz. resp. 10 Hz. The edge change of the square-wave signal acted as a trigger for the recording time of the local vehicle clock. Because of the equal length of each cable the vehicles were supplied simultaneously with the signal. Each of the vehicles was equipped with a separate in hardware implemented time server (PTP slave) with an own WLAN connection as well as a separate WLAN to communicate (UDP sender). The time emitter server has also been connected via WLAN to the network for synchronization (PTP master) and communication (logging-software). As part of the system implementation of the PTP based synchronization the timeserver solution of the project PTPd—Precision Time Protocol daemon [2] was utilized. On the vehicle side the EL6688 EtherCAT Terminal of the Beckhoff Automation GmbH was used. After several trials an exponential smoothing filter has been implemented which yielded the best results. Figure 3 illustrates the accomplished synchronization accuracy with and without a filter. In Table 1 more information about the measurement is given.

2.1.2 Network Time Protocol Synchronization

Because of the importance of the synchronization step during the toolchain and the huge maximum error, which is achieved with PTP without filtering another standard for synchronization, will be introduced. Network Time Protocol (NTP) is

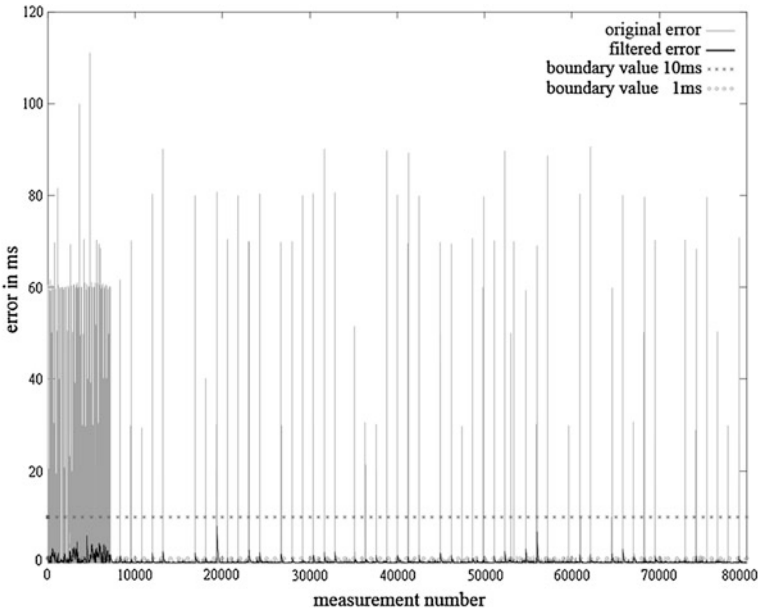

Fig. 3 Synchronization accuracy with PTP-measurement in a busy network with and without filtering

Table 1 Synchronization accuracy with PTP-measurement in a busy network with and without filtering

Measurement	E	E filtered	F	F filtered
Filter	–	Exp. smoothing	–	Exp. smoothing
Smoothing factor	–	$\gamma = 0.1$	–	$\gamma = 0.01$
Max. error	81.799 ms	21.266 ms	111.101 ms	7.945 ms
Min. error	0 ms	0 ms	0 ms	0 ms
Arithm. average	0.756 ms	0.501 ms	0.596 ms	0.284 ms
Standard average	4.215 ms	1.219 ms	4.336 ms	0.542 ms
3σ	12.647 ms	3.659 ms	13.009 ms	1.628 ms
Median	0.200 ms	0.168 ms	0.199 ms	0.105 ms

a standard (RFC-5905) for clock synchronization between computer systems which is currently available in version 4 [3, 4]. NTP is designed for a package based communication within a network resp. internet and uses the UDP protocol. Objective of NTP is a fault-tolerant clock synchronization within a network. The packages of the network have a variable time period.

Theoretically, NTP is able to calculate the weighted and averaged time delay of a non-deterministic transport medium depending on the number of subscribers. Asymmetric connections, for example different routes on a round-trip of a package, play a minor role in the standard. In Ethernet networks with conventional

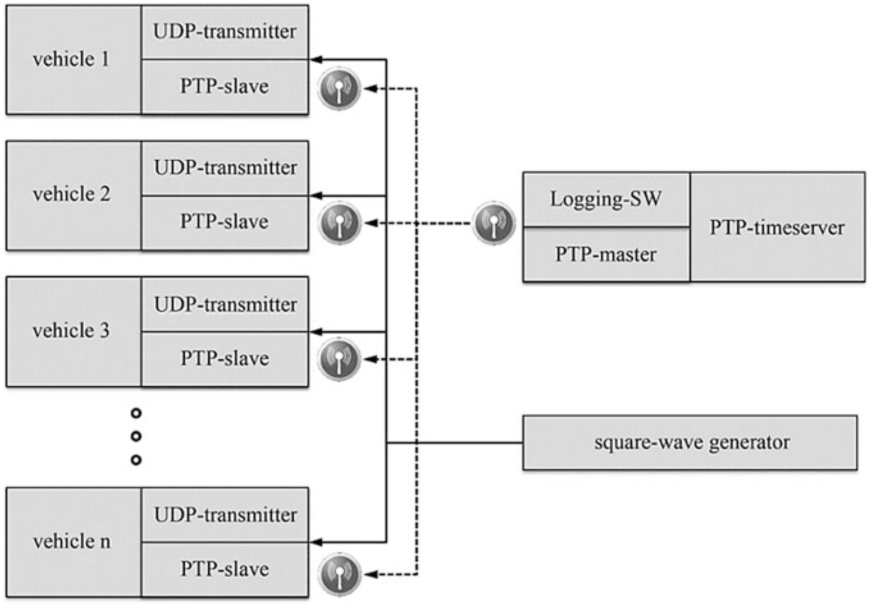

Fig. 4 Setup for NTP-measurements

topologies the deviation is usually in the range of microseconds. As part of the LivingLab the radio protocol IEEE 802.11 (WLAN) is used. Because NTP is also designed for asymmetric connections similar synchronization accuracies as in normal networks can be expected (Fig. 4).

To examine the synchronization accuracy an experiment similar to the PTP-experiment has been set up with the exception that no additional hardware was used for synchronization on the vehicle. Furthermore, the same WLAN connection is utilized for communication and synchronization.

As mentioned in the experimental examination of PTP the systematic requirements engineering methods were also applied to the following examination. Aim of the examination is to achieve the required synchronization accuracy of 1 ms resp. 10 ms without any additional hardware in the vehicle control. Therefore, several measurements with different NTP system implementations as well as filters were taken. The results are illustrated in Fig. 5 and Table 2.

2.1.3 Benchmark

Table 3 summarizes relevant results of the measurements and shows a comparison between both synchronization variants. The maximal permitted jitter of 10 ms can be achieved with the Precision Time Protocol as well as with the Network Time

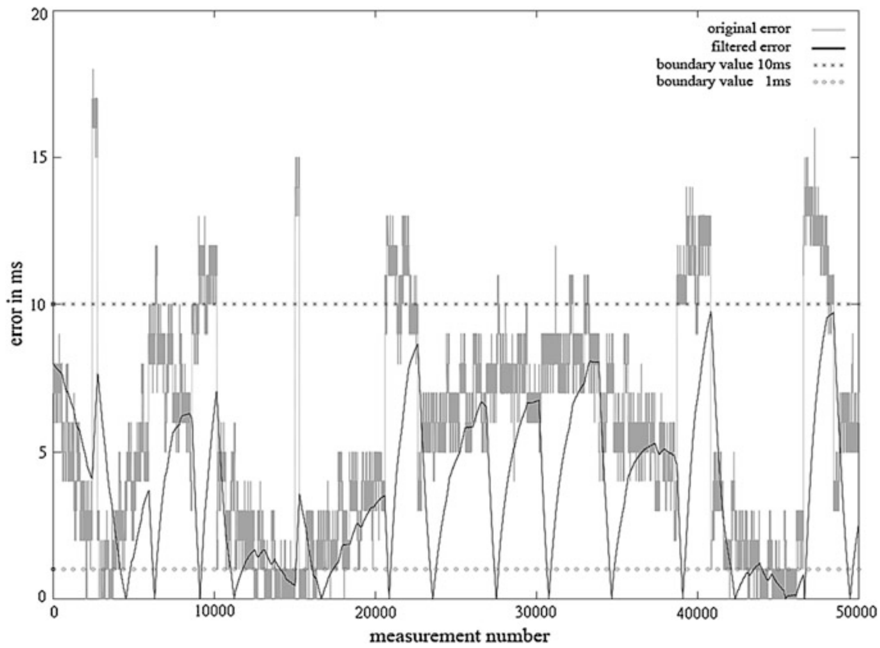

Fig. 5 Synchronization accuracy with NTP-measurement in a busy network with and without filtering

Table 2 Synchronization accuracy with NTP-measurement in a busy network with and without filtering

Measurement	I	I, filtered a	I, filtered b
Filter	–	Exp. smoothing	Exp. smoothing
Smoothing factor	–	$\gamma = 0.01$	$\gamma = 0.001$
Max. error	18.000 ms	15.879 ms	9.756 ms
Min. error	0 ms	0.001 ms	0.002 ms
Arithm. average	5.697 ms	5.480 ms	3.669 ms
Standard variance	3.675 ms	3.501 ms	2.567 ms
3σ	11.025 ms	10.504 ms	7.701 ms
Median	6.000 ms	5.618 ms	3.348 ms

Protocol. Neither of the two synchronization variants can reach the lower jitter boundary of 1 ms in the reference industrial environment, Cellular Transport System.

Table 3 NTP-measurements compared to PTP-measurements with and without filtering

Measurement	F (PTP)	F filtered	I (NTP)	I filtered
Filter	–	Exp. smoothing	–	Exp. smoothing
Smoothing factor	–	$\gamma = 0.01$	–	$\gamma = 0.001$
Max. error	111.101 ms	7.945 ms	18.000 ms	9.756 ms
Min. error	0 ms	0 ms	0 ms	0.002 ms
Arithm. average	0.596 ms	0.284 ms	5.697 ms	3.669 ms
Standard variance	4.336 ms	0.542 ms	3.675 ms	2.567 ms
3σ	13.009 ms	1.628 ms	11.025 ms	7.701 ms
Median	0.199 ms	0.105 ms	6.000 ms	3.348 ms

2.2 Sensor Models

After the synchronization step the sensor data will be acquired to detect objects. The sensory detection of objects contains measurement errors. Depending on the environment and the quality of the sensor the errors can have a vital impact on later data analysis. Therefore, the knowledge about the sensor behavior in an application is essential and constitutes one of the founding pillars of this publication. If the measurement behavior of a sensor is well known, the recent measurement can be evaluated by using predictive algorithms and can possibly be corrected. Measurement errors can be taken into consideration in the following process, for example during classification, likewise in the applied method. Probabilistic based sensor models are the basis of many research works particularly in the field of predictive algorithms, navigation, localization as well as mapping. For example, by use of sensor models the function principle of a range finder sensor with a part of its stochastic error can be modeled. Due to missing apriori knowledge certain errors cannot be modeled by use of sensor models. The so called beam model which is particularly suited for range finder sensors (e.g. laser scanners) is used as basis for this work. For each beam a model is built up incorporating:

- uniform distributed random measurements
- maximal sensor range measurement
- unexpected obstacles
- measurement noise around the mean

and all models are merged to a combination model [5].

As part of this research work a beam model of the SICK S300 Professional CMS was developed and has been exemplary tested for objects, which surfaces have different remission characteristics (Fig. 6).

The results of the experiment clearly show that the systematic errors, which depend on the remission characteristic of the examinee, cannot be mapped onto the SICK S300 Professional CMS without any prior knowledge because of the lack of knowledge about the detected object in an unknown environment. For this reason

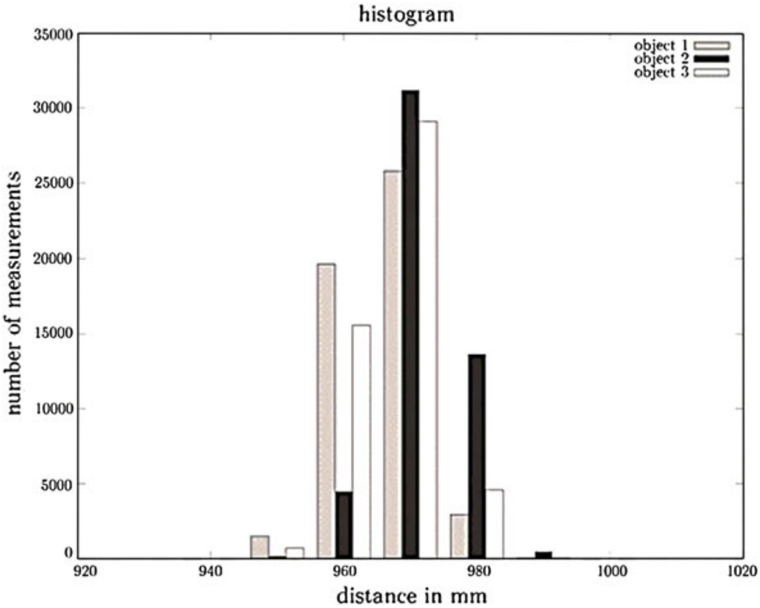

Fig. 6 Histogram of distance measurements to different test objects with a distance of 1,000 mm

the systematic error has not been considered in the modeling. Not considering the systematic error is one of the weaknesses of probabilistic sensor models. After the analysis of the experiments the measurement noise around the mean was in the measurement with the smallest standard variation σ at 0.58 and was in the measurement with the largest standard variation σ at 0.63. The average noise of all experiments amounts to approx. $\sigma = 0.61$. According to the probabilistic model this value will be used in further experiments for the SICK S300 Professional CMS.

3 Computer Vision

In the penultimate step of cooperative vehicle detection the algorithmic basis of the recognition has to be created. With the help of a laser scanner a scene is recorded. Subsequently, information about the detected object is generated and evaluated out of the data resp. points. First of all the acquired point sets are transformed into a global coordinate system and then segmented. Afterward the extraction of the detected objects and the classification of these through the developed methods take place. During the next paragraphs the different processing steps will be explained in detail.

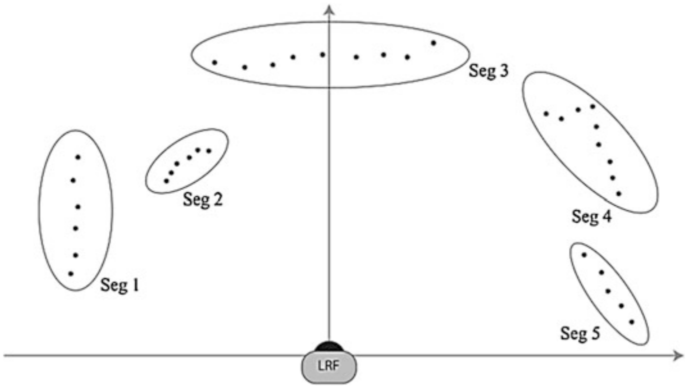

Fig. 7 Clustering of a laser scanner point cloud

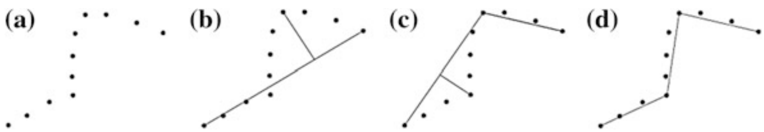

Fig. 8 Iterative end point fit

3.1 Segmentation and Line Extraction

Distance values of the laser scanner emerge from diffuse reflections of the laser spot at objects. Each point of the captured environment can be matched to an object.

The segmentation aims at the collection of single measuring points to segments so that the segments can be matched to an object [6–8]. After the segmentation each segment corresponds ideally to one object [9, 10]. The arranging into disjoint sets can be denoted as clustering [11, 12] and is shown in Fig. 7. Subsequently, the line extraction according to the *Iterative End Point Fit* procedure which is illustrated in Fig. 8 is applied.

3.2 Object Extraction

For a successful object extraction a list of candidates with segments, which are qualified based on their geometric properties for a later classification of cellular transport vehicles, has to be generated. Therefore, the form of the segment and its alignment has to be extracted. This procedure has to be as time optimal as possible and shall include all of the possible candidates for a later classification.

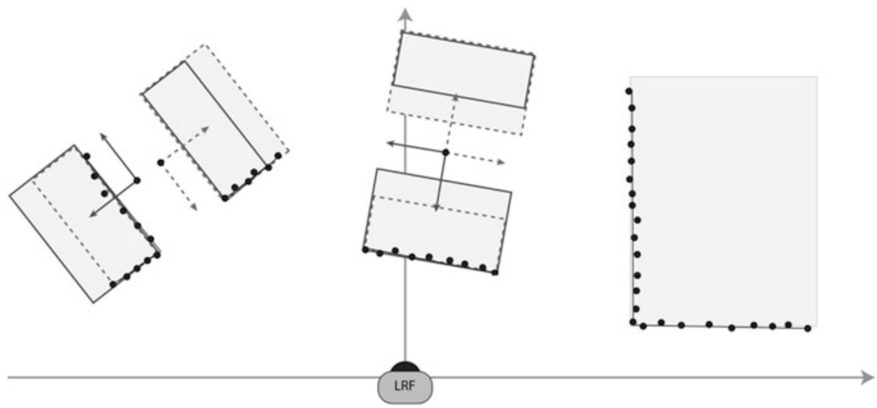

Fig. 9 Recognition of geometrical forms; possible vehicle positions are highlighted gray

From the point of view of a laser scanner the cellular transport system consists in rough approximation of blocks. Each block, which ideally consists of one segment or one pair of segments, has to be detected. Subsequently, the geometric properties of these segments have to be verified. In Fig. 9 possible pairs of segments which represent two unloaded vehicles and one rectangular object are exemplarily visualized. It has to be mentioned that the orientation of the vehicle cannot always be distinguished by one scan because of the similar shape of the front side and back side of the vehicle. In the next step the extracted objects have to be classified.

3.3 Classification

Within the developed classifier a disposition into two classes takes place:

- The class *vehicle* contains all possible extracted objects which may represent a vehicle.
- The class *no vehicle* contains all extracted objects which may for sure represent no vehicle.

Figure 10 shows three different kinds of classification. The ideal classification is visualized in Fig. 10a. This classification cannot be realized because of measurement noise and the lack of knowledge about the vehicle orientation. In Fig. 10b an incomplete classification is shown. This classification would not classify the right vehicle in Fig. 10b correctly. Therefore, the vehicle will no longer be used in further processing steps. Figure 10c visualizes the result of the classification method which has been implemented in this work. It consists of all possible vehicle candidates and this means that the ideal vehicle candidates and the false vehicle candidates are included. The advantage of this method is that in further processing steps all vehicle candidates are considered.

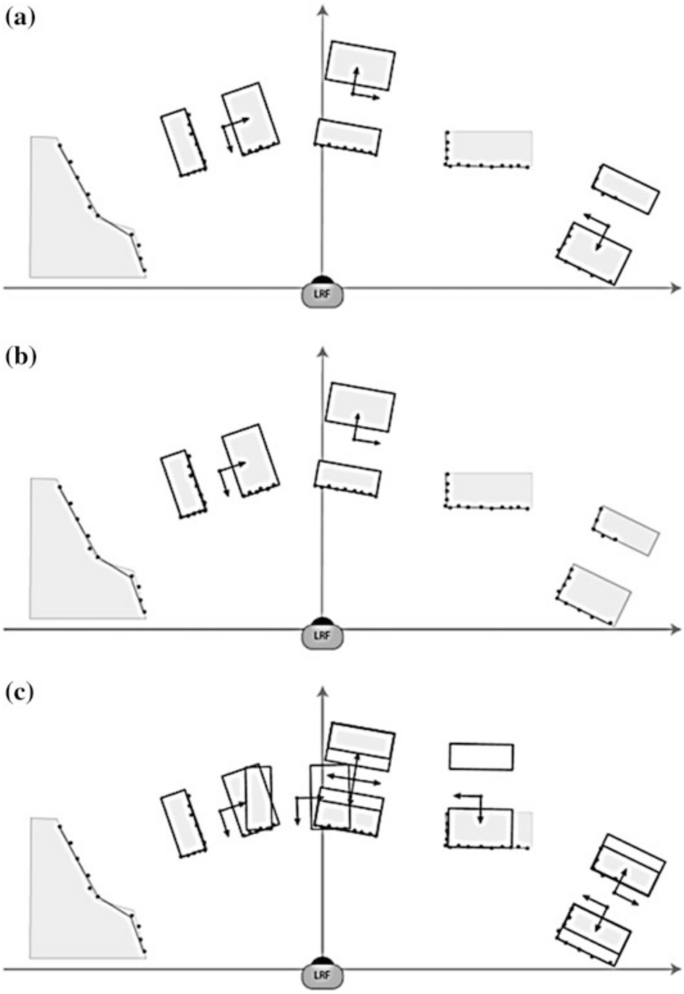

Fig. 10 Classification. **a** Ideal classification, **b** incomplete classification, **c** generic classififcation with presented method

3.4 Vehicle Detection

From the vehicle candidates, who are produced during the classification, the real vehicles as well as their exact pose have to be calculated. This paper has a focus on the set of candidates which shall be verified by the use of a probabilistic approach. Based on the developed sensor models in Sect. 2.2, the acquired data in a synchronous network (s. Sect. 2.1) and the methods of computer vision in Sect. 3, a new method with an approach of an occupancy grid will be introduced. This method assigns identity features to the extracted set of candidates and scores them.

To modulate the environment which is captured by a sensor the so called occupancy grids can be used. Thereby the environment will be divided into uniform, often rectangular cells of the same size. Those cells contain information about the state of occupancy in the environment. Occupancy grids can be updated online and therefore allow an immediate integration of new measurement data. Additionally, occupancy grids provide the opportunity to integrate several spatially divided measurement data sets, for example from a synchronized heterogenic sensor data network. For example, sensors like laser scanners, radar sensors, PMD-cameras or a merged data set of these sensors can be used [13–15]. In the LivingLab the sensor data of other vehicles can be integrated in the occupancy grid of one vehicle. It has to be mentioned that the merging of data is only possible if the vehicles have a common time base which can be achieved through synchronization methods (s. Sect. 2.1).

By the help of new measurement data the occupancy grid can be created. These measurement data generate occupancy probabilities for the grids. To integrate those probabilities at the right position into the existing occupancy grid the existing probabilities have to be merged with the new probabilities [16]. Figure 11 shows the process of detecting one vehicle by the use of occupancy grids. If one can assume that the occupancy probabilities of the cells are independent of each other, those can independently be updated [17, pp. 18–19].

4 Evaluation

The goals of the empirical evaluation are the qualitative and quantitative valuation of the developed algorithms as well as to analyze the methods for real-time capability in application-related, logistical scenarios. Initially, the individual methods of the vehicle recognition are qualitatively and quantitatively evaluated in several test set-ups. Therefore, the data of the individual vehicles as well as the merged data set are taken as a basis. The reference scenario illustrates a circulation between storage rack and a picking station (Fig. 12).

The recordings of the defined test set-ups are evaluated. Thereby, the quantitative as well as the qualitative appraisal of the detection take place on the basis of the classifier and the detection model. During the evaluation the poses of the vehicles are manually determined through consideration of the individual recordings and are compared to the results of the detection procedure. The following notation is used throughout the evaluation:

- *Correct candidate* is used for vehicle candidates if they correspond according to the manual verification to a real vehicle.
- *Incorrect candidate* is used if at the position of the vehicle candidate no vehicle is located.

The extraction of a candidate set out of a data set was described in Sect. 2.3. The goal of the candidate extraction is to add as soon as possible all visible

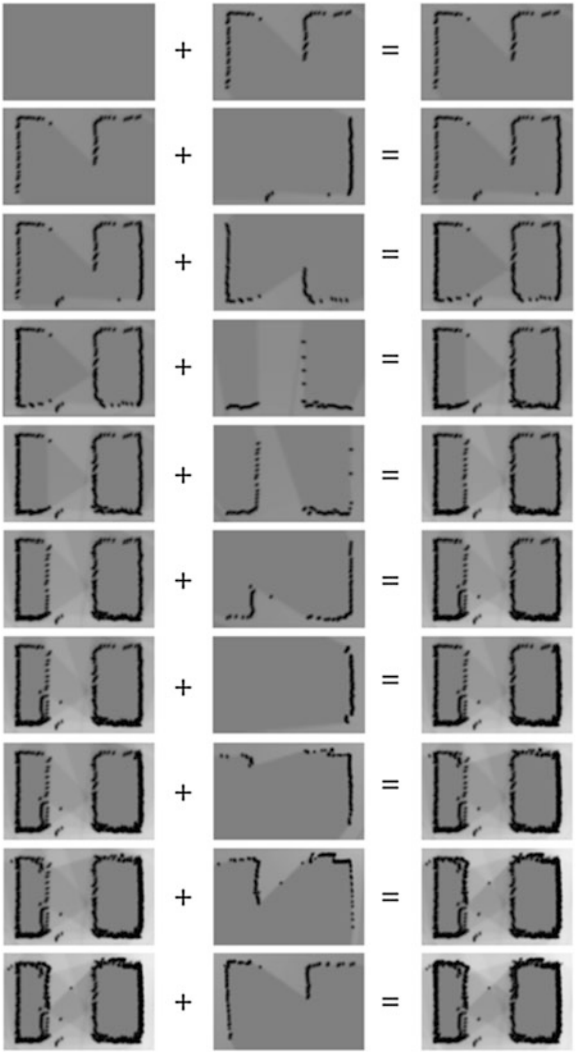

Fig. 11 Vehicle detection after several scans

vehicles to the extracted candidate set. Due to the fact that candidates who do not correspond to a real vehicle are filtered out in the following steps, the extraction of incorrect candidates plays a minor role as long as the number of those incorrect candidates is limited. Therefore, the detection rate shown in Fig. 13 is examined in the context of the quantitative appraisal. The extracted candidates were individually, manually examined and evaluated.

Based on the scenarios the average detection rate in Fig. 14 was examined. As appraisal benchmark the average identity criteria of loaded and unloaded vehicles in different distances was compared. This means that the average identity criteria *correct candidate* was calculated in all scenarios.

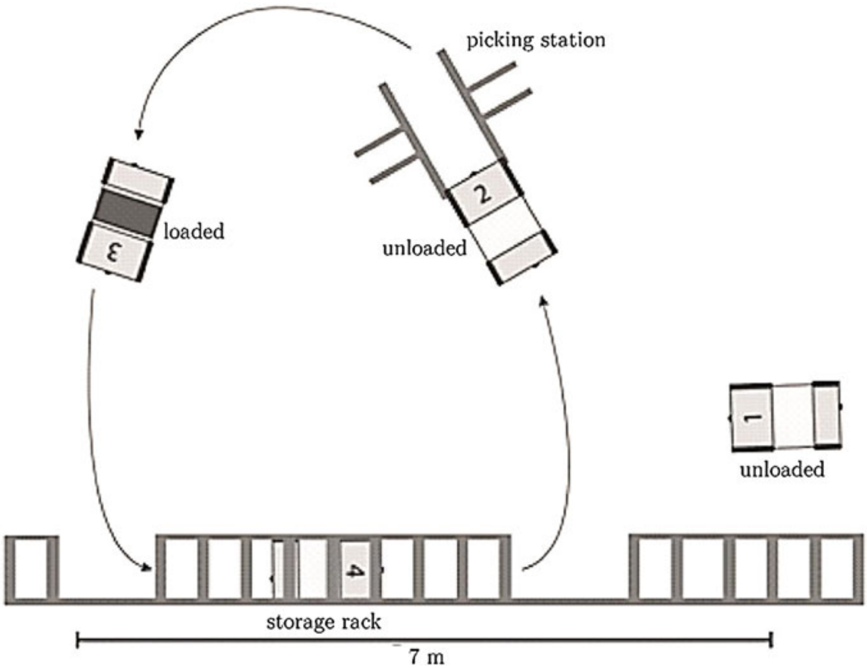

Fig. 12 Logistical setup of the interconnected cellular transport vehicles

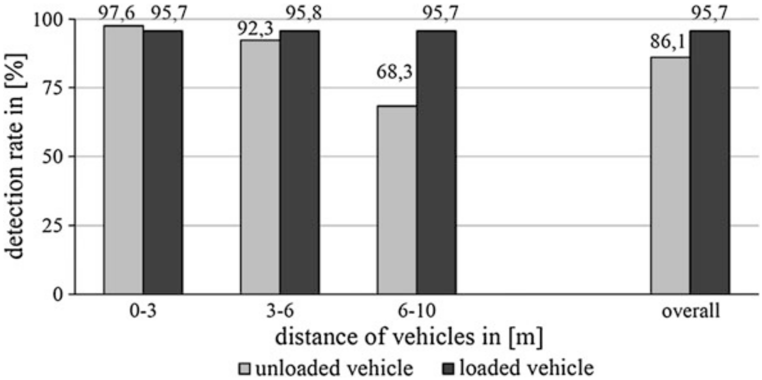

Fig. 13 Diagram of the detection rate of extracted vehicle candidates with different loading

5 Discussion and Outlook

With these developed methods a contribution to the enhancement of the cognitive abilities of cellular transport vehicles was achieved. By the help of a synchronized network, sensor data can be evaluated decentralized or centralized and they can be

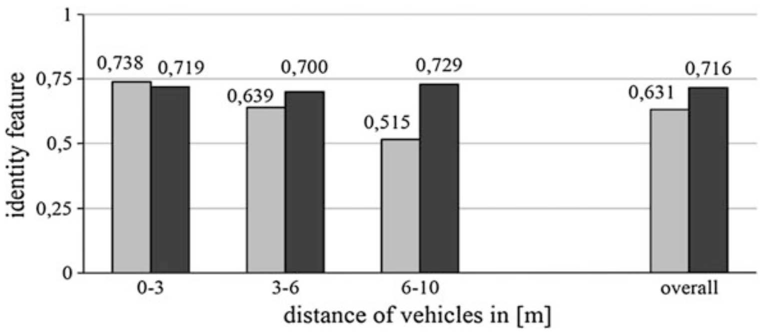

Fig. 14 Average identity feature of correct vehicle candidates

processed without a fallback onto proprietary solutions with additional hardware. In Sect. 2.1 the proof was given that through standard WLAN components a high precision time synchronization of the individual transport identities with standard protocols and an intelligent parameterization and filtering can be conducted. Developing novel sensor models in Sect. 2.2 which are based on a probabilistic approach provides a basis for further evaluations with pattern processing procedures which were developed in Sect. 2.3. Those methods in cooperation with the new vehicle detection method can be used in real-time in cellular transport vehicles with low computational power. The evaluation of the detection methods and performance which occurred in Sect. 4 emphasizes the adaptability of the developed processes because the system could be integrated into the LivingLab cellular transport systems at the Fraunhofer IML and the capability for real-time tasks could be proved.

The detection procedure which has been developed as a part of this work is currently extended to different tracking procedures and one resultant collision avoidance method. This one enables sustainable collision avoidance in the vehicle swarm with heterogenic sensors through dynamic, topographic environment models which are provided to all transport identities.

Distinct trends show that novel 3D-sensors will be largely deployed in cellular intralogistic and in the field of automated guided vehicles so that bounding volume of a vehicle and not only the area can be considered. Therefor one can better react to exterior influences. Furthermore, by the use of methods which has been developed in this work novel and inexpensive 3D-sensors, e.g. the Microsoft Kinect, can be used in the future. Currently, at the Fraunhofer IML research work to detect environment features, transport vehicles and persons by the use of 3D-sensors as well as native gesture controls take place. These sensors can be arbitrarily distributed to transport identities in a synchronized sensor data network. In the field of small-scaled autonomous transport systems a basis for a distribute collision avoidance system can be provided. This leads to considerable saving of system costs because just a fraction of the nowadays used sensors is necessary. Besides, a synchronized network for knowledge management of multi-agents-systems for time critical tasks can be utilized so that the partly existing disadvantages in the field of reactivity of multi-agents-systems can be compensated through deterministic information flow.

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3D-Computer Vision for Automation of Logistic Processes

Hendrik Thamer, Daniel Weimer, Henning Kost and Bernd Scholz-Reiter

Abstract The availability of low-cost range sensors has led to several innovative implementations and solutions in various application fields like object recognition and localization, scene understanding, human-robot interaction or measurement of objects. The transfer of the corresponding methods and techniques to logistic processes needs the consideration of specific requirements. A logistic application field that requires robust and reliable 3D vision systems is automated handling of universal logistic goods for (de-)palletizing or unloading of standard containers in the field of sea and air cargo. This paper presents a 3D-computer vision system for recognizing and localizing different shaped logistic goods for automated handling by robotic systems. The objective is to distinguish between different types of goods like boxes, barrels or sacks due to their geometric shape in point cloud data. The system is evaluated with sensor data from a low-cost range sensor and ideal simulated data representing different shaped logistic goods as well.

Keywords Automated logistics · 3D-computer vision · Object recognition · Machine learning

1 Introduction

Due to the availability of low-cost 3D-sensors, the analysis of range data is a current research topic in various application fields [1]. Regarding the automation of logistic processes, the interpretation of range data is an important step for

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automated handling of logistic goods by robotic systems. Hence, the development of robust and reliable 3D-computer vision systems is necessary. Especially the development of an automatic handling system for recognizing and localizing logistic goods such as boxes, barrels, or sack objects requires a suitable 3D-robot vision system [2, 3]. The task is to classify different objects according to predefined shape classes and compute gripping points for a robotic system in order to perform handling processes.

This paper presents a 3D-computer vision system for recognizing different types of logistic goods based on machine learning methods. The objective is to distinguish between the aforementioned three shape classes due to their geometric shape in 3D-point cloud data. After a correct classification process, a robot can be able to handle them automatically. Instead of comparing object candidates with a huge database at runtime, we train a model representation in an offline mode using machine learning methods. Concerning deformable goods like sacks, the machine learning approach should be more efficient regarding computation time than using a huge database which contains all possible deformations and rotations of potential objects. Additionally, the machine learning approach is more robust as it can accept deviations of object candidates. The recognition process consists of an offline training and an online recognition process. Within the offline training step, we extract global features from simulated sensor data. For simulation, we use a 3D-sensor simulation framework that generates point cloud data from virtual logistic scenarios due to specific sensor characteristics. Thereby, we can create a sufficient amount of training data without the need of a real hardware setup. Within feature extraction we use a global feature descriptor and two different machine learning methods. These are support vector machines and artificial neural networks. Both are compared to each other by the achieved results. In order to apply our method, the goods are segmented in the scenarios in a preprocessing step within the online recognition process.

2 3D-Computer Vision

Within 3D-computer vision systems, the recognition and 6 degree of freedom (DOF) pose estimation of objects is a major technical task [4]. The recognition process is often performed using features describing the shapes of objects. These features can be categorized in global and local features [1]. Global features describe the entire point cloud data and therefore require a prior segmentation step since the point cloud must contain only one single object that should be recognized. Points in the cloud not belonging to the object such as background can lead to a wrong classification result. Example global feature descriptors are (Clustered) Viewpoint Feature Histograms (VFH) [5, 6] or Ensemble of Shape Functions [7] which all store the resulting shape descriptions in a histogram. In contrast to global features, local features describe the local geometry of a single point. Usually, they are only computed for previously extracted key points and do not need a prior segmentation process. Due to the computation of the descriptor regarding only the local neighborhood of a point, they are more influenced by measurement noise compared to global feature descriptors. Example local feature descriptors are Spin Images [8], Fast Point Feature Histograms [9] and Signature of Histograms of Orientations [10].

Within the application scenario presented in this paper, single logistic goods lying on the floor should be correctly classified using an ASUS Xtion Pro sensor for point cloud acquisition. Since the investigated scenarios do not contain a high amount of clutter and occlusion, a global feature description technique is applicable for recognizing the shape class of different logistic goods since a correct segmentation of the objects is possible.

3 Object Recognition System

Our proposed system consists of an offline training process in which the model database is developed and an online object recognition process. Within the training process, models of the three defined relevant shape classes of logistic goods are learned by machine learning techniques. The application of machine learning techniques offers great benefits. Concerning deformable goods like sack, the machine learning approach is more efficient regarding computation time in contrast to storing all available models in a model database. This would lead to a high number of model database entries to cover all possible deformations and rotations. Additionally, the machine learning approach is more robust as it can accept deviations of object candidates by learning models of shape classes of logistic goods. Within our approach, we use simulated sensor data as a training set for the machine learning algorithms. Therefore, we avoid the need of performing experiments with a hardware setup which could be a time-consuming process. Figure 1 shows the structure of our approach dividing the entire recognition process in the aforementioned offline and online process. The following subsections explain the single processes in more detail.

3.1 Offline Training Process

Within the offline training process, a suitable amount of training data is necessary for supervised learning by using a machine learning technique. This is realized by generating simulated sensor data from virtual geometric models of logistic goods. Therefore, we have implemented a sensor simulation software which is able to realistically simulate the sensor data from commercially available range sensors such as laser scanners, Time-of-Flight (TOF) cameras and low-cost range sensors. The simulation is based on virtual geometric models of single objects or of whole environments and uses techniques from the field of computer graphics such as ray

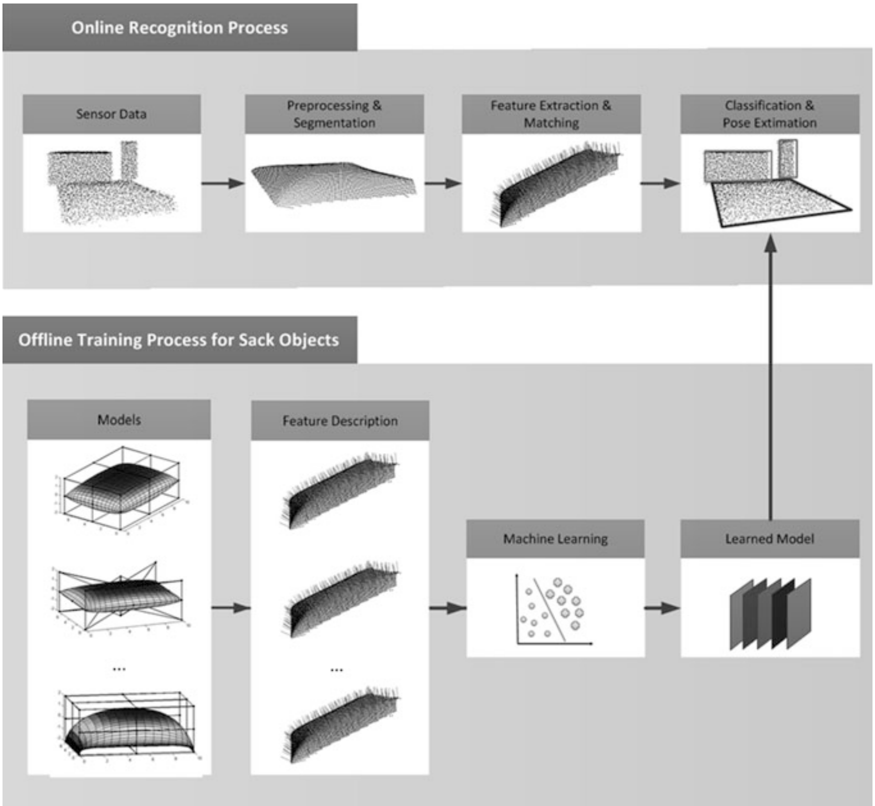

Fig. 1 Structure of the proposed object recognition system

tracing and hidden surface removal for run-time optimization. For each predefined shape class different geometric deformable instances are created and a suitable amount of training data is simulated. Additionally, we vary relevant properties of each simulation such as viewpoint, point density and sensor characteristics.

The data is automatically labelled to the corresponding shape class and described by using a global feature shape description technique. Here, we use VFH that store the geometric description in a histogram with 308 bins. Figure 2 shows a point cloud of a logistic good and the corresponding VFH histogram represented as graph. The generated feature histograms are used as training examples for machine learning techniques such as support vector machines or artificial neural networks in order to learn models for each predefined shape class. The resulting models are used for the final classification of single goods within the online recognition process.

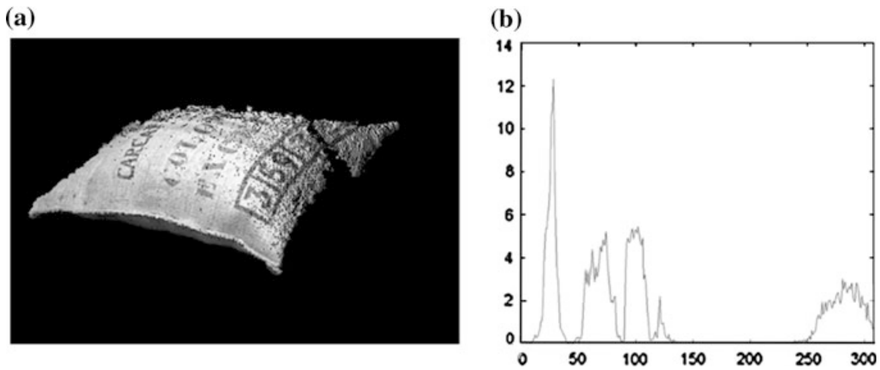

Fig. 2 **a** Point cloud of a sack object. **b** Viewpoint feature histogram

3.2 Online Recognition Process

The online recognition process consists of a preprocessing and segmentation step where the influence of measurement noise is reduced and single objects candidates are segmented out of the entire point cloud. Afterwards, the points are classified during a classification step and the pose is estimated. First, the points representing the background are removed from the point cloud by detecting and removing dominant planes in the scenario. The influence of noise is reduced by applying median filtering and removing points that are not detected through the dominant plane removal step by outlier removal algorithms. The remaining points represent possible logistic goods in the scene.

In order to separate the object candidates from each other they are clustered according to their Euclidean distance. Afterwards, the clusters represent single object candidates and VFH descriptions for each cluster are computed. Then, the descriptions are compared with the learned models and are finally classified to the best matching shape class. Figure 3 shows the entire process for an example packaging scenario with goods from all predefined shape classes. Figure 3b, c illustrate the results after preprocessing and segmentation. Figure 3d shows a rendering of the classified objects. For the reason of vividness, the rendered objects are augmented by the correct pose and dimension. If the sensor data contains a higher amount of occlusion or clutter and a segmentation based on the Euclidean distance cannot be performed, more appropriate segmentation algorithms are necessary in order to extract single object candidates.

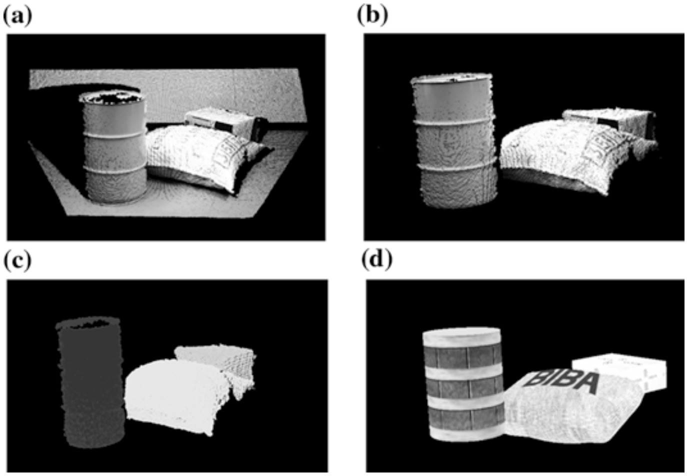

Fig. 3 **a** Example point cloud of a packaging scenario. **b** Result after preprocessing and segmentation. **c** Result after clustering to object candidates. **d** Classification results

4 Evaluation

The system is evaluated using ideal simulated sensor data as well as real sensor data acquired with the low-cost 3D-sensor ASUS Xtion Pro. By using ideal simulated sensor data, the theoretical optimal performance of our approach can be evaluated. The evaluation with real sensor data shows the practical usability in real world application scenarios taking measurement uncertainties such as noise into account. The shape description with global features is realized with VFH since the computation time of the descriptor is very fast and it has shown great potential within other application scenarios. The machine learning methods are a linear support vector machines and artificial neural networks using back propagation. Both methods are trained with 500 simulated training examples for each shape class. The examples include different instances of each shape class as well as sensor data acquired from different viewpoints and with a varying point density. For determining the cost parameter for support vector machines and the number of hidden layers of the neural network are determined by using a grid search.

4.1 Simulated Sensor Data

The system is evaluated with 30 simulated point clouds from different instances of each shape class. Therefore, the sensor simulation parameters such as field of view and angular resolution are adapted similar to the ASUS sensor used for real sensor data acquisition. Concerning sack objects, geometric models with local deformations are created in order to simulate different loadings. The results of the evaluation with simulated data are presented in Table 1.

Both machine learning methods show very good results concerning correct classification rates while analyzing ideal sensor data. Particularly deformed sack objects are almost classified correctly in each experiment showing the great flexibility of machine learning approaches.

4.2 Real Sensor Data

The real sensor data set consists of examples with 99 boxes, 48 barrels, and 56 sack objects. Similar to the experiments with simulated data, the data is acquired from different instances of each shape class and from different viewpoints. The achieved classification rates are presented in Table 2. Analyzing the real sensor data set shows a slightly better performance of neural networks dealing with measurement uncertainties. Nevertheless, both methods have difficulties dealing with barrels. Here, the main reason is the quality of the sensor data. The plane part of the barrel object is not correctly mapped in the point cloud and most of the plane is missing. The reason is the reflecting metal surface of the barrels used for the experiments.

These effects lead to misclassification and strongly affected the results. Here, the sensor data acquisition using TOF sensors could improve the classification results as they are generally more accurate and not that effected by measurement conditions. Regarding the classification rate of deformable sack objects, both machine learning approaches show good classification results confirming the flexibility shown in the experiments with ideal simulated sensor data.

Table 1 Experimental results obtained using simulated data

Machine learning method	Boxes (%)	Barrels (%)	Sack (%)	Total (%)
Artificial neural networks	90	90	93.33	91.11
Support vector machines	93.33	90	96.66	93.33

Table 2 Experimental results obtained using ASUS Xtion Pro

Machine learning method	Boxes (%)	Barrels (%)	Sack (%)	Total (%)
Artificial neural networks	78.78	66.66	94.64	80.03
Support vector machines	80.80	66.25	83.82	73.66

5 Conclusion

Automatic handling of logistic goods requires reliable and efficient 3D-computer vision systems for recognizing shape classes of goods. Generally, they must be able to distinguish between three shape classes and needs to be robust towards deformation of the goods too. Especially, free-form shaped goods such as sack objects have a high intra-class variance as their shape depends on the loading and positioning of the sack object. In order to deal with these requirements, this paper presented an object recognition system based on machine learning methods. The system was evaluated with real and simulated sensor data and the first results look very promising. Nevertheless, measurement uncertainties such as noise or completely missing parts caused by sensing principle of the low-cost range sensor strongly affected the classification results.

In further research activities, we will focus on improving the segmentation step since errors in this stage strongly affect the classification results due to the working principle of global feature description techniques. Additionally, scenarios with a higher amount of occlusions where a segmentation based on the Euclidean distance is not feasible could currently not be handled by our approach. Another research direction is the usage of local features in combination with machine learning techniques. This is relevant regarding scenarios where the goods are piled as in packaging scenarios within containers. Here, the local features can also be used for an improved segmentation. Furthermore, we will focus on the training step of the machine learning algorithms. Here, the selection of training examples have a crucial impact on the resulting classification results and offers possibilities to improve the results of our system. In further experiments, we will compare our simulated training set with training examples acquired by real sensors within the training process.

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"Staplerauge": A Framework for Camera-Based Sensor Functions on Forklift Trucks

Matthias Jung, Frank Hohenstein and Willibald Günthner

Abstract Computer vision seems a promising method for realizing the most important sensor tasks on a forklift with just one technology, hence significantly reducing integration costs on the forklift and with the IT-system in the background. This approach is highly flexible and easy to retrofit - additional features can be integrated by adding/changing software components. However suppliers of those sensor solutions, which are currently available, are mostly small or medium enterprises (SME) with little or no know-how in the field of computer vision. We have developed a software framework to enable and assist these companies with the design of such systems for logistics transport systems.

Keywords Computer vision · Software framework · Functional integration · Sensor functions · Forklift trucks · Fork allocation · Fork height · Barcode reading · Localization

1 Introduction

Tasks performed by forklift drivers ensure a high degree of flexibility in transport processes, but are also manual and error-prone in nature. To detect and fix these mistakes, a variety of sensor-based solutions, based on different sensor

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technologies for each function, is available. Combining these sensor systems requires a lot of costly integration work for both the forklift itself and the IT System of the customer.

Using functional integration (i.e. one technology for a couple of sensor functions) lowers integration costs significantly, because only one type of sensor with similar properties needs to be mounted on the forklift and integrated into the IT system. Various products e.g. [1, 2] and studies have proven a general ability of computer vision solutions to solve similar problems. Therefore computer vision seems a promising method for realizing the most important sensor tasks on a forklift:

- barcode reading
- localization
- fork height
- fork allocation status.

With these four functions goods in a warehouse can be tracked and traced within the warehouse more reliably by both identifying and tying their identity to their positions before and after transport. The barcode scan is used to identify the goods, the localization sensor determines the *(x,y)*-coordinates of the forks (and indirectly the goods), the fork height determines the z-coordinate of the goods being picked up or placed, and the fork allocation status sensor detects when goods are being picked up or placed—the moment to measure the other three sensors.

By using computer vision, those features will be implemented mostly in software instead of hardware. This approach is highly flexible and easy to retrofit in case of changing needs in the industrial application. Additional features can be integrated by adding new software components or upgrading the existing ones to improved versions.

However suppliers of sensor solutions which are currently available are mostly SME with little or no know-how in the field of computer vision. To enable and assist these companies in the design of such systems for logistics transport systems, we have developed a software framework, which

1. helps to create flexible computer vision solutions
2. simplifies the use of image processing and computer vision algorithms
3. includes demonstrators for some sensor functions.

2 Software Framework

The development of a computer vision solution with focus on forklifts consists of two main parts: On the one hand, it requires basic functions such as camera access (grabbing images, setting camera attributes), common image processing and machine learning algorithms; on the other hand it needs algorithms tailored specifically for use at forklift trucks.

The software framework offers various features to simplify the design of computer vision applications. This is achieved by implementing often needed image processing steps (from image acquisition over image preprocessing to image analysis) and the simplification of the combination of such processing steps.

To speed up the development process of such an application, those functions are bundled in a common environment to spare users the choice of the proper components and their integration into the software framework.

The demonstrators are then developed by using the software framework to both validate the concepts of the demonstrators and the framework at the same time. To further reduce the (entry) threshold, we provide an integrated development environment (IDE), which can be used to start programming right away without setup effort or license costs (see Sect. 2.2 for details).

2.1 Architecture

The central paradigm of the software framework is object oriented programming [3]. Classes (templates for objects) and algorithms from the following areas are provided:

- Sensorfunction (demonstrators)
- Image acquisition and distribution (VideoHub)
- Image processing and manipulation (Filter)
- (Camera-) configuration ((Camera-)Configurer).

The following (simplified) class diagram in Fig. 1 roughly sketches the architecture of the software framework.

2.1.1 Sensorfunction

The class Sensorfunction is the central component. Objects instantiated from this class implement a sensor function and can use objects of all other classes for their purpose. The demonstrators constructed for the project purpose (barcode detection, fork allocation status, fork height sensor, localization) are derived from this class. Each sensor function contains a chain of image processing filters which contain the image processing logic.

2.1.2 Design Pattern for Image Processing

We have identified the following criteria and constraints that apply to image processing applications on forklift trucks:

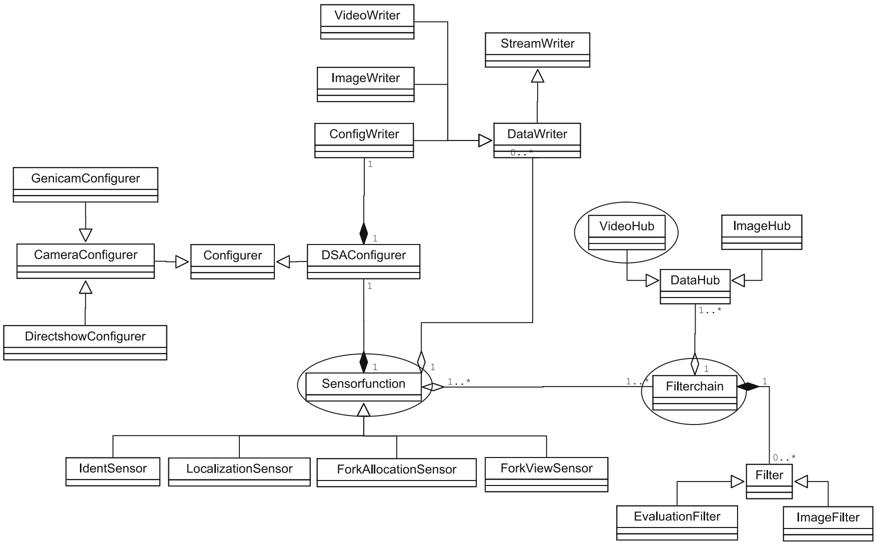

Fig. 1 Simplified class diagram (the core components are *circled*)

1. Amount of data to process: the input data bandwidth to deal with can be up to 125 MB/s with a 5 Megapixel camera stream at 25 images/second.
2. Many processes in logistics require a synchronous flow of material and information ("real-time"). The sensor systems must therefore generate their information with as few delay as possible.
3. The most important sensor functions (see Sect. 1) require no user interaction. The information generated by the sensors is mainly processed by the IT-system in the background—methods for user interaction are hence not considered as a part of the framework.
4. Data processing systems on forklifts are powered by the forklift's battery. Available industry PC products sold as forklift terminals have very limited resources in comparison to the average home pc, because they are mostly used for interaction with the forklift driver. This has implications regarding the choice of the proper software design pattern, as the software based on the framework will be executed on a single, compared to home computers, slow data processing system.

According to criteria 3 and 4 design patterns tailored for interactive systems (user interaction) and distributed systems [4] are not feasible as a basic concept for a software framework to be used under the given conditions. Specifically useful regarding criteria 1 and 2 is the *pipes and filters* design pattern [5] towards realizing an image processing application, as it was designed to efficiently manage big data streams.

Hence in the software framework the logic of all basic image processing functions is embedded inside Filter-objects, which generate an output when any input is given. Such components are connected to each other by so called *pipes*, meaning the output of one *filter* is connected to the input of another *filter*. Together the filters and pipes form a sequence of *filters*—a filter chain—represented by the Filter Chain-object. In the software framework there are two types of *filters*:

1. Image Filters take an image (and possibly other parameters) as input, modify it and supply the modified image (and possibly additional information) as output.
2. Evaluation Filters take the same input as Image Filters but supply the unmodified image and additional information extracted from the input image as output.

To provide a mechanism of abstraction a Filter Chain itself can serve as a *filter* within another Filter Chain. As a result a series of *filters*, which performs a more complex task, can be easily re-used in other Sensor functions.

2.1.3 Image Acquisition: Sharing an Image Source

The class Video Hub can be used to both share an image source and common image preprocessing results among multiple demonstrators. An instance of this class distributes copies of sensor-data (e.g. images grabbed from a camera or already preprocessed images) to the following filters—therefore it is possible to run common preprocessing steps to enhance the input image only once and use the result in independent sensor functions to save computation time without risking mutual interference between the sensor functions.

2.1.4 Integration of Cameras

The integration of cameras in the software framework features two basic functions:

- Image acquisition[1] and
- Changing camera settings to influence the images delivered by the camera (e.g. by changing the shutter time).

To make both functions available, making use of the driver API is necessary. With GigE Vision and Usb3 Vision [6] vendor independent standards to access camera video streams are available, but unfortunately the specifications of those standards are only available to member companies of the Automated Imaging Association (AIA) [7] effectively preventing a compliant open source camera driver. This is why the software framework cannot provide a generic way to access

[1] Grabbing an image from the camera through the camera driver.

cameras compliant to those standards. Thus, the user has to use and tether the driver provided by the manufacturer into his program instead (most manufacturers provide sample code for this task).

For the camera configuration the open and manufacturer independent Genicam [8] standard, which is supported by most GigE Vision cameras, can be used in combination with the software framework. This generic way of configuring a camera allows to set both standardized camera attributes and supports a way of setting non-standard attributes through a generic way to make available such unknown attributes to software programs.

Also rudimentary support [9] for camera drivers using Microsofts DirectShow API [10] is available. The major disadvantage of DirectShow with respect to industry-grade cameras is the fact, that only a short, fixed list of camera attributes is available for configuration independent of the camera vendor, while typically present special camera functions can only be addressed by vendor-specific extensions. Also DirectShow is only available for Microsoft Windows.

2.1.5 Image Processing Methods

According to Jähne [11] digital image processing is the processing of images from image acquisition with a sensor to the extracted information. Jähne divides it into four main parts:

1. Image acquisition[2]
2. Image preprocessing (image enhancement)
3. Feature extraction (application of filters and mechanisms to extract relevant objects from the not relevant background)
4. Image analysis.

While image acquisition and parts of the image preprocessing are handled by the camera, image processing software only has to process the given image from there. This means that the software framework has to deal with parts of the image preprocessing (mostly image enhancement) as well as feature extraction and image analysis. The digital image processing algorithms in the software framework were integrated via the OpenCV [12] library. This library was chosen because:

1. It is published under an open source license, which allows but doesn‘t force publishing of the derived sources (the latter is a major concern of the industry).
2. It offers a lot of algorithms from all relevant parts of image processing.
3. It is actively developed by a community, new algorithms are swiftly integrated.
4. A lot of documentation is available to help both beginners and experts.
5. Support and code snippets using the library can be found all over the Internet.

[2] Recording an image from the environment through the sensor.

Within the software framework standard image processing algorithms are encapsulated into Filter-objects, which allows them to be put together with other filters easily. The minimum amount of required parameters for each algorithm is reduced by setting parameters to generally useful default values within the wrapper classes.

2.1.6 Concept of Use

As stated above, a sensor function consists mostly of a list of (connected) filters. Among the input of the first filter is always a Video Hub, which supplies the video stream from a camera or video file (e.g. for debugging or testing). All downstream filters work on the output of preceding filters. The last filter supplies the desired information determined by the entire Filterchain.

To create a meaningful filter chain the following objects need to be instantiated:

1. a (Video) Hub
2. a couple of (different) Filters
3. a list, which will contain the above Filter-objects in a predefined sequence.

The input and output of the filters then need to be defined in order to create the connections between the filters. The user has to make sure, that all required inputs are connected to outputs of preceding filters. Such a list of filters is passed on to a Filter chain-object, which is responsible for managing and executing the list of filters as defined by the user. Custom filters programmed by the user can be integrated in the same way as the filters already provided by the software framework.

2.1.7 Example

The following program listing implements a very simple fork camera, which allows the forklift driver to watch from the fork's point of view – given the camera is mounted properly. The program (optionally) records the entire video feed. Recording can be disabled by setting `filter2->setActive(false);`

Example of a simple demonstrator implemented using the software framework.

```
// capture source
const double fps = 15.0; // 15 frames per second
GigeVisionVideoCapture* capture = new GigeVisionVideo
Capture(''192.168.1.10'');
capture->set(CV_CAP_PROP_FPS, fps);
VideoHub hub(capture);
// filters
// resize video to 800 × 600
ResizeFilter *filter1 = new ResizeFilter(Size(800,600));
```

```
// write video to file recorded.avi
VideoWriterFilter *filter2 = new VideoWriterFil-
ter(``recorded.avi'', CV_FOURCC('X','V','I','D'), fps);
// show video on screen
ImageOutputFilter *filter3 = new ImageOutputFilter
(``Video'');
// wait until next frame is available
WaitFilter *filter4 = new WaitFilter(fps);
// pipes (connections)
filter1->setInput(&hub);
filter2->src = &(filter1->dst);
filter3->src = &(filter2->dst);
filter4->src = &(filter3->dst);
// filterchain
list<Filter*> *filterList = new list<Filter*>();
filterList->push_back(filter1);
filterList->push_back(filter2);
filterList->push_back(filter3);
filterList->push_back(filter4);
FilterChain chain(filterList);
// execute filter chain indefinitely
for(;;) {
chain.apply();
}
```

2.2 Development Environment

To further reduce the (entry) threshold, we have put together an integrated development environment (IDE) based on Eclipse [13].

Eclipse was chosen because it is a popular state-of-the-art integrated development environment, available for all common development platforms, distributed under a license which allows passing the IDE to anyone without fee. Its features include but are not limited to code completion, integration of various compilers and debuggers for different programming languages, support for version control and the ability to add more features through extensions). Especially the distribution of the IDE to users of the software framework is not possible with commercial but very popular IDEs, like Microsoft Visual Studio or Embarcadero C++ Builder (formerly known as Borland C++ Builder).

The IDE is comprised of:

- Eclipse 4 (Juno, Service Release 2) [13]
- CDT (C/C++ development tools) [13]

- Subversive SVN Extension (SVN version control) [13]
- C/C++ compiler MinGW (gcc 4.6.2, 32-Bit) [14].

This compilation can be run from a USB Stick without installation and will be made available for Microsoft Windows. The Microsoft C++ compiler [15] can be integrated as well, given it is already installed by the user.

Users can build the same compilation for other operating systems with little effort.

3 Demonstrators

We have implemented a couple of important sensor functions for forklift trucks to validate the abilities of the software framework, and provide a basic skeleton solution for future products based on the software framework to build upon. In the following paragraphs the concepts of two of these sensor functions will be discussed.

3.1 Fork Height

The fork height determines the z-coordinate of the goods being picked up or placed, which corresponds to a specific storage shelf at the position of the forklift at the beginning or the end of any transport. The accuracy of the height sensor must therefore reliably allow the calculation of the correct storage shelf—meaning it must not report a height suggesting above or below the shelf. According to our industry partners in the project, typical high rack warehouse for standard EU-Pallets have a minimum distance of 80 cm in the z-direction between shelfs.

Our approach measures the distance between a camera mounted at the bottom of the mast looking upwards and an augmented reality marker mounted at the back of the fork carriage pointing downwards see Fig. 2.

This setup has the advantage that it is very robust and does not depend on any features from the forklift itself and can therefore easily be adapted for any forklift model.

The Aruco library [16] and its markers are chosen for this demonstrator, because it provides the necessary methods for marker extraction through a very simple API, which made integration into our framework very easy.

The following steps need to be performed in order to determine the distance from the camera to a marker:

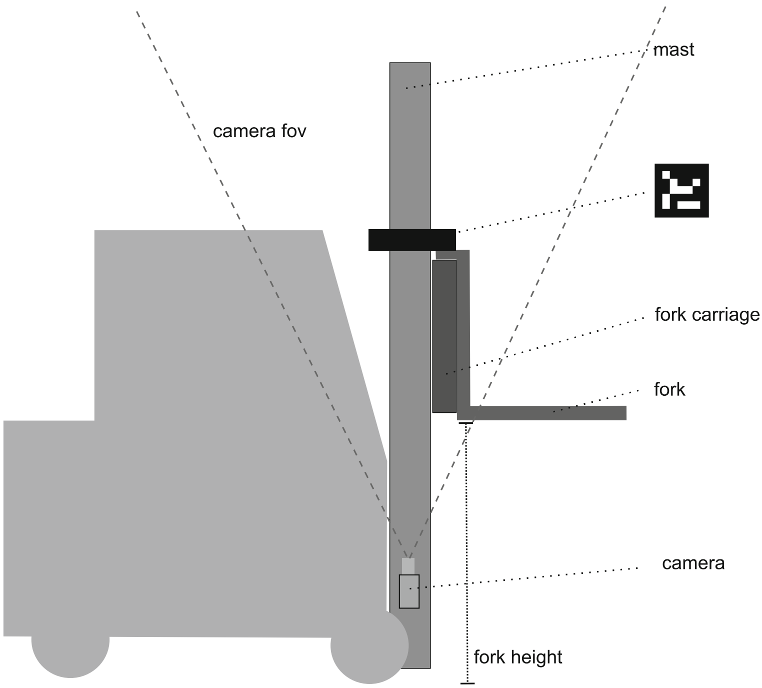

Fig. 2 Fork height demonstrator setup sketch

1. Find marker in the image and extract it. We have written a filter, which wraps the necessary functions to perform this step from the Aruco library [16].
2. Estimate the markers pose that is the mapping of the marker in the image towards the known marker. This can be achieved e.g. with the POSIT algorithm [17], which is also a part of the OpenCV library [12]. The result of this step are two vectors, a translation vector and a rotation vector, which characterize the relative distance and orientation of camera and marker. The orientation is not important in this case, as the marker cannot be rotated relative to the camera.
3. Determine the distance between the camera from the translation vector.

Caveats: Since the marker is not always in the field of view (fov) of the camera, the demonstrator cannot measure fork height lower than approx. 40 cm above ground. But as the information from the fork height sensor is mainly used to determine a storage shelf where goods are picked up/placed, with a height bigger than 40 cm, lower values can always be reported as 0 cm without reporting the wrong shelf.

3.2 *Marker-Based Localization*

Localization of a forklift truck requires the estimation of its position, that is the 2D position in the *(x,y)* plane plus the forklift's orientation angle to determine which direction the forks point towards.

Analog to the fork height demonstrator, the relative position between forklift and other markers can be determined to implement a localization demonstrator. In this case the pose estimation from one marker out of a set of markers mounted at the warehouse ceiling provides the *(x,y)* position of the forklift itself (here the rotation vector has to be taken into account to determine the forklift's orientation. This approach is inspired by the Sky-Trax [1] system.

Both demonstrators have most processing steps in common and should therefore be merged into one program to reduce the computational requirements.

4 Outlook

In the coming phase of the project the main focus is on the development of the barcode demonstrator and evaluation of the other demonstrators. The fork height demonstrator will be extended with the pose estimation of another marker mounted at the forklift's cabin (and visible to the same camera) to determine the tilt angle of the mast to further improve the measurement of the actual fork's height. We also plan to improve the quality of the marker-based localization demonstrator by taking the distance to multiple markers into account. Finally we are working on a concept for localization for forklifts inside warehouses without the need of markers.

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Part III
Transport Logistics

Integrated System for Combining Decisional Problems in a Distribution Centre

David Cipres, Carlos Millan, Ander Errasti and Emilio Larrode

Abstract The efficiency in distribution centres is conditioned by the management in the storage and picking process. To achieve this efficiency different coupled decisions have to be made for problems like storage, picking, truck-dock assignment and task assignment. The information of the activities, inside the facility and in the supply chain, is a key point to adapt the status of the process to the conditions of a changing environment. This paper describes a system to integrate information and decisions dynamically and validates it with a detailed simulation model. We show the results of the application in two case studies in actual facilities.

Keywords Distribution centre · Decisional system · Warehousing · Picking · Simulation · Operational efficiency

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1 Introduction

Efficiency in Supply Chains is mainly determined by the competence in operations management in the distribution centres. Different trends in manufacturing and distribution have made the order picking process more important and complex [1].

Although the Distribution Centres (DC) have a key role for the success or failure of supply chains [2] at the design stage, there is no systematic or scientific approach to the physical design of warehouses [3–5].

Order picking, the process of picking products from their storage locations to fill customer orders, is known as the most important activity in warehouses [6]. Order picking was identified as the most labour-intensive and costly activity for almost every warehouse long time ago; the cost of order picking is estimated to be as much as 55 % of the total warehouse operating expenses [1].

The warehouse design decisions are tightly coupled, and one cannot be analysed or determined in isolation from the others [7]. The integration of simulation, statistical analyses and meta-heuristic techniques is an effective and efficient way of optimizing a very complex logistic system such as the order picking systems [8].

An efficient warehousing management system could greatly reduce overall warehouse costs, which is achieved mainly by optimizing movements. Poor warehouse performance has different negative impacts in the warehouse and for the supply chains [9] with effects like: complex management, poor customer service and high logistics cost. Optimizing activities performed with transportation equipment could have significant impact on reducing energy consumption and CO_2 emission.

The paper is organized as follows: Sect. 2 describes the problem and the resolution steps. Section 3 is the literature review of the problems related to the paper. Section 4 is the methodology used to resolve the problem. Section 5 describes the case studies where the system has been applied. Section 6 shows the results obtained and at last Sect. 7 resumes the conclusions and the future work lines.

2 Problem Statement

In order to perform an efficient warehouse management diverse decisions have to be taken. The warehouse design decisions are tightly coupled, and one cannot be analysed or determined in isolation from the others [7]. Usually these decisions need information from different management systems: ERP, WMS, TMS, sometimes integrated, sometimes not. In the final stage the operator takes the decision with all the information at hand and his own experience.

The lack of experience in some cases and the weak integration of different IT systems could cause delays and inefficiencies in the processes, with the consequent cost in time and cost in terms of energy.

In order to solve these problems a system for combining decisional problems has been developed which integrates the main important operative problems in a distribution centre exploiting all the information available. The system is tested in two case studies, one with home appliance products and one with heavy industrial manufacturer.

In both cases there is a lack of efficiency detected. The decision process is mainly done based on experience and fixed rules with a WMS for registering the details of activities to operate the warehouse. Each company identified the warehouse as an opportunity to improve in the actual economic scenario.

The distribution centres selected, according to the classification of order-picking systems [1] could be classified as order-picking methods, employing humans, picker-to-parts, high level, and pick by order. The storage mode is stacked and conventional. The improvement strategy is to optimize the use of space and resources, minimize the loading time and to make the process as efficient as possible with the maximum service level.

3 Literature Review

Our research objective is to find a model to increase the distribution centre performance by the combination of different problems with a new IT system. With the combination of problems the evaluation of results becomes complex. Few authors address combinations of the decision problems. Yet, de Koster et al. in [1] say that this is necessary as there is interdependency in their impact on the order picking objectives.

Petersen and Aase in [10] have studied the impact of different combinations of the three previously mentioned operational policies developing a simulation model that considers fixed order sizes. Other authors [11–13] have also studied these strategies, but none of them took real demand information into account. Gu, Goetschalk and McGinnis in [7] state that there is a significant gap between academic research and practical application.

3.1 Storage Location Assignment Problem

The storage location assignment problem (SLAP) is to assign incoming products to storage locations in storage departments/zones in order to reduce material handling cost and improve space utilization. Different warehouse departments might use different SLAP policies depending on the department-specific SKU profiles and storage technology. The storage location assignment problem is formally defined as follows: Given information on the storage area, information on the storage locations and information on the set of items to be stored, determine the physical location where arriving items will be stored. The assignment is subject to performance criteria and constraints such as: Storage capacity and efficiency, picker capacity, response time and compatibility between products and storage locations [14].

Types of SLAP problems:

1. Storage location assignment problem based on item information (SLAP/II)

- Assignment Problem (AP)
- Vector Assignment Problem (VAP)
- Duration-of-Stay (DOS)

2. Storage location assignment problem based on no information (SLAP/NI)

- Closest-Open-Location (COL)
- Farthest-Open-Location (FOL)
- Random (RAN)
- Longest-Open-Location (LOL)

3. Storage location assignment problem based on product information (SLAP/PI)

- Dedicated Storage
- Random Storage
- Class-Based Storage

Different criteria can be used to assign a product (class) to storage locations. The three most frequently used criteria [2]:

- Popularity (defined as the number of storage/retrieval operations per unit time period).
- Maximum inventory (defined as the maximum warehouse space allocated to a product class).
- Cube-Per-Order Index (COI, which is defined as the ratio of the maximum allocated storage space to the number of storage/retrieval operations per unit time) (COI or turnover based storage location assignment rules include popularity and item size).

3.2 Order Picking

Picking is the most labour-intensive operation in warehouses with manual systems and a very capital-intensive operation in warehouses with automated systems so it is therefore a key process in warehouse design as it has a significant impact on capital and operating costs. Coyle et al. in [15] state that this activity's contribution could rise to 65 % of the total operating costs of a common warehouse.

Malmborg and Al-Tassan [16] describe four basic types of parameters influencing the operating performance of an order picking system, and these are the basis for the parameterization of the proposed dynamic models: Item features (transactions demand levels, item space requirements, and item assignment constraints); Storage equipment (vehicle route, speed and movement pattern); System operating rules (picking strategies, sequencing); and Physical configuration of storage area and unit load size (height, depth, number of storage aisles). To accurately model the operating performance of an order picking system in terms of its three fundamental measures of total space requirements, throughput capacity and service level, the interdependencies among these parameters must be reconciled. Simulation is an analysis tool that is capable of capturing these interdependencies.

Won and Olafsson [17] has highlighted that although previous research traditionally focuses on improving system throughput (total picking time and effective use of equipment), the primary concern of customers is often fast delivery of their orders (order maturity time). Nevertheless, it is possible that some initiatives to improve one of those performance measures might impact negatively on the other one. In this context, analysing performance evaluation trade-offs is an important task in order to align warehouse efficiency measures with customer requirements.

3.3 Truck–Dock Assignment

One of the key activities at distribution centres is the dock assignment for trucks. Trucks are assigned to docks for the duration of a time period during which the cargo and trucks are processed. Dock availability and times of arrivals/departures for each truck can change during the course of the planning horizon due to operational contingencies (e.g. delays, traffic control). Such changes in turn have impact on dock availability, since docks may become unavailable when required. Miao et al. [18] explains a model centred in cross docking operations to schedule docks well in order to increase the utilization and achieve better performance of the transhipment network. Most of the literature in this field has been published on cross docking operations like [19–21].

3.4 Workforce Assignment

The assignment of tasks to operators is one key point in the operational level strategy. Since interfaces between different processes are typically handled within the design problems at the strategic and tactical level, this implies that at the operational level policies have less interaction and therefore can be analysed independently [22]. The main decisions at this level concern assignment and control problems of people and equipment. Some of the main decisions are the assignment of replenishment tasks to the personnel and the assignment of picking tasks to order pickers.

3.5 Simulation

Simulation is a technique that uses the computer to model a real-world system, especially when those systems are too complex to model them with direct mathematical equations without disturbing or interfering with the real system [23]. The main advantages of simulation arise from the better understanding of interactions and identification of potential difficulties that simulation offers, allowing the evaluation of different alternatives and, therefore, reducing the number of changes in the final system. There are several simulation techniques; however, Discrete Event Simulation is the most commonly used [24].

4 Methodology

This paper proposes a methodology to integrate different decisional problems with a high degree of dynamism with an adaptive task dispatching system. The platform is integrated with online information from the IT systems and validated with a simulation model. This platform has been applied in two real companies from different sectors, which led to improvements in the efficiency in their DC. Two collaborative projects were launched with the operational department from each company. Diverse objectives were established. In addition to the operational cost in this paper we focus on indicators like the loading waiting times and the filling rate which are not widely considered in the literature.

All this information is available in the company IT systems but usually it is not considered in the day-to-day operations. The integrated system is based on a framework which combines information from different management systems. The information is used to improve the decision making process. Four main problems are merged in our system: The storage location assignment problem (SLAP), the Order-truck-dock assignment, the order picking and the workload assignment. These decisions have been selected because they have a high impact on the process cost and they are tightly coupled and one cannot be analysed or determined in isolation from the others.

The integrated system described in this paper is part of the AWARE platform from the work of the doctoral thesis from David Cipres. It is also one part of the research done under the national research project RAFUWARE.

4.1 Decision Problems

For the decisional problems we define a set of variables which could be measured from different IT systems and included in the algorithms. To achieve this goal we evaluate the following decision problems:

- **D1 Storage location assignment** (SLAP) concerns the assignment of incoming stock to storage locations. The objective is to assign incoming products to storage locations in storage departments/zones in order to reduce material handling cost and improve space utilization (Fig. 1).
- **D2 Order-Truck-Dock assignment**: This decision consists of the selection of the best shipment for the truck regarding the location of the load. The objective is to minimize the travels in the distribution centre respecting the constrains like filling rates or waiting times. An example is shown in Fig. 1 from the case II of this paper (Fig. 2).
- **D3 Order picking**: The process of picking products from their storage locations to fill customer orders. It is the most intensive task regarding resources and it is a directly related to the service level (errors and punctuality). Selecting the correct strategy and sequence has a big impact on the process efficiency.
- **D4 Workforce assignment**: In the DC there are different forklift operators for storage and picking activities. Initially, tasks were divided between teams, a team for storage and a team for picking. With the new IT system we combine actions. We assign the best action to each operator regarding his location and the task priorities. In addition, we consider auxiliary assignments to equilibrate the workloads (Fig. 3).

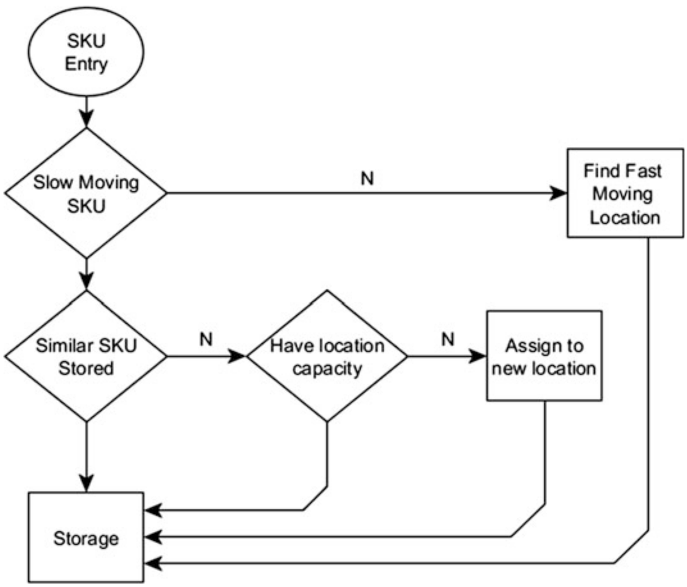

Fig. 1 Example of the order-truck-dock assignment schema applied in case I

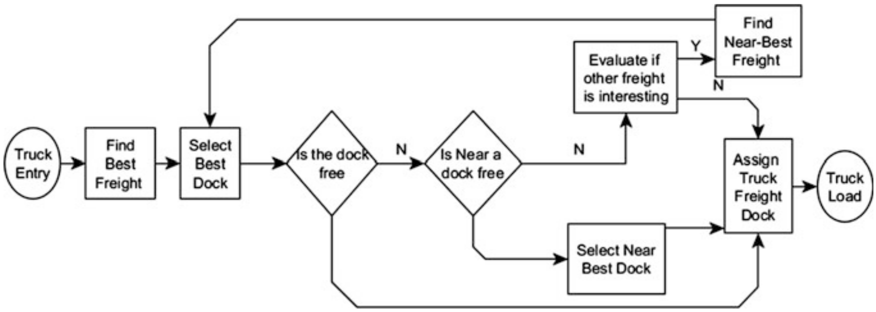

Fig. 2 Module relationships between the IT system, the algorithms and the simulation software

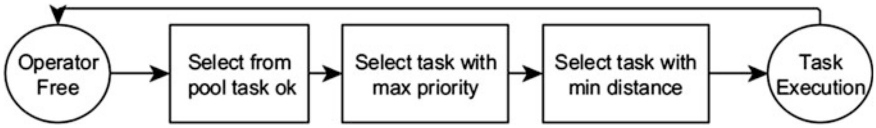

Fig. 3 Simulation model layout details

4.2 Priority Management

The precedent algorithms generate a collection of tasks, but the sequence is not specified. To determine the sequence of actions a balance between efficiency and urgency as indicates [9]. To be efficient, the WMS assigns a task to the operator which is near to its current position. Then it minimizes the empty travel distances between the tasks. Besides the travel distances the management system has to consider the urgency of the tasks. Urgency is not only caused by deadlines that need to be met, it may also be due to critical bottlenecks.

In our model we have designed a priority task schema which integrates constrains of the manufacturing process and the delivery scheduling. We defined a scale from 1 to 5 points. Lower values are assigned to the lower priority tasks. We group the task in three categories.

- Storage task: The priorities of these tasks are related with the status of the input buffer. If the buffer is below 50 % of the capacity, the priority is 2. Between 50 and 80 % the priority is 3, above 80 % the priority is 5, the maximum. The input buffer cannot be blocked; it will cause problems in the manufacturing process.
- Picking task: The priorities of these tasks are related to the waiting time of the shipment truck. If the waiting time of truck is below the 50 % of the OWT (objective waiting time), the priority is 3 and above 50 %, the priority is 4. A picking task has never a priority of 5; it is reserved for the storage actions.

- Secondary task: This category groups actions which have to be done in the DC but they are not directly connected to the material flow, like changing item locations or organize the items inside the mixed locations. This task has a priority of 2 points. They could be combined with the low priority of the storage task.

This priority distribution allows the combining of different tasks, taking into account urgency and efficiency. When the priority level is low, it generates more opportunities to combine movements and to execute the secondary tasks.

4.3 Simulation Model

The first step in the design of the simulation model is the objective identification [23]. Our interest is to increase the efficiency in the intralogistics processes (handling resources) and to reduce the load time of shipping trucks.

The model contains the following elements: the warehouse dimensions (layout, aisles, docks), item properties (reference type, rotation, size, geometry), operators (speed, timetable, skills, activities time duration) and truck (capacity, destination, orders, timetable).

The objective of the simulation model we developed is to evaluate these integrated decision problems; the evolution in time (dynamics) of the system is very significant. Depending on the delays, the sequence, the resource availability the solution could be quite different. For testing the impact of these new algorithms with the dynamics of the process we developed a discrete event simulation model. The simulation software selected is Enterprise Dynamics 8 [25].

We have applied this system in a manufacturing process where the delays in the shipping process were critical. We defined four main indicators to evaluate the performance of the system: Loading time, waiting time, Vehicle filling rate, Time per task. In addition we obtained data from the operator status (loading, unloading, travelling full, travelling empty…).

The exchange of information between the algorithms and the simulation model is made by messages. At the beginning of the simulation run, the inbound and outbound orders are scheduled. During the simulation, tasks are generated according to the schedule and the details for the flow are received from task calculation server by messages. Each message has information about the client, order, timestamp… and the task calculation server returns the decision including the location and the operator assigned. The decision is made by taking into account the information about the status of model (position, priorities) and the database containing the details of the process (level of stock, order details, skills…).

Due to the high quantity of data for the implementation of the model a network configuration is needed. The simulation server and the algorithms servers and the database server are independent. Each server runs in different machines in parallel, to reduce the simulation time.

5 Case Studies

The integrated system has been tested with real conditions in two distribution centres. Some of the details of the processes are omitted due to confidentiality agreements.

5.1 Case I: Home Appliance Distribution Centre

The distribution centre belongs to a home appliance manufacturer. The centre has a floor of more than 50,000 m^2 and is about 10 m high. It is divided into two zones; one for large items, which are stored as a stack (refrigerators, washing machines, ovens). The second zone is for small items (irons, bread toaster, mixers). They are stored in conventional warehouse. The picking for the big items is done by article and for the small items is done by pallet and by box. The warehouse has more than 50 docks for loading and unloading.

In this DC there are two picking strategies. In the stacked area, big items are picked following a single-order picking strategy. Products of the same geometry can be picked together with clamps forklifts. In the pallet area there is a zone picking strategy. Picking is simultaneous, or synchronized, between the areas. The storage is class based. Most of the products are grouped by business family.

The task assignment in this DC is organized by process: unloading, verification, storage, picking and loading. Each process has a dedicated group of operators. Some of them are polyvalent and they can work in different processes, but not at the same time, among other aspects, due to some software limitations.

The main characteristics of the decision algorithms in the system are:

- **D1 Storage location assignment**: Initially, the storage assignment was class-based, using the business family as key characteristic to group the items. With the new algorithms properties like rotation are included to assign the best locations (golden zone) for the most popular references. The turnover of the products is periodically updated considering the last weeks demand.
- **D2 Order-truck-dock assignment**: In this case the load of each truck is transmitted by EDI systems. So the content of the load could be known in advance. In this case the number of docks is high (more than 50) and blocking is rarely a problem. Dock assignment is done considering the location of the load in the DC trying to minimize the travelled distance.
- **D3 Order picking**: Within the DC there are two types of picking strategies, one for big items (stacked) and one for the little items (conventional warehouse). One of the important points for the system is the capacity to combine different task. So our system has to generate this task to evaluate the physical distribution in space and time inside the model. The calculation processes are complex because there is a high diversity of products and the number of rules and restrictions is high. We have generated a data model to help in the

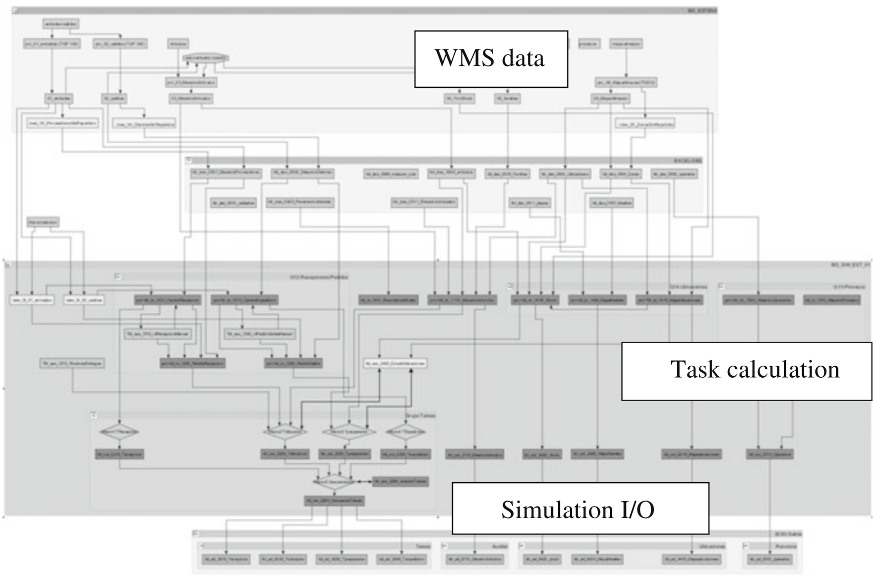

Fig. 4 Layout of one zone of the distribution center case II

transformation from master file data (order, stock, article master) to tasks considering the grouping criteria, pallet formation and replenishment. A detailed327 scheme for the data transformation process is shown in Fig. 6.

- **D4 Workforce assignment**: The task assignment strategy is the key algorithm to distribute the tasks considering the spatial location and time. Each operator has a skill matrix to determine its ability to perform the tasks. In the initial configuration the each warehouse (large items and small items) was divided into zones, grouping a set of families. The reason was to avoid long travels. In the new system this restriction was changed by the new algorithm shown in Fig. 3 where the assignment is based in the priority and the distance. With this strategy it is possible to combine movements in the near zones, obtaining high profits in the efficiency of the process.

5.2 Case II: Industrial Manufacturer

The second case study is an application for a manufacturer distribution centre. It belongs to a multinational manufacturing company. The company manufactures in Spain and distributes the products in Europe and the North of Africa. Products are voluminous and heavy. Each item is about one tone of weight and about one cubic meter of volume. The facility is about 300 m long and 60 m wide with a maximum capacity about 10.000 sku stored. The distribution centre is divided in three areas similar to Fig. 7. In the north side, each area has an input from the manufacturing

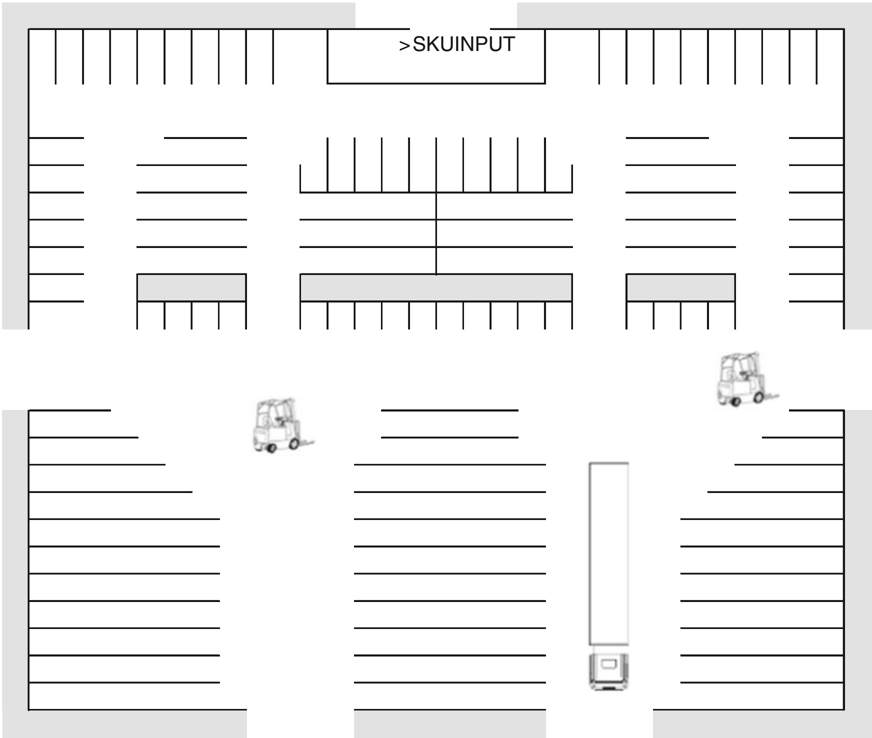

Fig. 5 Example of the storage location assignment schema applied in case I

process and some docks in the south side. The products can be stacked, depending on the reference, until five or six levels.

The handling process is made by forklifts which take the items one by one. The number of locations is less than the number of references. Some of the locations are dedicated to one reference and other locations have a mix of references inside. With the stacked storage, the mixed locations could lead to extra movements if the desired reference is not on the top of the stack. When the workload is not intense, some operators spend time classifying the mixed references.

It is organized by irregular aisles. Each aisle has different locations with different depths. The locations near the dock are assigned to the fast moving shipments, in those locations the storage is the same than the final freight. In the other locations, the locations are assigned to a single reference or multi reference.

The arrival of products in the distribution centre is continuous, 24 h per day and 7 days for week. The sequence is determined by the production plan. The warehouse operates three manufacturing machines. In the company the throughput of the manufacturing system is a high priority, the warehouse operations play a secondary objective. The process ends with the loading of the SKU, in trucks. This last process is the point where the problem is detected. The load time is long and it becomes critical especially in the central hours of the day when the workload is high. The initial configuration of the warehouse was in teams grouped by the process: one team for storage and one team for loading. In order to reduce long distances, each worker has a preferred zone to operate. The operator assigns the location of each item based on his experience, usually the nearest open location. The location is recorded in the WMS.

The main characteristics of the decision algorithms in the system for this case are:

- **D1 Storage location assignment**: The initial location assignment in this warehouse was dominated by the manufacturing rules. The production plan has higher priority than the rest of the activities. One team is dedicated to the storage of the materials arriving from the manufacturing process with the rule of the first-empty location. This strategy causes accumulation of items around the input, and the loading time increases due to high movements inside the DC. The new strategy is not the optimal but is a step in the improvement process. The storage is class-based, considering the main classes: Fast moving references, reference locations and mixed locations (with more than one location). The decision algorithm is represented in Fig 1. As an example the main variables evaluated in the algorithm are: Duration of stay of the item, volume of the item, future volume of the reference, distance to dock of the location, location filling rate or number of references of the location.
- **D2 Order-Truck-Dock assignment**: The order-Truck-dock assignment in this case consists of the selection of the best shipment for the truck regarding the net weight, and the best dock regarding the occupation of the loading platforms. When the truck arrives at the distribution centre, there is usually more than one piece of freight (set of SKU) available to dispatch. The assignment strategy is a balance between maximizing the truck filling rate and minimizing the waiting time.
- **D3 Order picking**: The picking process is made item by item, due to weight and volume restrictions. In this case the decision is to select the best item from different locations to configure the shipment. The picking location is selected depending on the distance to the dock assigned. Depending of the configuration of the freight, the distance and the loading time in the process could vary from 10 to 40 min.
- **D4 Workforce assignment**: With the integrated system, each operator has a skill matrix, with the preferred working zone and the abilities in the different task. The decision algorithm is similar to Case 1 and it is represented in Fig. 3. In the case the distances are large, additional restrictions are made to avoid long travels.

6 Results

After completing the validation process, the analysis is made with the data of seven production days. The model starts with the same layout as the real facility. Each day the model simulates the arrival of the items and the freight shipments with the same resource timetable.

Data collection plays a key role within simulation, as the data must truly emulate the realities of the system to the levels of accuracy and detail required. The data for this case study was filtered with a consistence analysis to avoid outliers in the simulation model. The model is validated by simulating a standard day in collaboration with the experts from the company.

To evaluate the integrated system we ran a simulation of seven consecutive days. To make comparisons with the real system, the initial layout of the model (sku assigned to location) is the same as the WMS in the real layout. The inbound flow and the outbound shipments are also the same.

For reasons of confidentiality the data results in this chapter have been scaled with a multiplier factor to avoid direct references. The relative effects between the initial solution and the new system have been maintained.

6.1 Results for Case I

In the Case I there are two main decisions to evaluate, the zone assignment and the combination of movements. In the initial configuration each warehouse (large items and small items) was divided into zones, grouping a set of families. The reason was to avoid long travels. After applying the new system we made an analysis reducing the number of resources with the impact of zoning. Results are shown in Fig. 6. This graph indicates the impact to the number of trucks that were delayed with the new strategy. Reducing the number of operators the delay was bigger using the initial zone strategy. With the new system using the operator teams the number of trucks that were delayed was between 2 and 5 %.

Another interesting result is shown in Fig. 7 where we compare the amount of tasks finished in the distribution centre during one day. Scenario A is the initial situation, scenario B is the system activated, without zoning restriction and combining movements. Figure 7a shows the picking tasks. They have high priority, so in both scenarios (initial and with the integrated system) all the tasks are finished on time, all the trucks are on time. On the second graph (Fig. 7b), the number of storage actions is represented. This task has minor priority, we observe that in scenario B, the number of tasks realized is higher with this strategy, and the number of resources is the same. The integrated system allows to increase the productivity by about 15 %.

In general the results obtained in case I show an overall increase in the efficiency at the operational level.

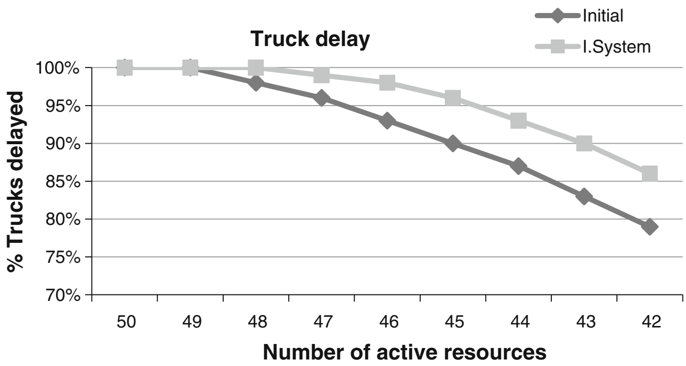

Fig. 6 Influence of the resources in the delay of trucks with the integrated system

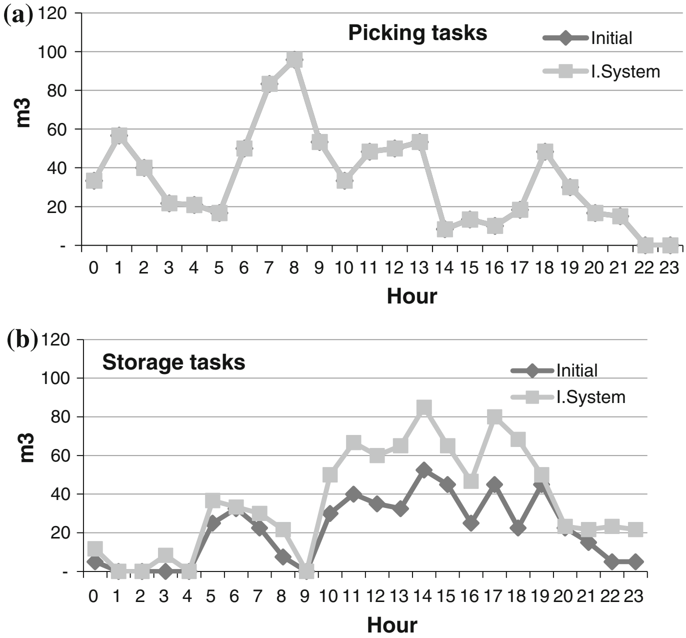

Fig. 7 Volume of the items moved in picking task (**a**) and in storage task (**b**) with the initial strategy and with the integrated system

6.2 Results Case II

The main objective in Case 2 is the reduction of the waiting time for the shipments. The detailed results are shown in the following table. The average improvement is a reduction of 24 % of the waiting time (Table 1).

Table 1 Result of comparison in the waiting time with the initial solution

Days	Initial	I. System
1	18	18
2	15	19
3	31	24
4	17	18
5	36	18
6	28	20
7	30	17
Average	**25**	**19**

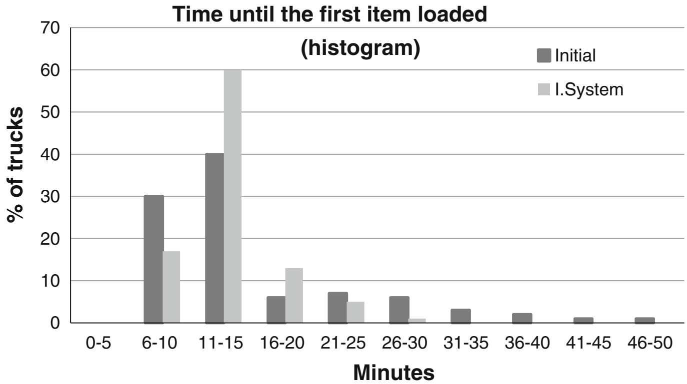

Fig. 8 Truck waiting time between entry time and the load of the first item

One of the main objectives is to minimize the time which we need for loading trucks in the distribution centre. In this case the objective function is the sum of the loading time and the waiting time. In addition there is a restriction to the minimum vehicle filling ratio. With the appropriate setup of the system we could obtain reductions of 24 % in the waiting time of outgoing trucks.

The time wasted until the first item is loaded is shown in Fig. 8. In the first group (between 6 and 10 min) the percentage of trucks is high in the initial strategy (30 %) and it is lower in the integrated system (17 %). The histogram "long tail" shows a high delay that arrives after 50 min in the worst case. With the integrated system the times are centred between 15 min with a maximum value of 30 min.

The Table 2 shows that the filling rate of the trucks stays in similar levels as in the original process, although the freights assigned are different. The range of the filling rate is the same, between 96 and 99 % and the average is the same, namely 97.6 %.

Table 2 Result of comparison in the filling rates

Days	Initial (%)	I. System (%)
1	97.23	96.72
2	98.26	98.26
3	97.23	99.28
4	97.23	97.75
5	96.41	98.16
6	100.00	97.03
7	96.82	95.80
Average	**97.60**	**97.57**

7 Conclusions

The decision-making in the logistics processes in distribution centres can be improved with the use of IT systems that integrate different problems. In the literature there are not many examples of combinations of decision problems. In the combination of decision problems dynamic effects are important. The system designed for the four coupled decisions has a positive impact in the overall efficiency of the operations in a distribution centre.

To obtain good decision, the information of the process is essential. All the calculations need high quality data with a high level of detail. Actual IT systems allow the integration from diverse data sources in the decision making process. To validate the effects of the dynamic effects the evaluation with a discrete event model helps to quantify the impact of all decisions simultaneously.

Two case studies are presented from two different sectors. Important efficiency enhancement is detected in the indicators: higher productivity rates, reduction of the waiting times, and better workload levelling.

The future work lines are related to the evolution of the system with the selection of the main significant variables, with the higher impact in the process. Another work line is focused on the improvement of the simulation model to identify the minimum level of detail and exploring multi-agent simulation to evaluate the decision making process.

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Measurement and Optimization of Delivery Performance in Industrial Railway Systems

Uwe Clausen and Maike Rotmann

Abstract A concept of performance measurement systems in the context of industrial railway systems has not been elaborately evaluated in research or in practice yet. This paper reviews existing approaches and characterizes the standard process of industrial railway system. Focus of the study is the development of performance goals and indicators and to point out the importance of influencing factors. These impacts are identified, described and analyzed regarding possible correlation among each other.

Keywords Performance measurement · Transport management · Efficiency

1 Introduction

A significant challenge for producing companies is the supply of in-house stages of production and processing. In companies where transport is faced with great quantities, the most efficient means of transport are industrial railways. In general, railway features for different planning models depend on the continent; a comparison of North American and European Railway Systems has been drawn in a study of Clausen and Voll [1]. However, a major problem with this kind of transport systems is the missing transparency of railway processes. Mostly, neither the location of the traction unit nor the explicit duration of single processes (e.g. service time, waiting time) is known or measured using real time systems [2]. In addition, despite a considerable amount of literature being published on

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performance measurement systems, far too little attention has been paid to railway systems and in particular to industrial railway systems. Hence, the purpose of this paper is to examine parameters influencing a performance measurement system in the field of industrial railway systems.

The objective conflicts of high efficiency, optimization of resources and an increasing service level will be outlined. So far, neither research nor best practices have found run controlling instruments that enable the measurement or evaluation of railway delivery performance.

1.1 Literature Review

The first serious discussions and analysis of performance measurement, which has its origin in the Anglo-American regions, emerged during the 1980s [3]. During the 1990s the focus of company performance was set on operational productivity. Today's performance is defined by a holistic view which is due to increasing competition challenges and information exigencies [4]. There is a large volume of published studies describing the term performance. Leong et al. [5] defined four key dimensions of manufacturing's performance: quality (manufacturing of products with high quality), delivery performance (speed and reliability), cost (production and distribution at low cost) and flexibility (reacting quickly to changes). Neely et al. [6] defined the measure of performance as a metric used to quantify the efficiency and effectiveness of an action. Carter et al. [7] add economy as key figure to this preceding definition, while Bredrup proposes the third dimension—besides efficiency and effectiveness—as adaptability [8]. While a variety of definitions have been suggested, this paper will use the definition suggested by Neely et al. Both key figures—effectiveness and efficiency—have been discussed in literature. Especially the term of effectiveness appears to be a fuzzy concept which is hard to measure [3, 9]. Therefore, in this paper effectiveness in the context of railway systems will be interpreted as quality of scheduling.

A widely known and often applied framework of performance measurement systems is the balanced scorecard by Kaplan and Norton, which is based on four perspectives: financial, customer, internal business processes and learning and growth. Thanks to a small number of financial and non-financial indicators, the authors aim to determine whether current performance deviate from expectations [10]. One of the limitations of this framework is pointed out by Klingebiel [3], who criticizes the missing information concerning the transforming of objectives to subsequent hierarchy levels. Other well-known performance measurement systems have been designed by the European Foundation for Quality Management (EFQM-Model) [11], by Lynch and Cross (Performance Pyramid) [12] and by Hronec and Anderson (Quantum Performance Measurement System) [13]. All these frameworks have a holistic approach in common, which includes besides quantitative factors also qualitative respectively soft figures. A performance measurement system for industrial railway systems requires a strong link to operational data and to the measurement of impacts on the performance. The circumstance that railroad companies are mostly service providers implicates amongst other following challenges [14]:

- Services are more difficult to measure than production of goods
- Logistics does not generate market performance and thus monetary results are not measurable
- Logistics performance is generated along the whole company and requires thus several measuring points
- The flow-orientated perception of logistics in order to control and manage processes requires unusual information.

Moreover, within the scope of performance measurement systems, an often applied key figure as Return-On-Invest is difficult to integrate in controlling systems of logistics service providers [15] and hence demands a new approach.

Very little was found in the literature on the question of performance measurement in the field of industrial railway systems. In an empirical study of 1972, Waldschmidt investigated cost parameters and their influences with focus on the steel industry [16]. More recently, Matzke formed a general rating system for industrial railway systems in 1999 which identifies over 500 key indicators with the aim to enable the comparison of different operational railway concepts [17].

1.2 Methodology

Recently, numerous guidelines how to design a performance measurement system have been published. The chosen approach in order to design a performance measurement system for industrial railway systems is based on the model of Rose, who described eight steps as a guide for developing the right metrics [18]. The methodology suits well as a top-down approach is chosen and the ability of particular analysis of influencing figures is given:

1. Performance category: identification of performance categories that include an organization's strategy
2. Performance goals: operational definition of the performance categories
3. Performance indicators: identification of operational indicators in order to accomplish the performance goals
4. Parameter: analysis of influencing figures regarding performance indicators and goals
5. Elements of measure: determination of data sources
6. Means of measurement: definition of required characteristics of figures and sources
7. Performance metrics: description and definition of figures
8. Specific metrics: possibilities of interpretation and trials.

The results of step 1–4 will be described in the following.

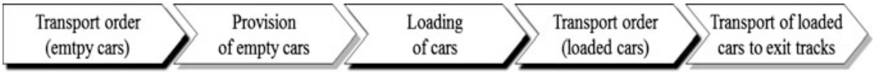

Fig. 1 Simplified standard process of industrial railway systems (authors' illustration)

2 Performance Measurement System

2.1 Process Analysis of Industrial Railway Systems

The standard process of an industrial railway system is characterized by transportation of goods on a customer's factory premises. The transport is to be construed as a service and depending on the established scheduling system different quality and performance expectations are set. Factory premises typically possess different loading points from where loaded cars are conveyed to correspondent exit tracks for further transportation. These loading points can be homogeneous as well as heterogeneous regarding infrastructural premises or freight. A simplified standard process can be seen in Fig. 1, process chain elements highlighted in grey stand for processes operated by the railway, black ones stand for loading point processes.

Significant differences between industrial railway systems can be found in the mode of scheduling: The transportation can be operated on demand or by means of time slots. Time tables, being used in passenger transport, are not common and required for industrial railway systems. Depending on the mode of scheduling in use, different parameters concerning operating procedure and quality variables such as service time gain importance. In this paper, the focus lies upon an on-demand scheduling system, which is due to the situation of the examined case study and importance of influencing parameters.

2.2 Performance Categories and Goals

According to the definition of Neely et al. [6], performance of a company can be described as dimension of effectiveness and efficiency, which are further considered as performance categories (step 1). While logistics efficiency is often seen as relation of logistics performance and logistics costs [3, 19, 20] or figuratively as "to do the things right" [21], effectiveness is much more difficult to measure ("to do the right things"). Metaphorically speaking, a railway system can be efficient although the transport goods do not reach their destinations. In the scope of this paper, effectiveness will be defined as scheduling quality.

Weber built a performance measurement system based on the definition that is also suggested by VDI of efficiency based on logistics performance and costs (step 2). He classified performance variables in three categories (quality, time and volume) and suggested to measure suitable parameters by means of degree of achievement. In this context, he pointed out that the commonly-known interpretation of efficiency as relation of input and output cannot be used in this case. This is due to the construction of the ratio system: a lower achievement in cost targets (e.g. by intermission of maintenance work) would lead to higher measured efficiency, which cannot be constructive in the long term. Instead, Weber suggested an aggregation method by multiplication or by weighted average [15].

2.2.1 Effectiveness

Effectiveness can be measured by means of an algorithm that allocates orders to traction unit. The target function takes into account the shortest track system and earliest availableness of traction units. Process quality can also be achieved by maximization of traction unit availability. An important finding of an empirical study in the field of steel industry was the correlation between breaks, the associated downtime of traction unit and service level. Figure 2 shows exemplarily how employees' breaks increase once per shift while at the same time service level decreases as well as amount of orders increases. Optimization should target on levelling of breaks or—if possible—on alignment of breaks with order situation.

2.2.2 Efficiency

The approach concerning efficiency used in this paper (Fig. 3) is based on the idea of three different logistics performance categories (quality, time and volume). Quality is concretized by the goal 'high delivery service' which includes delivery time, delivery reliability, delivery quality and flexibility. 'Short cycle time' is characterized by means of short waiting time, transport time and response time. An

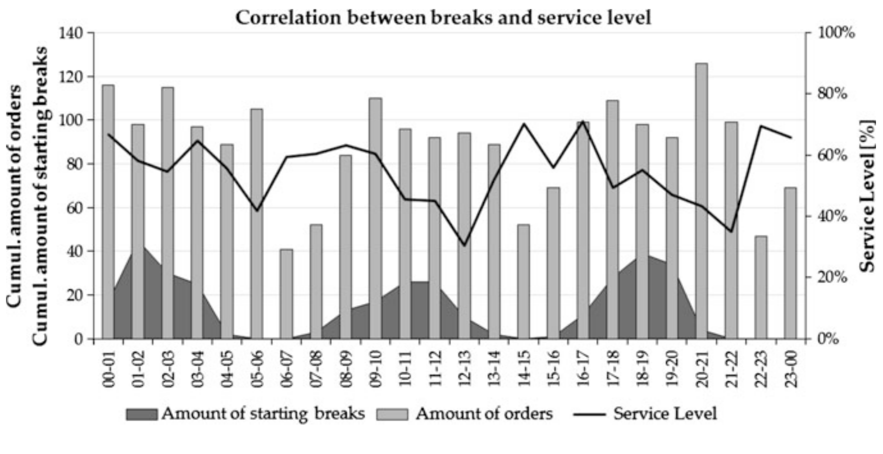

Fig. 2 Correlation between breaks and service level (authors' illustration)

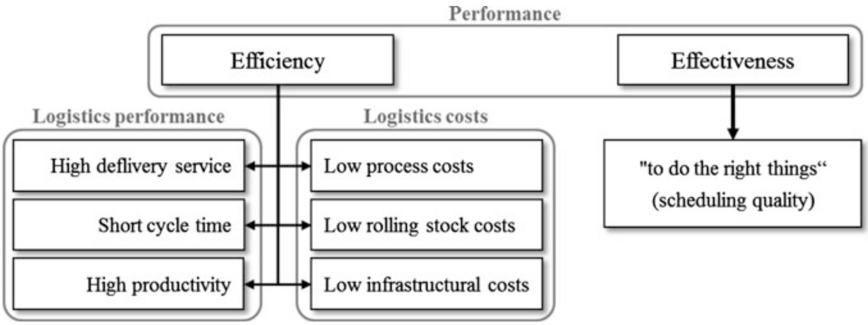

Fig. 3 Performance categories and goals (authors' illustration)

inbuilt characteristic of the industrial railway companies is the fact, that they do not have any influence on the amount of freight as it is pre-set by customers. Thus, the approach of the third dimension of performance 'volume' has to be redrafted and changed into productivity, which can be interpreted as capacity utilization of the traction unit.

Even though service processes concerning performance are difficult to categorize due to their abstract nature in comparison to manufacturing processes [3, 22, 23], especially costs of industrial railway systems seem easier to measure. In this context, it is important to point out that in contrast prices of logistics services are difficult to compare and thus can be misleading [24]. Below-mentioned cost categories can be described via following cost factors:

- Process costs include costs for human resources, fuel and lubricants
- Rolling stock costs stand for costs that incur concerning freight cars and traction units
- Infrastructural costs contain costs for maintenance and investments regarding e.g. rail tracks and turnouts.

According to the design of the performance measurement system, the analysis of influencing figures is required and will be described in the following.

2.3 *Railway-Specific Influences*

Several studies have shown a lack of knowledge concerning influencing variables and their cause-and-effect relation [21, 25]. Not only are the influences on performance key indicators difficult to measure, but also possible correlation between each influencing variables.

To measure railway specific influences, categories of impacts have been established (see Fig. 4).

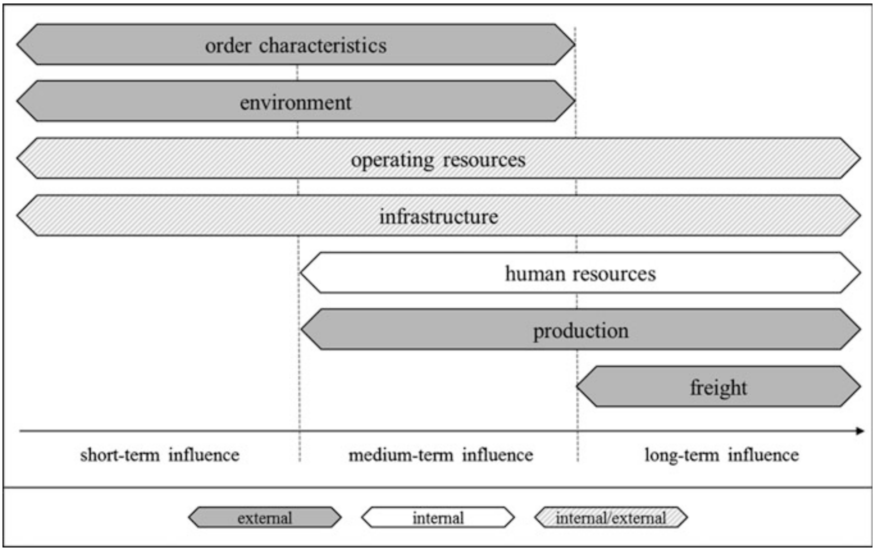

Fig. 4 Categories of influencing figures in industrial railway systems

The specifications of orders, production and freight are exclusively influenced by the customers/loading points, while the environmental aspects cannot be influenced at all. Conditions and supervision of operating resources and infrastructure can be controlled either by customers or by railway services, depending on the case study. The following Table 1 will demonstrate and describe the specific influences of every category.

Every influencing figure has to be measured in the context of railway performance and the impact on previously defined goals. After measuring the required parameters the question on how the defined impacts influence among one another suggests itself. There are three possibilities of correlation of factors [26]:

1. Factor A is influenced by factor B
2. Interaction between factor A and factor B
3. Factor A influences several factors B, C, etc.

For further analysis it is important to quantify the direction and intensity of influence [27]. One widely-used statistical method is the empirical correlation coefficient of Pearson and Bravais that enables the investigation of correlations of a two-dimensional sample [28]:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - n\bar{x}\bar{y}}{\sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right)\left(\sum_{i=1}^{n} y_i^2 - n\bar{y}^2\right)}} \tag{1}$$

Table 1 Influencing figures of order characteristics

Category	Influencing figure	Description	Time interval of measurement
Order characteristics	Amount of recipients per order	An order can consist of one or several recipients. The higher the amount is, the higher is the shunting effort	Continuously
	Sequence of loaded cars	If an order consists of several recipients (e.g. A and B) there is an optimal sequence of cars. In case of 4 loaded cars the sequence would be AABB or BBAA, deviances cause shunting effort	Continuously
	Amount of orders (absolute)	The degree of capacity use of traction unit is decisively influenced by the absolute amount of orders	Per shift
	Amount of orders per hour	The complexity of scheduling increases if the demand does not occur evenly spread	Hourly
	Utilization of load line	Every load line has a predefined length that can be used for every load. In case of underachievement of capacity and constant amount of freight the shunting effort increases	Continuous
Environment	Limitations due to weather	Snow, ice or heat do have a high influence on the infrastructure and can thus restrict railroad operations	In case of occurrence
Operating resources	Inventory of cars	The amount of cars on factory premises influences strongly the possibility of shunting. Inventory has to be measured per type of car	Per shift
	Amount of car types	The higher the amount of different types of cars, the higher is the car inventory and the shunting effort. Car types can also be defined via transport relations	Nonrecurring, else in case of changes
	Availability of traction units	Traction units can be unavailable for normal operating schedule for different reasons: dysfunctions, illness of employees or unscheduled demands of the production	Per Shift
Infrastructure	Limitations due to maintenance or dysfunction	Railway services can be limited by maintenance or unscheduled dysfunctions which have to be measured concerning duration and effect	In case of occurrence

(continued)

Table 1 (continued)

Category	Influencing figure	Description	Time interval of measurement
	Available length of sidings	The length of sidings influences the variance of shunting possibilities and the maximum amount of cars on factory premises	Nonrecurring, else in case of changes
Human resources	Sickness figures	It is necessary to measure these figures, if a task cannot be executed due to an employees' sickness	Per shift
	Accident frequency rate	The accident frequency rate stands for the relation of accidents to working hours	Per shift
	Limitations of qualifications	Not every employee possesses the required qualifications to handle every traction unit in every area of factory premises	Nonrecurring, else in case of changes
Production	Amount of failures in loading process	If a car has not been loaded according to safety regulations it has to been conveyed back to the loading point and unloaded or corrected. Every failure causes additional shunting effort	Per shift
	Inventory of loading points	The inventory of loading points is directly linked to the loading itself and has to be measured per loading point	Per shift
Freight	Time- criticality of freight	Due to their physical characteristics and to production requirements a classification per freight concerning time-criticality is necessary	Nonrecurring, else in case of changes
	Amount of heterogeneous freights	Different freights may require different car types	Nonrecurring, else in case of changes

n scope of sample
x_i random variable of criterion X
y_i random variable of criterion Y
$\bar{x}$ arithmetic average of random variable x
$\bar{y}$ arithmetic average of random variable y

The correlation coefficient can only reach a value between −1 and 1, 0 implies a non-existing linear correlation. Before applying the formula on empirical data, an objective-logical analysis of possible correlation between factors was carried out to avoid nonsense correlation (see Fig. 5). These theses are based on numerous expert consultations. The dots stand for no correlation, while plus and minus are symbolic for positive or negative correlation with the correspondent intensity.

		Inventory of cars	Amount of car types	Availability of traction units	Amount of failures in loading process	Inventory of loading points	Amount of orders per hour	Sequence of loaded cars	Amount of recipients per order	Utilization of load line	Amount of orders (absolute)	Limitations due to maintenance or dysfunction	Available length of sidings	Limitations due to weather	Time-criticality of freight	Amount of heterogeneous freights	Sickness figures	Accident frequency	Limitations of qualification
Operating resources	Inventory of cars		○	○	○	++	○	○	○	○	○	○	○	○	○	○	○	○	○
	Amount of car types	+++		○	○	++	○	++	++	-	○	○	○	○	○	○	○	○	○
	Availability of traction units	○	○		○	--	○	○	○	○	○	○	○	○	○	○	○	○	○
Production	Amount of failures in loading process	+	○	○		+	○	○	○	○	○	○	○	○	○	○	○	○	○
	Inventory of loading points	+++	○	○	++		++	+	+	++	+++	○	○	○	○	○	○	○	○
Order characteristics	Amount of orders per hour	○	○	○	○	-		+	+	+	+	○	○	○	○	○	○	○	○
	Sequence of loaded cars	○	○	○	○	○	○		+++	○	○	○	○	○	○	○	○	○	○
	Amount of recipients per order	○	○	○	○	○	○	+++		○	○	○	○	○	○	○	○	○	○
	Utilization of load line	○	○	○	○	--	-	○	○		---	○	○	○	○	○	○	○	○
	Amount of orders (absolute)	+++	○	○	++	---	+++	○	○	○		○	○	○	○	○	○	○	○
Infrastructure	Limitations due to maintenance or dysfunction	○	○	○	○	++	○	○	○	○	○		++	○	○	○	○	○	○
	Available length of sidings	○	○	○	○	--	○	○	○	○	○	○		○	○	○	○	○	○
Environment	Limitations due to weather	○	○	○	+	+	○	○	○	○	○	++	○		○	○	○	○	○
Freight	Time-criticality of freight	○	○	○	+	+	○	○	○	○	○	○	○	○		○	○	○	○
	Amount of heterogeneous freights	○	+++	○	○	++	○	○	○	○	○	○	○	○	○		○	○	○
Human resources	Sickness figures	○	○	---	○	○	○	○	○	○	○	○	○	○	○	○		++	○
	Accident frequency rate	○	○	--	○	○	○	○	○	○	○	○	○	○	○	○	++		○
	Limitations of qualification	○	○	-	○	○	○	○	○	○	○	○	○	○	○	○	○	○	

Fig. 5 Expected correlation between influencing figures (authors' illustration)

With the help of empirical data of a case study, several correlations could be measured an analyzed. While there was a significant positive correlation between some factors (left-hand chart), other expected correlation could not be proved (right-hand chart) (Fig. 6).

Further investigations and research have to be focused on the numerical quantification of intensity of influences and the impact on the performance. Related to the praxis an important and legitimate question could be for example, if an increasing amount of failures in loading processes in terms of performance measurement can be equalized by an additional traction unit and if so, the question about the critical value has to be responded.

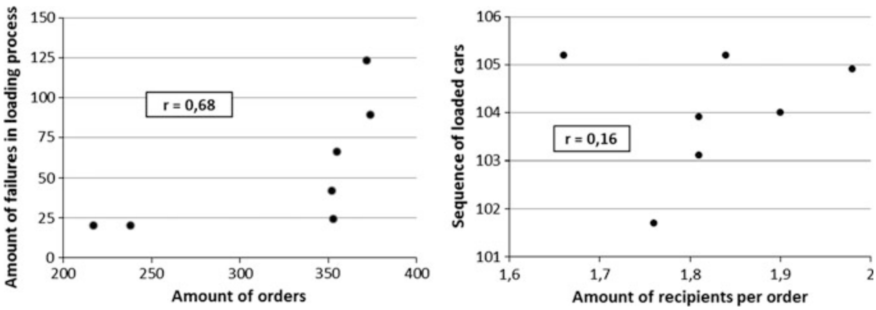

Fig. 6 Exemplary correlation coefficient between influencing figures (authors' illustration)

3 Conclusions

The purpose of the current study was to examine the impacts and parameters influencing a performance measurement system. Returning to the question posed at the beginning of this study, it is now possible to state that performance of railway systems is strongly depending on impacts that are set extrinsic as well as intrinsic. Performance categories and goals and their indicators have been described. The empirical findings provide a new understanding of performance within railway services which vary strongly in comparison to manufacturing companies. Logistics performance and logistics cost, as dimensions of efficiency, are specified by means of indicators that are valued via degree of achievement. This degree has to be predefined by the use of data oriented towards the past and expert consultations. The most obvious finding to emerge from this study is that the major challenge of the approach is the identification, description and quantification of influencing figures. While theses concerning correlation amongst influences could be approved, the quantification and concrete impact on every performance indicator will be explored in further research.

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Development of a Logistics Reference Model for Subsurface Construction

Georg Judmaier and Helmut Zsifkovits

Abstract Tunneling and subsurface construction is an important economic sector in Central Europe, due to the topographic situation, the extension of hydropower plants, the improvement of traffic networks as well as the urban infrastructure. Currently, projects like the Swiss New Railway Link through the Alps (NRLA), the Vienna and Stuttgart Central Stations and the Austrian Southern Railway are under study or construction. In the past, the methods of construction of modern subsurface installations have been supported by numerous studies and research work. A field of research which is rarely represented in this context compared to the other disciplines is logistics. Even though there have been a few initiatives in research and application, an integrated logistics view and model is missing. Due to the specific situation, every subsurface structure is unique and has special characteristics, and the requirements on logistics planning and execution differ. Especially geologic formation and the applied construction method change on every site. Still, there are numerous processes and tasks which remain the same for any project. A methodical approach to describe the structure, the actors, the interfaces, the processes and their interaction are process reference models. They are used in different branches, companies and level of detail to lay the foundation for controlled and repeatable processes, and give the possibility to benchmark them. Moreover, the framework and elements of these models can be reused for various applications in their domain. This research analyzes the framework for the application of process reference models for subsurface construction logistics and defines requirements on the structure and processes as well as the interaction between them. Furthermore, the development of a construction logistics reference model for subsurface construction is shown.

Keywords Logistics reference models · Subsurface construction · Construction logistics · Subsurface construction logistics reference model

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1 Introduction

In the logistics of stationary industrial production, crucial improvements and revolutions of the last decades mainly go hand in hand with standardization and unification. The development originated in the 19th century with the standardization of ways and networks in the postal system, then continued with the standardization of products and parts in automotive industry at the beginning of the 20th century, and in the 1950s Toyota can be seen as a pioneer of standardizing processes [1]. This starting point of research and application of process modeling, visualization and standardization led to tremendous changes in the organization and structures of a majority of companies from a functional to a process-based paradigm. The development of logistics entailed an evolution from a transport, handling and storage domain to a flow-oriented control, design and management discipline.

For a period of time it seemed that the construction industry had missed this train of development in logistics, especially in the engineering, design and standardization of business, support and operation processes. In comparison to the stationary industrial production the building industry makes only limited use of logistics methods and techniques, due to the uniqueness of features in every building and the conservative nature of planning and operation processes. In particular, the interactional structure of logistics processes and principles in application is not standardized and only partly transferable to different sites and construction areas [2].

An approach to a unified process landscape and a multifunctional and modular mapping of structure, actors, interfaces and processes in a class of domains is provided by reference models. Domain in this research refers to a field of activity, in particular the construction logistics. These reference models have been used in business informatics for many years, motivated by the construction and design of standard software solutions, in order to reduce the working time spent on programming and adaptation of the system, and to establish comparable and measurable processes [3]. There have been numerous developments of reference models for different kinds of application and in various branches of industry. In contrast, there are only scatted initiatives in construction and building industry.

In construction industry, the Project CORE (Construction Companies Processes Re-engineering) in 1996 can be viewed as a starting point for the research of business process reengineering and reference modeling. This spark only partly fired the construction industry. In addition, most of the construction companies have implemented selected tools or structures of process management. Some large European construction companies maintain departments for building process management and there are a lot of different initiatives in improving the processes in logistics, the construction operation as well as the administrative areas. The use and development of process reference models is reluctant, though.

This research paper assesses, based on the branch, the language, the type, the model elements, the level and the logistics activity of logistics process reference models and discusses their applicability in the domain of construction logistics.

2 Reference Modeling

Process reference models are the next step from the concept of business process re-engineering (BPR), which has developed since the late 1980s [4]. Early BPR efforts were often based on information system design techniques, where the actual state of a system was evaluated and a "to-be" process, excluding non value-added parts, was developed. Process reference models are a step ahead; they offer a cross-functional framework, where BPR is the base as well as the metrics. Best practices and the structure are applicable to a domain of processes, companies or branches and complete the development to a process reference model as can be seen in Fig. 1.

On the one hand they have the task to break the magic triangle of costs, time and quality by "leaning" the business processes, and on the other hand they provide a model that can be described explicitly, communicated consistently and redesigned to achieve competitive advantage. But how can this framework be understood?

The name involves the attribute "reference", which often has the meaning of referring to a standardized model. In most cases, this is extended by a character of recommendation, so that the reference can be seen as "best practice" or "best of breed" [5].

The "model" definition is subject to an ongoing discussion. In the context of reference modeling it is understood as the construction of a map of a real or intended situation, which is created on the basis of the perception of the developer and also influenced by the modeling purpose [6]. This generic map containing a

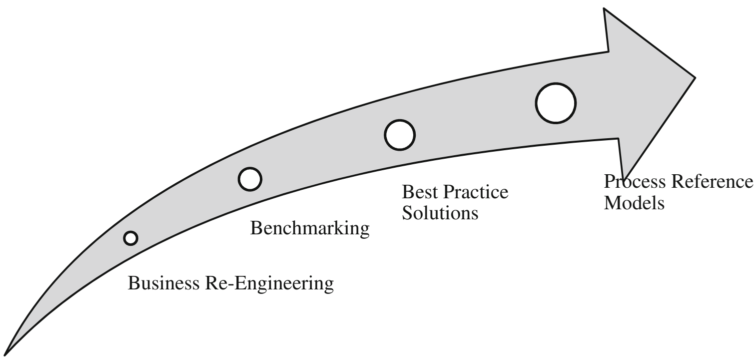

Fig. 1 Development of process reference models

sum of processes within an evaluated area lays the foundation for most business engineering and reorganization methods and initiatives. In addition, there are other tasks that are fulfilled by the modeling of business, administration and operation processes.

The modeling in business informatics and engineering serves different functions such as education and training, communication, analysis, development and design [7].

If the participation in a business process involves more partners, a common understanding is necessary and has to be developed. Process standards lead to this shared view on processes and are one of the key success factors of cooperation. Their main task is mapping the structure, the actors, the interfaces and the processes of domains in a more or less generic way and giving a methodical approach to standardizing interaction. Furthermore, the framework and elements of these models can be reused for various applications in their domain.

Moreover, reference models provide enterprises with an initial process engineering solution and grant them the variance to define the degree of detail of the model and the business content [8].

2.1 Systemization and Classification of Process Reference Models

For this research work, selected logistics reference models were investigated and classified for different characteristics. The attributes of the assessment are the application in different industrial branches, construction, intralogistics, manufacturing plant engineering, trade and transport. The area examined next is the data provided by the reference model and whether the model structure is documented and designed in detail. A very important factor for the development and the application as well as the acceptance of the model is the language. There are different approaches to mapping and depicting the actual state and to projecting the "to-be" state. Frequently used languages for reference modeling are function trees, "Integrierte Unternehmens-Modellierung" (IUM, "integrated enterprise modeling"), process or value chains and event-driven process chain (EPC).

The classification of the management levels into a normative, a strategic and an operative level is based on the "St. Galler Management Model" [9]. The logistics process reference models are evaluated on their development focus and application in major logistics activities such as transport, sourcing and procurement, intralogistics, production, distribution, return/recycle and information logistics. Consequently, it is assessed whether fundamental model elements like processes, metrics or best practices are incorporated. Finally, according to Scheer, they are classified into procedural, industry-specific and software-specific reference models [10].

This assessment lays the foundation for the evaluation of logistics reference models on their applicability and translation to construction processes and companies.

3 Assessment of Logistics Reference Models

Beside the structured evaluation of the reference models focusing on the named factors, an overview on the development, application and nature is given in the next paragraphs.

The Integrated Process and Performance Reference Model for Third Party Logistics was developed in a framework sponsored by the German Ministry for Economics and Innovation. The project team was a consortium of logistics companies and the Research Institute for Rationalization (FIR) of the RWTH Aachen. The goal of this reference model was the development of standard logistics processes for third party logistics providers. Based on the structure of the SCOR (Supply Chain Operations Reference) model, processes of third party logistics providers were evaluated, mapped and metrics as well as best practice solutions were defined. The reference model was expanded by a metrics system which is called "performance management system" [11].

The Reference Model for Handling and Consignment was developed by Fraunhofer IML in Dortmund and can be used by third party logistics providers as well as manufacturing companies. Focused on the support of enterprises in planning and optimizing the processes of consignment, it gives an overview on inefficient handling processes used in practical application, offers recommendations and shows "best practice" solutions. The modeling language used is IUM and the model is divided into a function and an information domain. The functional domain describes the actors, processes and interfaces in hierarchical classes, which can be used as modules for the application. The information domain provides the process descriptions of the functional view. Metrics are recommended to measure the performance of the processes in handling and consignment [12].

The Reference Model for International Logistics Networks is a product of the co-operation between different companies in the logistics and software development sector and a scientific partner, the Department of Logistics at the Technical University of Berlin. This model constitutes the basis for the development of a generic "open-interface" logistics technology platform in the domain of transport logistics. The language for the description of the processes, actors and interfaces is IOM (Integratives Organisations- and Informationsmanagement), which represents an enhancement of IUM. The main structure element is a process chain consisting of five steps that are order registration, order preparation, order planning, order execution and order post-processing. This cycle is mapped by the support of a software tool to generate a general process map and derive a detailed map of the sub-processes and standard transactions. This lays the foundation for the development of the IT systems needed to link the partners along the transport supply chain [13].

The alignment of IT and business strategies in the area of trade logistics was the motivation for the construction of the Reference Model for Trade Logistics. A procedure of mapping and modeling a retail logistics supply chain is proposed and validated. The development was performed in the framework of a PhD thesis at the Department of Economics and Logistics at the University of Cologne. eEPC, an enhanced EPC design is used as a modeling language, which is able to map the organizational unit, the event, the function, the data object and the IT application [14].

The SCOR Reference Model is a development of the consulting firms PRTM and AMR and a handful of companies which established the Supply Chain Council (SCC) as a platform to distribute and improve the model. It has been known and widely used in supply chains all over the industries. The development is supported by different industry-specific workgroups to secure the applicability in different branches. This reference model comprises a generic structure of the supply chain processes and provides a wide range of metrics and best practices to measure and improve the logistics sequences. The description and definition of the model ends at the implementation level, the company specific processes, steps, actors and interfaces are not within scope of the SCOR framework [15]. There have been some attempts to use the SCOR Model in construction supply chains [16].

The Value Reference Model (VRM), former known as Value Chain Operation Reference Model (VCOR), is a model distributed and administrated by the Value Chain Group, which is am member-governed non-profit organization. It has roots in the research project “Product Design for Supply Chain”, where the SCOR Model was improved. In an extended framework, Lean/Six Sigma and further Business Process Re-Engineering methods were combined with the objective to support complex strategic transformations. This effort ended in the development and definition of the Value Operations Reference Model in 2002. It comprises reference processes for different branches and introduces maturity indices and best practices beside of classical supply-chain metrics [17].

Efficient Consumer Response (ECR) is a paradigm, which is also viewed as process reference model and is rooted in the consumer good and retail industry in the late 1980s. In Europe, the ECR initiative opened out into the association of trade and manufacturing companies. The beginning can be seen in the collaboration between Procter&Gamble and Walmart. Two components, category management and efficient replenishment, lay the foundation for a shared marketing and supply chain management and optimizing the logistics processes [18, 19].

The CPFR (Collaborative Planning, Forecasting and Replenishment) is a further development of the ECR model, which was published by the Voluntary Interindustry Commerce Standards (VICS) in 1998. It enhances the ECR approach by joint planning and forecasting practices of the actors along the supply chain, which leads to more transparency, shorter response times and lower inventory levels. The CPFR conceptual model has been divided into a set of process flow models, data flows, a logical data model, and a data dictionary. Beside the processes, the model defines standards for data transfer and structure as well as system architecture options [20, 21].

4 Logistics Reference Models and Their Application in Construction

As can be seen in Table 1, only one logistics reference model used in construction industry could be found. Most of the models contain all the necessary data, making them applicable to different tasks, with the constraint that some can only be used in their domain or branch. Only few generic and domain-independent models, like SCOR or VRM, exist.

A lack of defined processes, metrics and best practices for the specific construction processes could be identified, although the generic processes of SCOR and VCOR are easily applicable for business processes such as sourcing or planning the supply chain. The majority of operational construction processes could not, or only to a limited extent, be supported. This can also be derived from the structure of the management level shown in Table 1. The models that are more strongly focused on the operation are not in the domains of construction or related, like the similarly project-based plant engineering. The generic approach of these models provides the flexibility to use it for different processes along the supply chain, but does not support the specific processes of construction logistics such as material management, transport organization or additional services like access control or safety and documentation issues.

The lack of domain-specific models and the rising demand on logistics of subsurface construction sites, call for development in the area of construction logistics. Furthermore, the interaction of different actors and a wide range of subcontractors require standardized and repeatable processes, and clearly defined interfaces. This can be covered by process reference models and is a step towards an integrated construction logistics platform.

4.1 Construction of Reference Model for Subsurface Construction

Several researchers have investigated methods and procedures for the construction of reference models; a detailed summary is provided by Fettke and Loos [22]. A generic, clearly structured approach for the development of such models is specified by Schütte [23], which was used as the guideline for the construction.

Based on the problem definition, the framework of the reference model is constructed. The framework is designed to cover the major logistics processes needed in erection of subsurface and tunnel structures, irrespective of construction

Table 1 Classification of logistics reference models

		Third party logistics	Handling and consignement	International logistics networks	Trade-logistics	SCOR	VRM (VCOR)	ECR	CPFR
Branch	Construction	–	–	–	–	•	–	–	–
	Intralogistics	•	•	–	–	•	•	–	–
	Manufacturing	–	•	–	–	•	•	•	•
	Plant engineering	–	–	–	–	•	•	–	–
	Trade	–	–	•	•	•	•	•	•
	Transport	•	•	•	–	•	•	•	•
Data	Actors	•	•	•	•	•	•	•	•
	Interfaces	•	•	•	•	•	•	•	•
	It-Systems	•	–	–	•	•	•	•	•
	Model	•	–	•	•	•	•	–	•
Language	IUM/IOM*	–	•	•*	–	–	–	–	–
	Function tree	•	•	–	–	–	•	–	–
	Flow Chart	•	–	–	–	•	•	–	–
	Process/Value Chain	•	–	–	–	•	•	•	•
	EPC	–	–	–	•	–	–	–	–
Level	Normative	–	–	–	–	–	•	•	•
	Strategic	•	–	•	•	•	•	•	•
	Operation	•	•	•	–	•	–	•	•

(continued)

Table 1 (continued)

		Third party logistics	Handling and consignement	International logistics networks	Trade-logistics	SCOR	VRM (VCOR)	ECR	CPFR
Logistics Activity	Transport	•	–	•	–	–	–	–	–
	Source/ Procurement	–	–	–	•	•	•	•	•
	Intralogistics	•	•	–	•	–	–	–	–
	Production	–	–	–	–	•	•	–	–
	Distribution	•	•	•	•	•	•	•	•
	Return/Recycle	–	–	–	–	•	•	–	–
	Information logistics	•	–	•	•	•	•	•	•
Model Items	Best Practices	–	–	–	–	•	•	•	•
	Metrics	•	•	–	–	•	•	–	–
	Processes	•	•	•	•	•	•	•	•
Type	Procedual	–	–	–	•	•	•	•	•
	Industry-specific	•	•	•	•	–	–	•	•
	Software-specific	–	–	–	–	–	–	•	•

• reference model belongs to domain
– reference model belongs not to domain
* International Logistics Networks

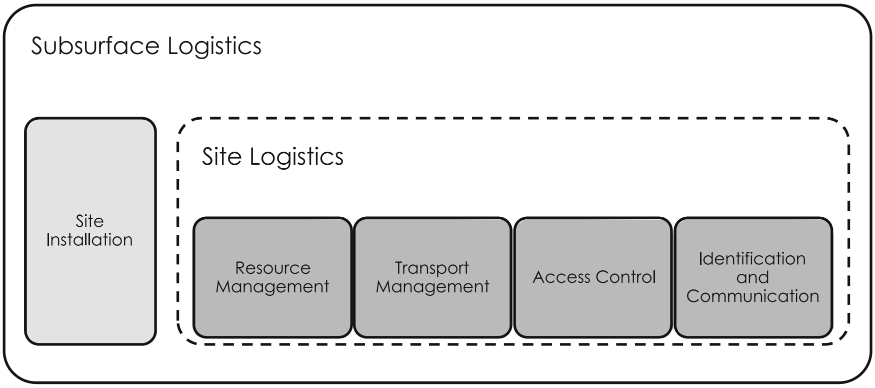

Fig. 2 Main processes of subsurface logistics

method. In case of the use of a tunnel boring machine, the handling of the tubbings, which are prefabricated concrete elements for the inner lining, is an additional process in resource management and transportation on site. The framework has been also aligned to the sub-contractor structure, so that the outsourcing of different processes is supported. During construction of the reference model structure, the lack of existing logistics process structure and their documentation was a major aspect. This was leading to a tri-modal approach in the construction of the modeling structure. At first, construction logistics processes where identified by an extensive literature research, followed by the assessment of existing logistics reference models and their processes on the applicability for subsurface construction. At last, the evaluation of logistics on different tunneling construction sites, based on interviews, observation and data analysis, was performed. The comparison, clustering and aggregation lead to the identification of the main processes, and the derivation of level 2 processes. The result of this clustering is presented in Fig. 2.

The main processes on subsurface construction sites can be divided into the site installation, which was not the focus in the development of the reference model, due to the singular occurrence, and the site logistics, summarizing the ongoing

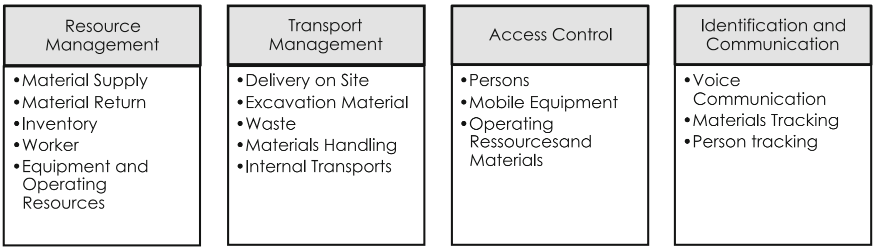

Fig. 3 Sub-processes in site logistics

processes on subsurface construction sites. These include resource management, where the construction supply chain is coordinated and the inventory as well as the production factors are planned. The transport management on site is a crucial factor for success of construction projects. Especially in urban areas, where the space for storage is limited, supply and transport have to be aligned to the progress in tunnel driving. A task that is included in the understanding and processes in construction logistics, which could not be found in a similar way in stationary industrial production, is access control. Especially staff and mobile equipment have to be controlled and access has to be documented. As a further main process, identification and communication were defined. Beside voice communication, tracking of material and staff is part of this process section. Person tracking gets more and more in focus on tunneling construction sites, because of safety and documentation issues, and lays the foundation for the improvement of production and logistics processes. Figure 3 shows the sub-processes or level 2 processes of subsurface construction sites.

After the definition of the sub-processes, the actors and the interfaces have to be identified. Their interaction is modeled by the use of UML, specifically BPMN, to define the base for an integrated construction logistics platform, and an initial process engineering solution can be provided to the construction companies.

5 Conclusion and Outlook

Construction logistics increasingly finds its way into practice of the construction industry, although these are mainly scattered initiatives. A way to support these efforts is the use of logistics process reference models. They are an initial point for process management initiatives and contribute to the performance of the companies by providing standardized structures for the implementation of a process management system.

The result of the assessment of the models shows that process reference models in the domain of construction logistics are applied to a very limited extent, and that the existing logistics models at the operational level focus on transport or intralogistics processes. So a deduction or translation of the operational production processes is hardly possible. On the other hand, the generic models provide a proven structure for the general processes, but lack especially this process level, where the construction industry differs from the stationary industrial production.

Due to the investigation of existing reference models and the evaluation of logistics processes on site, a process structure and hierarchy could be identified and the framework for a logistics reference model was established. This model will be consequently applied on construction sites to verify the intra- and inter-model consistency. Further research will be focused on the developments of metrics and a metrics toolbox for construction logistics.

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Part IV
Logistics Facilities

A Life-Cycle Approach to Characterizing Environmental Impact of Logistics Equipment in Container Ports: An Example of Yard Trucks

Nenad Zrnić and Andrija Vujičić

Abstract The incitation for this paper is the necessity to research the trends in sustainability regarding the mitigation of environmental impacts of logistics equipment in container ports. This paper discusses environmental impacts of the most common type of cargo handling equipment used at container terminals which are yard trucks, by using the methodology of life cycle assessment. The conventional yard trucks are compared with zero or near zero emissions counterparts in order to reveal the most environmentally efficient ones. The comparative life cycle assessment, which forms the major part of this paper, illustrates how this methodology could be applied as comparison and decision making tool in order to identify the entanglements that might arise from unaware application of technologies advertised as 'green' or eco-friendly.

Keywords Life cycle assessment · Port logistics · Yard trucks · Environment

1 Introduction

Of the 20 global megatrends one of the most significant trends for intralogistics as a part of logistics sector (energy consumption in intralogistics is estimated to about 25 % of the whole logistics sector [1]) is climate change and environmental impact, while one of the main research thrusts is 'Green Logistics' [2]. Although the logistics greenhouse gas (GHG) footprint may appear relatively modest

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(estimated for around 5.5 % of global emissions), the transport sector has been increasing its output of these gases, while other sectors are reducing their footprint [3]. For this reason it is quite sure that in the next few decades a major challenge for the companies in logistics sector will be to implement practical and cost-effective carbon mitigation strategies to cut their GHG emissions in an effort to achieve very ambitious carbon reduction targets at national, EU and global levels by 2050.

Companies can reduce carbon emissions from their logistics operations in many ways. According to [3], there are several ideas for decarbonisation of logistics activities while the focus is on five key freight transport parameters: reducing freight transport intensity, shifting freight to less carbon-intensive transport modes, increasing vehicle utilization, raising the energy efficiency of freight transport operations and finally reducing the carbon intensity of the energy source (i.e. the amount of CO_2 emitted per unit of energy consumed either directly by the vehicle or indirectly at the primary energy source for electrically-powered freight transport operations, what will be particularly considered later in this paper) used in logistics. Obviously, decarbonisation must be followed by developing innovative technologies [4] in order to improve intermodal transport chains, logistics services and consequently environmental performances of logistics equipment.

In recent years, in addition to road vehicles, an increased interest focused on environmental impacts of non-road or off-road vehicles is apparent and accordingly the corresponding emission models are developed. For instance, report [5] reviews and evaluates actual methods used to estimate air emissions from freight transportation activities and determines their suitability for decision making and public education. In this report all freight modes are represented, including heavy-duty trucks, rail, oceangoing vessels, harbor craft, cargo handling equipment (CHE) representing logistics equipment in ports, and air freight. To the extent possible, three geographic scales have been analyzed for each mode, namely at the national, regional, and local/project levels.

CHE is used to move freight at sea and river ports and other intermodal facilities that transfer goods between modes, such as inland freight terminals. Container terminals use CHE most extensively, while truck-to-rail equipment and dry bulk terminals also have high use of CHE. The variety of CHE types in use is related to the variety of freight handled. In the same way, the amount of CHE and its activity are related to the overall amount of freight throughput for a given facility. Depending on the type, use, and number of CHE, their emissions can be significant contributors to overall goods movement emission inventories. Thus, determining emissions from container terminal CHE is important in any land-side emission inventory [6]. Due to their use solely to move goods, all CHE mobile source emissions are related to freight.

Generally, CHE emissions at ports are estimated using either the off-road emission models or methods similar to those in the models [6]. In order to understand the environmental impact of container terminals, various models and tools that quantify the emissions of relating sources are used or developed. Each model can vary greatly in terms of complexity and accuracy on one side, and time and resources on the other side. The non-modeling approach to create an emission inventory of CHE is to directly measure emissions or energy consumption. Although it could be considered as the most accurate way, it is also the most expensive and time demanding and can only be done in the aftermath. Direct emissions measurement thus disables the early stage planning process and is more suitable for establishing the baseline inventory. The modeling is therefore more appropriate as a preventive approach, as support for decision making [4]. The complexity of the modeling methodologies can also vary depending on the intended use and users and can also be time and resource consuming if a detailed and validated model is wanted, according to Liu et al. [7]. Regardless of which modeling approach is chosen, it enables the prediction of emission of any source at a port without actually ever visiting the facility. This can also be used for comparison of different types of CHE. The drawback of modeling is that any uncertainty in baseline parameters can eventually lead to significant uncertainty in the final results of the estimated CHE emissions. This is of great importance, particularly when a comparison of any type of CHE is made, since even the slightest aberration in the early modeling can result in favoring one piece of equipment over another.

The significance of CHE emissions is also revealed by the fact that many ports today are considered to be the largest sources of air pollution in coastal cities. For instance, according to the data collected in report [5] in 2007, the Port of Long Beach found out that 81 % of the CHE port wide emissions was caused by its container terminals and that 8 % of the total NO_X emissions were due to CHE; the Port of Houston found out that 15 % of its 2007 total NO_X emissions came from CHE; New York/New Jersey found out that 25 % of their 2006 NO_X emissions were due to CHE. To get better fuel economy and accordingly to reduce GHG emissions, ports around world consider to use either 'low carbon' (hybrid) or 'zero emissions' (electric) technologies that are currently deployed for port equipment such as cranes—Rubber Tired Gantry Cranes [8] and Mobile Harbor Cranes [9], yard trucks [10] and other vehicles.

2 Strategies to Mitigate Environmental Impacts of Yard Trucks

The yard trucks are heavy-duty off-road single cab vehicles designed for towing trailers with containers in terminals. They are by far the most common type of CHE used at container terminals, especially in North America and often cover over 50 % of the total CHE population [11]. In typical operations at a container terminal yard trucks support almost every CHE for the swift ferrying of the containers across the terminal.

The duty cycle of yard trucks consists of long idling periods and stop and go movements with high or low load accelerations. This results in inefficient operation of diesel engines and significant air emission and noise pollution. Based on some annual port emission reports and available air emissions inventories, it is stated that yard trucks contribute half of the entire terminal carbon and particulate matter (PM) emissions associated with CHE [12]. This is due to the fact that currently, conventional yard trucks are equipped with internal combustion engines (ICE) with fuel consumption reaching an average of up to 10 liters per hour [12].

Despite major advances in technologies for improving vehicles environmental performance (especially in the automotive industry), the application of diesel alternatives for off-road vehicles is still in 'baby steps'. Several solutions are being on and off recognized as top contenders for making mainstream application. The corresponding industries are forced by policy makers and the environmentally concerned public to actively pursue a pathway to mitigate emissions; the possibilities range from alternative fuels to powertrain variations. Based on the market success of hybrid passenger vehicles and re-emerging electric vehicles, the heavy duty off-road manufacturers can exploit the potential of well understood technology that can be integrated into yard trucks. The transition from ICE to broad use of zero (electric) and near zero emission (hybrid) is the most governed solution at present and seems to be the most feasible.

The hybrid solutions for yard tracks exploit the random duty cycle in order to improve the overall efficiency of diesel engines. In a yard truck equipped with a diesel hybrid drive system, the engine is shut down during idling periods and regenerative braking allows kinetic energy normally wasted during braking to be captured by the hybrid energy storage system, subsequently improving fuel efficiency and lowering emissions. There are two hybrid systems available for yard trucks, which defer only in the concept of kinetic energy storage. The first is the electric hybrid system which endorses a battery storage solution, while the second is based on hydraulic high pressure accumulator energy storage.

The diesel electric hybrid yard truck uses basically the same hybrid technology proven in on-road hybrid vehicles. The battery pack (most common is lithium-ion) or ultra-capacitor is used to store kinetic energy when decelerating or braking. Stored energy is later used to assist the ICE during acceleration, or for short distance zero emissions movement in battery mode. The latest evolution of electric hybrid yard trucks is the plug-in hybrid with the additional option of battery recharging at a grid. With this feature a diesel generator set could be used as range-extender enabling the downsizing of ICE.

The hydraulic hybrid yard truck is an alternative to electric hybrid trucks which are often criticized for battery fallibility and hazards potential. The hydraulic hybrid system uses a high accumulator and a low pressure reservoir filled with hydraulic fluid and nitrogen (N_2) to capture kinetic energy. During vehicle braking, the rotating energy of the wheels is used to pump fluid from the low pressure reservoir into the high pressure accumulator where nitrogen is compressed. Up to 70 % of the kinetic energy stored can be reused for vehicle acceleration [13]. The system can also be equipped with a start-stop feature enabling engine shut down to eliminate idling.

One of the latest trends in CHE industry is the fully electric yard truck, advertised as zero-emission equipment since it has no "tail-pipe" emissions. This system uses an electric motor and a battery storage system (lead, nickel or lithium-ion battery packs). The electric yard truck range is from 80 to 150 km, depending on battery pack size which is up to 300 kWh. Overall autonomy is sufficient for two shift operations. The overall success of the electric yard truck concept in making mainstream is linked to the outlook of battery development for electric vehicles.

3 Life-Cycle Approach to Characterizing Environmental Impacts

As mentioned before, in response to the demanding task of reducing emissions the CHE industry offers a variety of solutions for yard trucks. However, concerning the implementation of the emerging technologies in order to reduce environmental impacts of the CHE it is complex to predict which one of implemented technologies would be appropriate for the struggle with changes in the environment that we are experiencing. But, our level of knowledge, or uncertainty, is different from that related to any particular technology.

A significant parallel in planning and orientation in environmental sustainability presents the basis on which the methodology is selected. Attention to emergent methodologies developed to help decision makers to identify and the public to understand that the broader scope of environmental sustainability underpins the life cycle assessment (LCA) as established development tool.

LCA is nonetheless suggested as one of the key tools of the sustainability era and thus outlined in ISO 14040 [14]. It is a technique to estimate the environmental aspects and potential long-term impacts of the whole life-cycle of products or services, compiling and inventorying the implications of the system's inputs and outputs and interpreting the results of inventory and evaluation phases according to the given situation. The LCA considers the ecological impacts of the systems examined, particularly in the light of environmental and human health and depletion of natural resources. It is a systematic approach for analyzing the entire life cycle stages form raw materials to the manufacturing step, introduction to a market to maturity and eventual decline and end-of-life (including recycling and waste *disposal)*. Hence, it is often identified as "cradle-to-grave" analysis [15].

Based on inventory data, LCA offers proper information without need for on-site measurements, necessary in early stage planning in order to avoid illusory decisions or strategies. This equips designers and policy makers with instruments for analysis and assessments, helping them to visualize and focus on certain reliability measures on the most important fields in which one could intervene.

The LCA methodology was originally devised for the analysis of an industrial productive system. However, the flexibility of the approach has made it useful over a wide range of uses. As an instrument of analysis, LCA can provide an interesting approach for the analysis of the environmental impacts of logistics and corresponding equipment as well. The application of LCA studies in the field of intralogistics (material handling) and logistics (transport) has drawn some attention to the recent engineering researchers, but a modest number of literature items on the subject is offered, e.g. [10, 16–18]. However, as concluded in [3] the decarbonisation of logistical operations cannot occur in isolation. Carbon reduction efforts in different logistics sectors will need to be coordinated and the LCA conducted to ensure that on an 'end-to-end' supply chain basis GHG emissions are minimized [3].

4 Comparative LCA of Yard Trucks

The LCA methodology was used in order to quantify and compare the potential environmental benefits of transfer from conventional yard trucks to hybrid or electric solutions. The case study, which forms the key part of this paper, illustrates how LCA methodology might be applied in practice and, equally significantly, identifies the types of difficulties that might arise from an unaware application of technologies advertised as green or eco-friendly. The life cycle comparison of four yard truck models was conducted regarding the ISO 14040 regulations [14] and similarities in the life cycle stages of each model, given that chosen models are matching in function.

4.1 Assumptions

In order to simplify the LCA comparison having in concern its goal and scope and intended purpose, certain simplifications and assumptions are made. These are done relating to duty cycles of yard trucks and dock side operation experience avoiding data uncertainties. Therefore conventional diesel model yard trucks are determined as base models, while the other three: hydraulic hybrid, electric hybrid and full electric cover use over 98 % of the same construction and components (chassis, wheels, diesel engine, cabin, interior features). Adopting this modeling principle most of inventory base of conventional diesel yard truck can be used for the creation of an inventory base of hybrid and electric models.

The assessment is split into three life cycle stages. The first stage covers raw material extraction and depletion, manufacturing and distribution to dock yard and is referred to as 'upstream'. The second is the 'use' stage, which is the longest and with highest environmental impact. The final stage is 'end of life' and it deals with scrap disposal and recycling. The 'cut-off'' principle is applied in the manufacturing phase, in order to simplify the case study, leaving out parts, components and processes that weight less than 5 % of total mass of the chosen model, or have a contribution of no consequence to the overall environmental impact. The allocation of parts and components from an assembly location, which is very common in vehicle manufacturing is ruled out (i.e. transportation of the engine to the vehicle assembly plant).

The LCA is conducted using GaBi software developed by PE International as most represented LCA tool on the market. The electric power grid mix is EU-25 with responding emissions. Thus for the container terminal location it was assumed that it is a port at EU seas, rivers or inland waterways. In order to provide the most accurate data for the study, the GaBi software inventory data on 'end of life' is compared with results from Zackrisson et al. [19] and Majeau-Bettez et al. [20] who researched lithium-ion battery disposal and recycling and Schweimer and Levin [21], Liu et al. [22] and Renault [23] for the diesel engine life cycle. For the diesel engine used for conventional and two hybrid trucks it was assumed that it is an on-road engine for an off-road vehicle, due to availability of inventory data for on-road engines. The effect of the actual duty cycle and the operator's driving habits on engine loads are ruled out.

4.2 LCA of Yard Trucks

The size of selected conventional yard truck, set for a base model for LCA study is the same as for hybrids and electric vehicles, and the dimensions are presented in Fig. 1. The net weight is 7 tons and gross combined weight is 40 tons. The powertrain variations are shown in Table 1.

The Functional Unit (FU) is also defined according to the LCA practice. The FU for the yard truck is defined as one operating hour at container terminal (yard work), where 40 % of the time is spent in idling, 35 % of time is related to lower load and 25 % with high load. The annual operation time for yard trucks in this

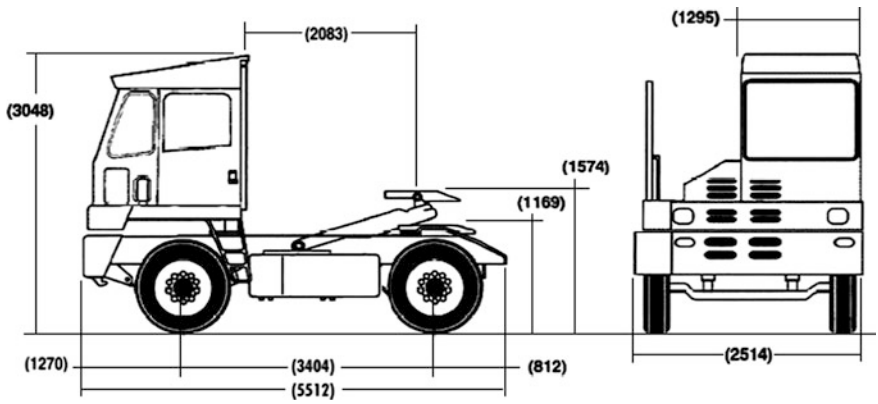

Fig. 1 Base model of a yard truck with dimensions in millimeters

Table 1 Powertrain variations of compared yard truck models

Powertrain	Feature	Conventional diesel	Hydraulic hybrid	Electric hybrid	Full electric
Diesel engine	Size	6.7 L	6.7 L	6.7 L	–
	Power	150 kW	150 kW	150 kW	–
Battery	Capacity	–	–	5 kWh	150 kWh
Electric	Power	–	–	80 kW	140 kW
Motor	Voltage	–	–	150 V	230 V
Hydraulic	Pressure	–	400 bar	–	–
System	Power	–	160 kW	–	–
Reservoir	Capacity	–	0.5 kWh	–	–

LCA comparison is 2,500 working hours. The life cycle is 10 years. The fuel consumption of the selected models is calculated based on LCA software inventory and checked with reports from Calstart [12].

5 Results

The results conducted assessment are classified and characterized in accordance with ISO 14040. For the comparative LCA the most significant impacts are evaluated and presented via a life cycle impact assessment (LCIA) problem-orientated method developed by the Institute of Environmental Sciences from Leiden (CML 2001) and the damage orientated Swiss method Ecoinvent.

The ‘upstream’ stage illustrates significant differences between yard trucks equipped with diesel engine and electric motor. The environmental impact of lithium-ion battery pack production is much greater than of conventional diesel engines. The global warming potential (GWP) of a 150 kWh battery pack selected for electric yard truck model is approx. 40.000 kg of CO_2 equivalent, which is twenty times larger than GWP of 6, 7 L diesel engine. This ratio is an ‘issue’ that determents the ‘upstream’ stage.

The results of the ‘use’ stage reveal less environmental impact of electric yard trucks over other three models. This is due to the selected EU-25 power grid mix with an average of 0.539 kg of CO_2 eq. per kWh. Other power grid mix scenarios could influence results of the electric yard truck in both directions. The two hybrids show a certain reduction of the environmental impact in range of 20 % over the conventional ones, but in small favor of hydraulic due to the burden of electric hybrid’s batteries impact.

The ‘end of life’ stage is again influenced by lithium-ion batteries of electric yard trucks, while conventional and hybrid versions share nearly the same results. The additional abbreviations used in Table 2 are: acidification potential (AP), eutrophication potential (EP), phosphate (Ph.) and radioactive waste (RW).

Table 2 LCIA of yard trucks in kg (CML 2001-problem method)

Yard truck	Impact	Upstream	Use	End of life	Total
Conventional diesel	GWP [CO_2 eq]	35.850	499.152	247	**535.249**
	AP [SO_2 eq]	192	6.508	1	**6.701**
	EP [Ph. eq]	9	1.201	0.06	**1.210**
	RW	117	0	0.8	**118**
Hydraulic hybrid	GWP [CO_2 eq]	38.880	432.126	265	**471.271**
	AP [SO_2 eq]	210	5.647	1.00	**5.859**
	EP [Ph. eq]	9	973	0.06	**982**
	RW	135	0	0.9	**136**
Electric hybrid	GWP [CO_2 eq]	43.135	438.101	1.239	**482.475**
	AP [SO_2 eq]	278	5.725	1	**6.009**
	EP [Ph. eq]	14	986	1	**1.001**
	RW	140	0	0.33	**140**
Full electric	GWP [CO_2 eq]	68.025	269.500	4.950	**342.475**
	AP [SO_2 eq]	361	1.430	3	**1.817**
	EP [Ph. eq]	25	65	4	**94**
	RW	221	875	1	**1.097**

6 Conclusions

The development of innovative technologies in transport is strategically focused on improving environmental performances and reducing emissions. The same applies to ports and container terminals (sea, river and inland) as intermodal nodes. Although, the researchers are mostly focused on seaports, the sustainability pathway is applicable for transport flows on inland waterways (i.e. container transport on the Danube—see Acknowledgements). One way is to develop an innovative, container-specified inland vessel and logistics system which allows to meet the operator's targeted costs, optimize time-management (reliability), answer to inland shipping-specific bottlenecks, improve carbon footprints and thus successfully interact efficiently with road and railway transport. Therefore, it would be recommendable to prove the real environmental benefits of newly established innovative technologies.

The comparative LCA of different yard truck concepts reveals limitations of applications of electric-diesel hybrid technology for off-road vehicles in terms of environmental benefits. On the other side, the results promote full electric yard trucks as cleaner solution if the right power grid mix is selected. However, the hydraulic-diesel hybrid could turn out as more simple near future alternative, if the battery technology goes to a standstill. The presented example illustrates the importance of life cycle thinking for decision making and identifying the drawbacks of technologies promoted as solutions to mitigate environmental impacts.

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Throughput Maximization of Parcel Sorter Systems by Scheduling Inbound Containers

S. W. A. Haneyah, J. M. J. Schutten and K. Fikse

Abstract This paper addresses the inbound container scheduling problem for automated sorter systems in express parcel sorting. The purpose is to analyze which container scheduling approaches maximize the throughput of sorter systems. We build on existing literature, particularly on the dynamic load balancing algorithm designed for the parcel hub scheduling problem, and adapt the existing algorithm to include travel times on sorters. Then, we conduct computational experiments to analyze the performance of different scheduling approaches for different operational scenarios and system layouts.

Keywords Online scheduling · Parcel sorting · Sorter systems · Inbound operations

1 Introduction

In this paper, we focus on sorter systems in express parcel sorting. Figure 1 distinguishes the basic physical layouts of sorters with a line configuration from more complex sorters with a loop configuration. We focus on the latter but the analysis and the results are applicable to sorters with a line configuration as well. Note that an *infeed* is a conveyor where operators place items to be transported

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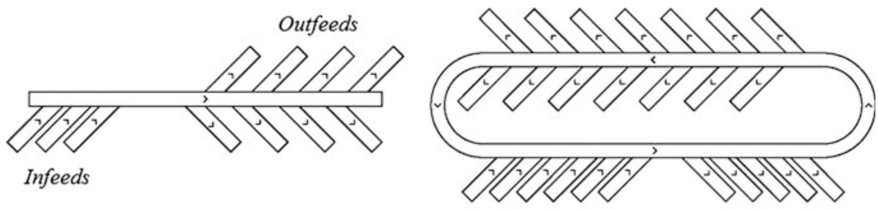
towards the main conveyor in a sorter system. On the other hand, an *outfeed* is a catchment conveyor that represents an exit point for items upon sorting. An important operation is scheduling inbound containers to unload at the infeeds of the sorter system. In this paper, we study container scheduling algorithms that lead to better use of automated sorter systems. Such algorithms allow system users to have better systems' performance without installing additional equipment.

In practice, a lot of information about the contents of specific containers is available in the network. For example, when loading a container at a depot or airport of origin, the information about the number of parcels in the container and their destinations is registered. However, this information is not used at the hub where this container arrives. System users typically apply a first-come-first-served (FCFS) policy when unloading inbound containers. As a result, uncontrolled peak flows for a particular outfeed may arise. Peak flows for outfeeds may cause them to be overloaded, which may reduce the capacity (measured in sorted items per hour) or at least increase material handling costs.

In sorter systems, outfeeds are generally coupled to specific destinations or regions of destinations. When an outfeed coupled to a particular destination is full, a sorter in a line configuration transports the corresponding items to the outfeed for unsorted items, which leads to an area (downstream the sorter system) where unsorted items are collected. The capacity of the sorter system is indirectly reduced, because the unsorted items have to be re-loaded onto the sorter system for a second delivery attempt. Another solution is to manually sort the parcel, which may increase handling costs significantly. In a sorter system with a loop configuration, a full outfeed results in *recirculation*. This reduces the sorter capacity directly, since a recirculating item claims space that otherwise could have been used by another item. In this context, balancing the workload across outfeeds may help reducing the overload incidents and thereby reduce recirculation. This in turn might increase the operational capacity of existing sorter systems.

The main problem we tackle is how to schedule the unloading of inbound containers using the knowledge about their contents, in order to balance the workload on sorters. To this end, we build upon the state-of-the-art scheduling algorithm from literature and present an adapted version of this algorithm to model more realistic travel times on sorters. In this paper, we investigate which scheduling algorithm to use for different operational scenarios and system layouts.



(a) Line configuration **(b)** Loop configuration

Fig. 1 Basic configurations of sorter systems

The rest of this paper is organized as follows: Sect. 2 provides a review of relevant literature. Section 3 discusses container scheduling algorithms in parcel sorting. Section 4 presents the experimental setup and the results of computational experiments. Finally, Sect. 5 ends with concluding remarks.

2 Literature Review

The *parcel hub scheduling problem* (PHSP) [1], is one of the first studies that focus solely on scheduling inbound containers at parcel sorting hubs. McWilliams et al. [1] use a sorter system in line configuration, where they try to minimize the *makespan* of the sorting process. They use a simulation-based scheduling algorithm (SBSA), which is based on a genetic algorithm, to solve the problem and show that their approach is superior to the arbitrary scheduling (ARB) approach, which randomly assigns available containers to available infeeds. McWilliams [2] shows that similar results can be achieved using iterative local search or simulated annealing techniques. McWilliams [3] aims at an approach to balance the workload on the loading docks. He solves small problems to optimality using a binary minimax programming model. For big problem instances, he uses a genetic algorithm that outperforms the SBSA and ARB approaches used in [1]. McWilliams [4] shows that iterative approaches provide solutions that are on average 6 % better than the solutions provided by the genetic algorithm. McWilliams [5] develops a relatively simple *dynamic load balancing algorithm* (*DLBA*). While the other algorithms require information on all trailers in a particular shift, this algorithm only requires knowledge of the trailers that are waiting to be assigned to an unloading dock. He finds that the DLBA outperforms the ARB (makespan reduction of 15 %). Moreover, the DLBA is generally better (makespan reduction of 8 %) in large complex problems than the approach of [4].

McAree et al. [6] test the bin and rack assignment model (BRAM) using a realistic case from a large package sort facility. They design this algorithm for air terminals where inbound containers are assigned to bins to be broken into individual pallets. Their main goal is to minimize the operational cost. Since the BRAM is too complex to solve, they develop a new algorithm that finds a solution by iteratively solving the bin assignment model (BAM) and rack assignment model (RAM), both of which are formulated as mixed integer programs. McAree et al. [7] find solutions for different layouts with running times ranging from a few minutes to a few hours, which is slow for online scheduling decisions.

Werners and Wülfing [8] consider a sorter system of a Deutsche Post parcel sorting center, where each parcel is unloaded at an unloading dock, sorted into a chute and then assigned to a loading dock. The authors aim at minimizing the total distance travelled on the sorters. In order to solve this problem, they hierarchically decompose the problem into two sub-problems. They show that their approach ensures a balanced workload over the different areas in the sorting center, whilst providing robust solutions. However, they do not discuss the container unloading operations.

Conclusion. From our review, we find the DLBA [5] of the PHSP [1] to be the most relevant study from different perspectives. First, the DLBA is an online algorithm that does not require full knowledge about incoming containers but uses existing knowledge about containers that are already at the sorting hub. Second, it is a fairly simple and fast approach, which can be implemented easily in practice. Finally, impressive reductions are reported in the makespan of the sorting operation [5].

3 Scheduling Inbound Containers

In this section, we first describe the state-of-art load balancing algorithm (Sect. 3.1), which is the DLBA [5] as developed for the PHSP [1]. Thereafter, we adapt the DLBA to incorporate non-zero and variable internal travel times (Sect. 3.2).

3.1 The Dynamic Load Balancing Algorithm

The DLBA [5] constructs unload schedules for inbound containers using an online scheduling approach, which assumes that the infeeds of the sorter are parallel identical resources. The DLBA, triggered when an infeed becomes idle, evaluates all containers available and selects the container that (when assigned to the idle infeed) minimizes the overflow (number of excess parcels) on outfeeds. This is done by balancing the flow of parcels over the sorter system. Thus, monitoring the state of the system is essential. In other words, information is required on an infeed becoming idle and on the number of parcels going to a certain destination (at each moment in time) in the system. The latter includes the parcels flowing across the sorter and the parcels in the inbound containers being processed at the other infeeds. This information is known because parcels' tags are read when they are unloaded from the containers to the infeeds and when they exit the sorter system at the outfeeds.

The DLBA assumes zero internal travel times on the sorter. As a result, a parcel loaded on an infeed is immediately unloaded at an outfeed. Note that the assumption of zero internal travel times is not a stronger assumption than the assumption that internal travel times are fixed and equal for any infeed–outfeed pair. This assumption means implicitly that all infeeds are identical. Therefore, if a container arrives and there are multiple infeeds idle, then the DLBA assigns the container to an arbitrary infeed. The restriction of zero internal travel times might be a valid simplification for small single-sorter systems where internal travel times for any infeed–outfeed pair are comparable, or when unloading a container requires much more time than the internal travel time of parcels in the system.

However, this may not hold for larger systems or when the time to unload a container is short compared to the travel time on a large sorting system with multiple loop sorters, multiple infeed areas, and routing complexities. Therefore, in Sect. 3.2, we propose an adapted version of the DLBA that takes internal travel times into account.

3.2 The Adapted-DLBA

In this section, we propose the *Adapted-DLBA (ADLBA)*, which is an online algorithm that modifies the DLBA to incorporate (unequal) travel times on the sorter (without possible traffic delays). For the PHSP, the DLBA only keeps track of the total number of parcels in the system destined for a specific outfeed. Incorporating travel times means that the workload should not only be balanced over the different outfeeds, but also over time. Moreover, for the ADLBA, it is important to know at which infeed a container is docked since travel times to outfeeds may differ amongst infeeds.

Determining the expected outflow (the number of parcels that arrive at the chute) for each outfeed at each moment in time indicates the excess in capacity (if any) of the outfeed at some moment in time. However, not only the number of excess parcels is relevant, but also the rate at which these excess parcels arrive. We choose to use the squared value of excess flows as an optimization criterion to heavily penalize large excess flows. Another possible goal function would be a minimax goal function that minimizes the maximum excess amount. A drawback of this approach is that it may not properly distinguish different solutions. For example, a solution in which only one outfeed exceeds its capacity by n parcels is considered the same as a solution in which all outfeeds exceed their capacity by n parcels. Obviously, the latter case is much worse.

Determining the squared excess outflow on a continuous time scale is impractical. A computationally less challenging approach is to use *time buckets*. In the time bucket approach, we determine for each parcel in which time bucket it is likely to arrive at the outfeed. The size of the time buckets is an important model parameter since it affects the level of detail that can be achieved. In order to achieve sufficient detail, we use a time bucket size of one minute. This is approximately a quarter of the time required to unload a single container and roughly equal to the smallest travel time between infeed–outfeed pairs in the sorter systems that we study. Using time buckets of one minute provides sufficient detail but also results in valid and meaningful outflows. Table 1 presents the mathematical notations for formulating the ADLBA.

The main idea of the ADLBA is to make a selection on which containers to unload at idle infeeds in order to minimize the excess outflow over outfeeds *and* over time. Moreover, we show how to deal with an arriving container if multiple infeeds are available once the container arrives.

Table 1 Mathematical notations for the ADLBA

Notation	Description
I	Set of infeeds (i ε I)
0	Set of outfeeds (o ε 0)
T	Set of time buckets (t ε T = {1,2,...})
C	Set of inbound containers ($c \in C$)
tb	Length of one time bucket in seconds
F_0	Outflow capacity of outfeed o (in parcels per hour). Note that it is common practice to define the capacities of sorter systems in parcels per hour
F_i	Capacity of infeed i (in parcels per hour)
$f_{c,\,o}$	Number of parcels in container c destined for outfeed o
$t_{i,\,o}$	Internal travel time from infeed i to outfeed o (in time buckets) excluding possible traffic delays
$f_{c,\,total}$	Total number of parcels in container c
a^c	The time when the first parcel from container c is announced at an infeed (in seconds)
$TB_{c,\,o,\,start}$	Number of the first time bucket in which the parcels from container c which have the destination outfeed o are expected to arrive at outfeed a
$TB_{c,\,o,\,end}$	Number of the last time bucket in which the parcels from container c which have the destination outfeed o are expected to arrive at outfeed o
$FL_{c,\,o,\,start,\,end}$	Number of parcels from container c that are expected to arrive at outfeed a in any time bucket from $TB^{container}_{c,o,start}$ until $TB^{container}_{c,o,end}$ Note that these are auxiliary variables that depend on alternative assignment decisions
$Flow_{t,\,o}$	Actual total expected outflow of parcels at outfeed a in time bucket t based on all assignment decisions made so far
$Flow_{i,\,c,\,t,\,o}$	Expected outflow of parcels at outfeed o in time bucket E if we decide to assign container c to infeed i at time a^c
$EF_{i,\,c}$	Total expected overflow of parcels at all outfeeds, summed over all time buckets in the planning horizon if container c is assigned to infeed i at time a^c

Given an idle infeed, we examine the containers available in the queue at the sorting hub. For each container c, we examine the $f_{c,\,o}$ values for every outfeed o (Table 1). Next, we find the time bucket in which the first of these $f_{c,\,o}$ parcels are expected to arrive at the destination outfeed o and the time bucket in which the last of these parcels are expected to arrive at this outfeed. Then, we evenly spread the $f_{c,\,o}$ parcels over the time buckets from the first time bucket until the last time bucket. In this way, we determine the expected outflow of parcels to outfeeds if a container c is selected to unload.

Now, given container c assigned to infeed i, then for each destination outfeed o (to which parcels exist in the container), we determine the values of $TB_{c,\,o,\,start}$ and $TB_{c,\,o,\,end}$ using the following equations:

$$TB_{c,\,o,\,start} = \left\lceil \frac{a^c + \frac{3{,}600}{F_i} + t_{i,o}}{tb} \right\rceil, \tag{1}$$

$$TB_{c,\,o,\,end} = \left\lceil \frac{a^c + \frac{3{,}600}{F_i} \cdot f_{c,\,total} + t_{i,\,o}}{tb} \right\rceil. \tag{2}$$

Then, we calculate the expected outflow from container c at outfeed o as follows:

$$FL_{c,\,o,\,start,\,end} = \frac{f_{c,\,o}}{TB_{c,\,o,\,end} - TB_{c,\,o,\,start} + 1}. \tag{3}$$

Note that the time required to unload a container ($3,600/F_i \cdot f_{c,\,total}$ seconds) depends on all parcels inside the container, while the expected outflow arriving at a specific outfeed depends only on the parcels destined to this outfeed.

The variable $Flow_{t,o}$ keeps track of the total outflow of parcels at outfeed o in time bucket t based on all assignment decisions made so far. Therefore, we increase the value of $Flow_{t,\,o}$ (for $t \in \{TB_{c,\,o,\,start}, \ldots, TB_{c,\,o,\,end}\}$) by $FL_{c,\,o,\,start,\,end}$ when the assignment decision of a container is fixed.

In order to make an assignment decision, we have to select one of the containers in the queue to unload at an idle infeed. Therefore, we have to determine the objective value for an assignment decision of a specific container to a specific infeed. In this regard, time buckets in the past are irrelevant, and information about time buckets that are relatively far in the future is not reliable, because recirculation and traffic conditions may alter these predictions. Therefore, we focus on the total expected outflow in the next 15 min. We introduce the set H, which defines all time buckets that are part of the planning horizon. Then, for every alternative decision of assigning a container c to an infeed i at some time a^c, we calculate the total expected outflow for each outfeed and each time bucket $t \in H$ and store these values in the variables $Flow_{i,c,t,o}$. Then, we determine the objective value for each assignment decision as follows:

$$EF^2_{i,\,c} = \sum_{t \in H} \sum_{o \in O} (\max\left\{0, Flow_{i,\,c,\,t,\,o} - \frac{F_o \cdot tb}{3,600}\right\})^2. \tag{4}$$

We aim to minimize the $EF^2_{i,\,c}$ value, which represents the cumulative squares of the overflows over all time buckets and outfeeds if container c is assigned to infeed i. Figure 2 presents the general procedure to implement the ADLBA.

4 Computational Studies

In this section we describe the experimental setup (Sect. 4.1) and discuss the implementation results (Sect. 4.2).

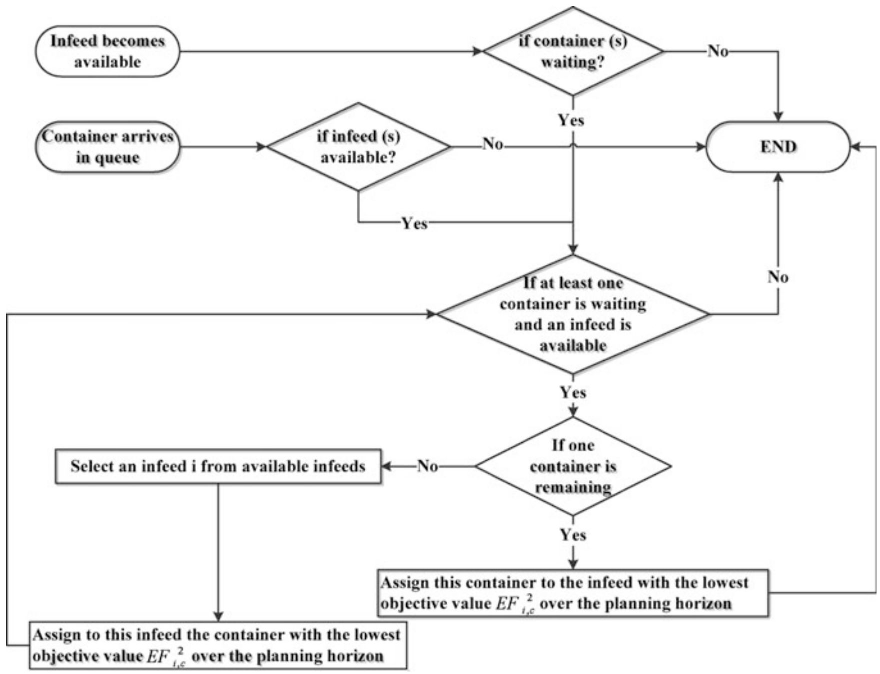


Fig. 2 Main logic of the ADLBA

4.1 Experimental Setup

We test the performance of four algorithms: first-come-first-served (FCFS) as a common current practice, arbitrary scheduling (ARB) as an academic benchmark, the DLBA, and the ADLBA. We use the Applied Materials AutoMOD simulation software package to apply the scheduling approaches on simulation models that are based on three system layouts that are frequently delivered by our industrial partner. We do not invest in the control logic of sorter systems beyond simple local traffic control rules as this paper focuses on inbound operations scheduling. The system layouts (Fig. 3) are as follows:

(a) A single sorter in loop configuration with one infeed area and one outfeed area, where each area consists of three conveyors (layout 110).
(b) A single sorter in loop configuration with two infeed areas and two outfeed areas, where each area consists of three conveyors (layout 120).
(c) Two sorters in loop configuration, where each sorter consists of one infeed area and one outfeed area. In turn, each area consists of three conveyors. Crossovers are conveyors with limited capacity that connect the two sorters (layout 22c).

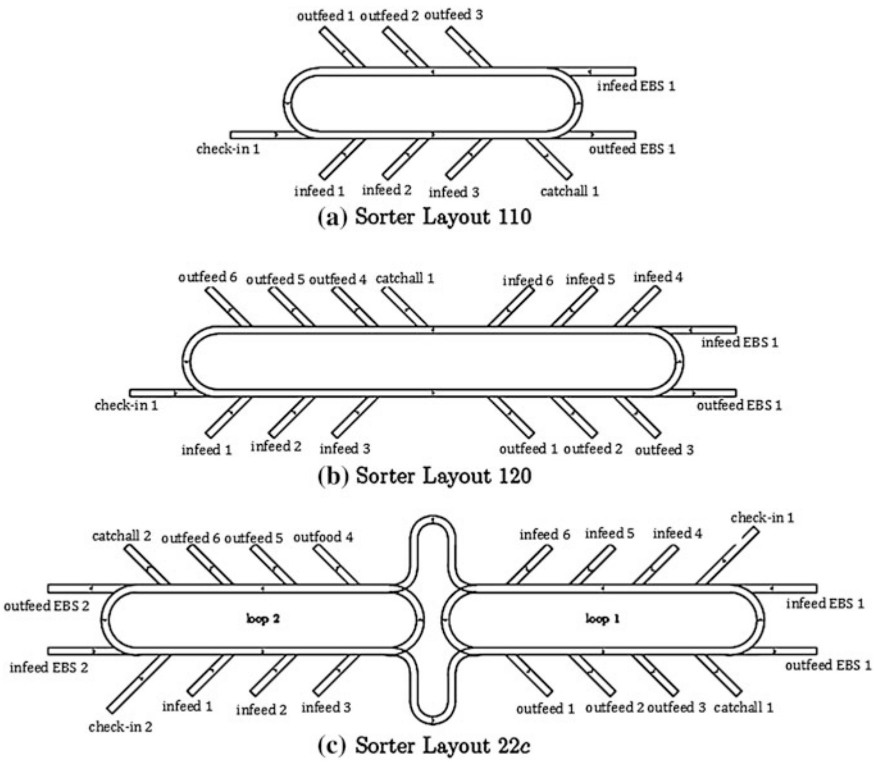


Fig. 3 Layouts of the modeled sorter systems

Regarding datasets, the number of destinations we model equals the number of outfeeds. However, we distinguish the contents of containers based on the quantities of items going to certain destinations. A *homogeneous* distribution means that inside one container, each destination has the same probability of occurrence.

A *heterogeneous* distribution means that some containers hold significantly more items for destination ‘a’ while other containers hold more items for destination ‘b’. For this case, we use containers with a *preferred destination*, where the preferred destination has 0.50 probability of occurrence while all other destinations have equal probabilities of occurrence that sum up to 0.50.

4.2 Results and Discussion

In the boxplots used to show results, the central rectangle spans the first quartile to the third quartile. The segment inside the rectangle shows the median and the two whiskers indicate the extreme values that are not outliers (i.e., within 1.5 times the interquartile range of the first and third quartile). Finally, ‘+’ symbols indicate outliers.

Homogeneous Containers. Fig. 4 shows that for layouts 110 and 120 there is no statistical difference between any of the scheduling approaches. However, for layout 22c the ADLBA approach outperforms all others, with a throughput that is approximately 25 items per hour (1.5 %) higher. The original DLBA performs statistically just as well as FCFS and ARB. A possible explanation for this behavior is related to the infeed assignment problem. FCFS, ARB, and DLBA assign a container to an available infeed irrespective of its location on the sorter system, and so when containers are homogeneous there is no clear optimization criterion. However, the ADLBA assigns the containers to infeeds that are selected based on the

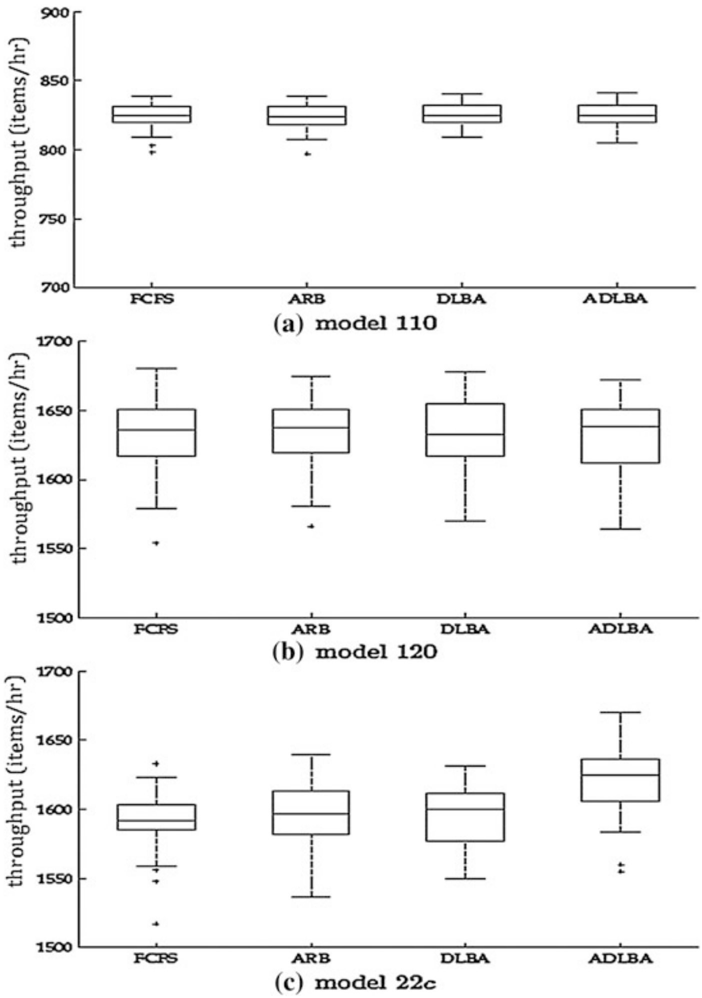


Fig. 4 Throughput using homogeneous containers

load balancing criterion. Therefore, although containers are similar, the ADLBA still balances the workload over the two separate sorters and over time.

Heterogeneous Containers. Figure 5 shows that the load balancing algorithms (DLBA and ADLBA) outperform the FCFS and ARB in all simulation models. In particular, the DLBA outperforms FCFS by 11, 52, and 63 items per hour (1.4, 3.7, and 4.5 %) for layouts 110, 120, and 22c respectively. As containers become differentiable, the original DLBA proves to be slightly better than the ADLBA for all layouts. For layouts 110, 120, and 22c the differences are respectively 6, 15, and 18 items per hour (0.8, 1.0, and 1.3 %).

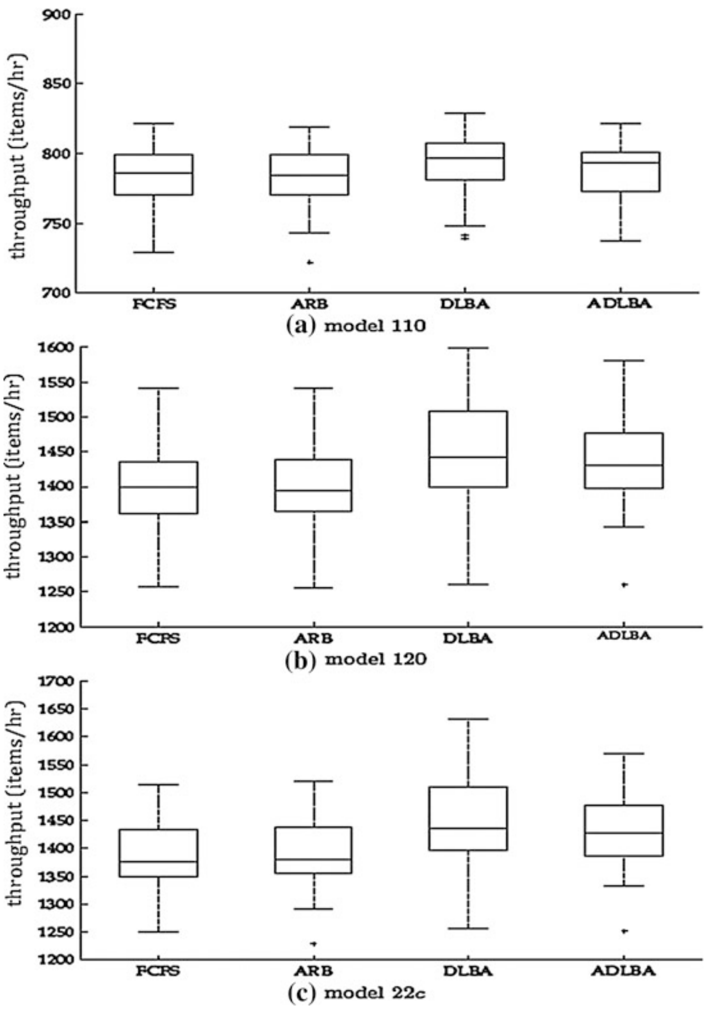


Fig. 5 Throughput using heterogeneous containers

Recommended Approach per Scenario and System Layout. The ADLBA performs better with homogeneous containers and in complex sorter systems, where the logic of balancing the flow over the outfeeds (at different sorters) and over time proves to be beneficial. However, in relatively simple parcel sorter systems, the ADLBA is not likely to contribute much to the performance because in such systems internal travel times are comparable. When containers become more differentiable the DLBA outperforms the other algorithms in all system layouts. Therefore, we conclude that the differences among the contents of containers overrule the differences among (estimated) travel times on sorters.

5 Conclusion

In this paper, we studied inbound container scheduling for sorter systems in parcel sorting. In our analysis, we used the state-of-the-art algorithm from literature as the first building block and adapted it to incorporate internal travel times on sorters.

We analyzed the performance of different scheduling algorithms using different operational scenarios and different system layouts. Then, we gave advice on which scheduling approach to use for each system layout and operational scenario.

In general, we note that in certain cases (at least in the layouts we tested) invoking much detail at the scheduling level by estimating travel times on the sorter, is counterproductive. In fact, the estimated travel times are disrupted by imbalances in travel delays on the sorter, especially when the workload is high. For these cases, we recommend approaches that use less detail at the scheduling level. However, in future research, we will invest in methods to improve local traffic control in order to make the estimations of internal travel times on sorters more reliable. Moreover, we will study container scheduling in baggage handling (at airports) as another application area.

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Model Based Systems Engineering and Warehouse Design

Leon McGinnis, Michael Schmidt and Detlef Spee

Abstract This paper reports on the results of an ongoing collaboration between the Fraunhofer IML and the Georgia Institute of Technology to develop engineering methods and tools to support warehouse design. The effort has adapted methods and tools from the broader systems engineering discipline, and has exploited the legacy of warehousing research at both institutions. Using OMG SysML^{TM}, formal semantics are being defined for describing primitive warehouse functions, warehouse systems, and the resources for implementing systems; this allows formal documentation of all phases of warehouse design. Moreover, these warehouse models can be linked directly to a variety of analyses, as well as legacy domain knowledge, to support warehouse design decisions. The theoretical and technical prerequisites for true computer aided warehouse design are in place, and provide insights into how the design of larger logistics systems might be similarly supported.

Keywords Logistics systems · Warehousing · Model-based systems engineering · Design

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1 Introduction

According to Miriam-Webster (http://www.merriam-webster.com/dictionary/system) a "system" is:

> a group of devices or artificial objects or an organization forming a network especially for distributing something or serving a common purpose <a telephone system> <a heating system> <a highway system> <a computer system>.

Clearly, society relies on such (logistics) systems to create and distribute (and reclaim/reuse/recycle) the products which make modern life possible. An important subset of logistics systems are those which can be characterized as "discrete event logistics systems", or DELS, i.e., systems in which discrete physical quantities (products, packages, people, etc.) move through a network of resources where the resources perform some specific conversion process (change location, age, physical configuration, information, etc.) with a specific start and end time. The resources could be local, e.g., within a single warehouse, or could be distributed in a global supply chain, e.g., for aerospace or semiconductor products. These are "systems of systems", in that they "integrat[e] independently useful systems into a larger system that delivers unique capabilities" (see [1]).

Designing logistics systems shares many features with designing airplanes, satellites, ground vehicles, or missile systems, namely that there are many decision makers representing different organizations and different intellectual disciplines, and their design decisions interact in often complex and non-obvious ways. Over the past sixty years, the discipline of systems engineering (SE) has emerged to provide standards and practices to support these kinds of system design decisions. One goal of this paper is to argue that systems engineering approaches can be applied to the design of DELS.

Rapid advances in computing hardware and software are enabling the evolution of SE toward "model based systems engineering" (MBSE), in which "models replace documents as the primary product or artifact of SE processes" [2]. Consider the design/development of a new automobile model. Many of the engineering disciplines involved in automobile design already use advanced modeling tools to define and analyze structures and their performance (using, e.g., finite element methods, computational fluid dynamics, algebraic differential equation solvers, etc.) and controls and their behavior (using, e.g., Simulink or LabView, or other control modeler/solvers). One promise of MBSE is that this large collection of models can be made more consistent, and perhaps even interoperable, significantly impacting new automobile development time and risk. The vision currently being pursued in the automotive industry is one in which design artifacts can be rapidly translated into analysis models, which can be integrated transparently to achieve full-vehicle simulation capability.

This vision is supported by a number of software developments, including: (1) new systems modeling languages, such as OMG's Systems Modeling Language™ or SysML (http://www.omgsysml.org/); (2) the availability of high quality modeling and solver tools for design specification and analysis, spanning multiple engineering disciplines; (3) maturing standards for data representation and maturing scripting languages; and (4) the emergence of analysis integration platforms like ModelCenter (http://www.phoenix-int.com/software/phx-modelcenter.php). While still a novel approach, requiring significant development, there are reports of success, such as [3] or the many examples in [4]. A recent presentation by Stoewer [5] identifies the challenges to full realization of MBSE. A second goal of this paper is to argue that MBSE can dramatically improve warehouse design, in terms of design time and cost.

MBSE is by no means a mature discipline; both the supporting software tools and the best practices in application are constantly evolving and improving. The evolution of model integration capabilities, for example, is quite rapid. Certainly, the application of MBSE to warehouse design also is, at best, a relatively novel idea. Thus, what we will present is not a software package for warehouse design, but rather a proof of concept that argues for greater investment in the research and development needed to make it a routine part of the logistics systems designer's toolkit.

The remainder of the paper is organized as follows. Section 2 will briefly discuss the state of warehouse design technology and particularly the roles of domain knowledge and analytical tools. In Sect. 3, the application of MBSE to warehouse design will be discussed, and a specific warehouse design workflow will be suggested. The role of decision support in this warehouse design workflow will be discussed in Sect. 4, and the challenge of integrating the design process with executable decision support tools will be described in Sect. 5. Finally, Sect. 6 will present a summary of the paper and conjecture on the future of these efforts.

2 Warehouse Design Technology

It is not easy to ascertain the contemporary state of warehouse design, because much of the practice of warehouse design is conducted by private firms using proprietary methods and tools. However, the excellent assessment by Baker and Canessa [6] not only considers the published research and business press, it also surveyed practitioners and concluded:

- There is no "standard protocol" or workflow for warehouse design.
- The essential, common steps include: (1) defining data needed and developing the instance data to determine requirements; (2) data analysis to define warehouse requirements; (3) specifying the units of handling and the basic flow pattern through the warehouse; (4) selecting, sizing, and configuring technologies to support the flow pattern; (5) physical arrangement of warehouse systems; and (6) detailed warehouse performance evaluation.
- Re-iteration of steps is typical.

- A great deal of domain knowledge (i.e., experience) goes into each of the common steps, but especially steps 3 and 4.

Today, warehouse design is accomplished using *ad hoc* processes, supported by *ad hoc* use of general purpose computing tools, such as spreadsheets, databases, CAD software, and discrete event simulation packages. This is very different from, say, the design of integrated circuits, internal combustion engines or commercial aircraft, where integrated domain-specific design specification and engineering analysis tools support a highly formalized domain-specific engineering workflow.

Successful warehouse design is driven by a clear understanding of what the warehouse must accomplish in the flow of goods from suppliers to customers. Generally, this involves receiving and storing bulk quantities of product from suppliers, and then retrieving goods to assemble and ship specific orders to the warehouse's customers. Data are needed to completely understand the inflow of goods to the warehouse, how the goods must be stored in the warehouse, and the outflow of goods from the warehouse. The specific data requirements can vary by industry, and perhaps even within an industry, so data definition depends on domain knowledge and experience.

How the data are analyzed, and the nature of the conclusions from those analyses also may depend significantly upon domain knowledge and experience. The kinds of analysis are described, e.g., by Rowley [7], McGinnis and Mulaik [8], Frazelle [9], and Rushton [10]. The mechanisms for analysis, however, are specific queries to general purpose spreadsheets or databases. Frazelle [9] gives a detailed description of some of the kinds of queries that are useful.

The essence of warehouse design is specifying the units of handling and the flows through the warehouse. This requires identifying how goods will be segregated for storage and handling purposes, e.g., by environmental requirements, unit of handling, or frequency of use, and also identifying how goods will be retrieved from storage and handled to assemble customer orders. Not much has been written about how this critical decision is made, and Baker and Cannesa [6] indicate that this is largely driven by domain knowledge and experience. Apple et al. [11] illustrate the use of tables and charts to try to capture some of this domain knowledge for reuse.

Once a basic flow architecture is in place, decisions about the choice of technology, or about particular operating policies, such as the order picking policy, are supported by a very broad array of operational performance models. See, e.g., the surveys by Gu et al. [12] or de Koster et al. [13]. However, there is no common source for computational implementations of these kinds of analytical models; anyone who uses them must implement them.

3 MBSE and Warehouse Design

MBSE is a "work in progress" and the reader interested in learning more has a number of good sources, including:

- Two very good textbooks addressing SysML and MBSE [14, 15].
- An OMG-sponsored wiki (http://www.omgwiki.org/MBSE/doku.php).
- A website sponsored by a European affiliate of OMG (http://mbse.gfse.de/).
- MBSE-centric tracks at every national or international INCOSE meeting (see, e.g., www.incose.org).

In the context of warehouse design, the intent of MBSE can be understood easily from the diagram in Fig. 1.

Warehouse design specifies the physical and to some extent the logic structure and behavior of the warehouse. This specification depends significantly on other strategic decisions, such as how suppliers will be managed regarding frequency, composition, accuracy, and timing of deliveries, and how customers' orders will be handled in terms of response times and fill rates. Warehouse design must include details of individual systems, such as storage or material transport. This can be quite challenging if complex automated systems are anticipated, e.g., for part-to-picker order picking. All aspects of the order picking/assembly process itself must be specified, including decisions such as pick wave duration, which

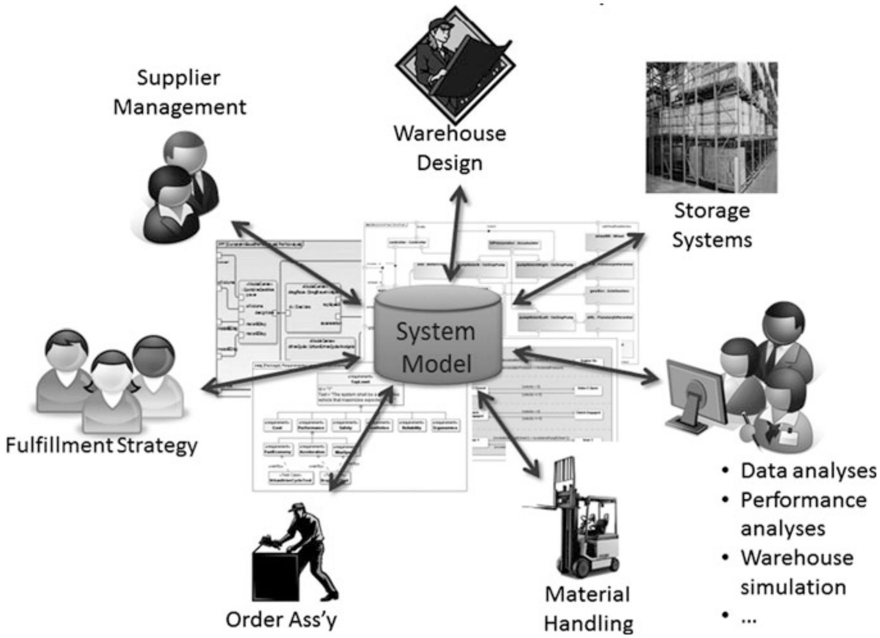

Fig. 1 MBSE in the warehouse design context

may be influenced by storage system configuration, dock door configuration, and customer order response time requirements.

In short, there are many interacting decisions which together will determine how the warehouse behaves in any particular scenario. There also are, potentially, many different kinds of analyses which might be used by one or more decision makers to try to understand the impacts of particular decisions. Explicit in Fig. 1 is the idea that all relevant data and design decisions should be captured in a single comprehensive and centralized model. Implicit in Fig. 1 is the idea that the models used by individual decision makers should be consistent with this central system model and should use data associated with the central system model.

If there is to be a central system model which captures the decisions of all the related warehouse design decision makers, then a fundamental requirement is that there is a common semantic framework (or domain semantics) for specifying those decisions. In other words, as an example, the expression of the order fulfillment strategy must be consistent with the expression of the order assembly process. It is not absolutely necessary that all decisions are expressed in exactly the same semantics, provided it is possible to unambiguously translate from one decision maker's semantics to another. On the other hand, robustness and scalability will be greatly enhanced if a single unified semantic framework is used by all. Similarly, it is best if there is a common syntactic framework as well.

SysML plays a vital role in this regard. As an object-oriented graphic language, it provides a suitable platform for specifying the domain semantics in a manner that is accessible by all the domain stakeholders (the various decision makers). Thus, they can participate directly in the development of the necessary semantic framework. SysML also provides the syntactic framework both for specifying the domain semantics and for applying the domain semantics to the design of a particular warehouse.

However, it is not sufficient to describe only the warehouse "artifact" itself. In adapting MBSE to warehouse design, it is also necessary to describe the associated "design artifacts". The design process itself results in conceptual models which are related to but quite distinct from the physical/logical model of an actual warehouse.

The following paragraphs briefly describe the use of SysML and the specification of both domain and design semantics. Further details can be found in [17].

3.1 SysML and Domain Semantics

The goal here is not to provide a complete semantic reference model for warehouse design, but rather to demonstrate how SysML can support the development of such a reference model. A fundamental modeling construct, or *stereotype*, in SysML is *block,* which can have a number of properties, such as values, operations, parts, and references. Within SysML, the *block* stereotype can be used to represent physical or logical elements of a warehouse or its context. The

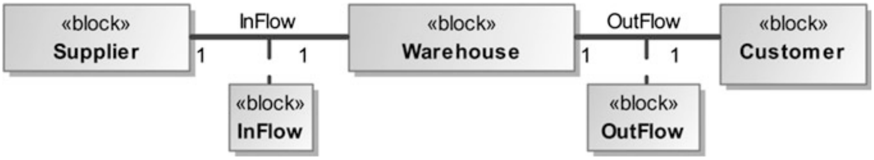

Fig. 2 Warehouse context

warehouse context is illustrated in Fig. 2 and a set of functions which the warehouse must be capable of performing are illustrated in Fig. 3.

The simple *block* construct may be used in several ways to define the warehouse domain semantics. Because *block* is a stereotype, it can be used directly to define classes of entities or concepts. For example, Function in Fig. 3 is a type of *block*. Function is further refined using the SysML *generalization* to create more specific kinds of functions, with their own specific kinds of properties. These new functions could themselves be further refined if necessary; e.g., the Store function might be further refined by the unit of handling stored, or by the environmental conditions of storage.

To support warehouse design, a particularly important semantic reference model will define the resources that will be used in the instantiated warehouse. Figure 4 illustrates how SysML can be used to define categories of resources, assigning stereotypes to these new categories. Figure 5 illustrates how the Equipment category can be further refined.

Consider the category of *Storage* shown in Fig. 5. This category can be further refined to develop a library of storage technologies from which a designer could select to implement specific storage functions. There are many different ways that such a library might be organized, using the SysML generalization concept; what

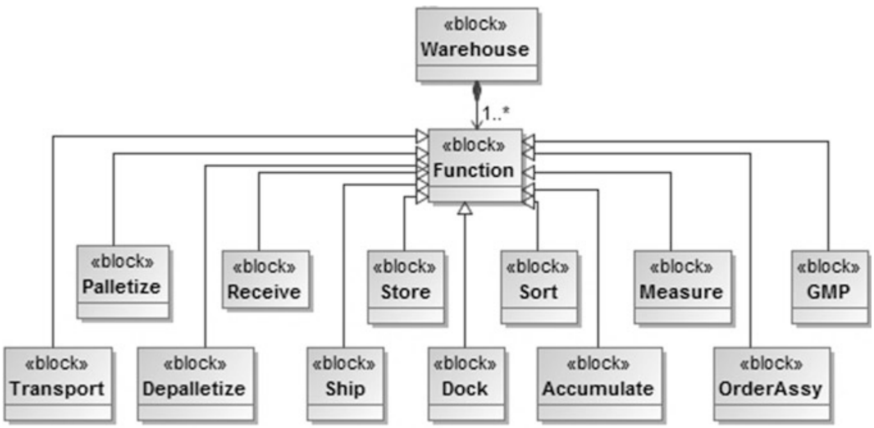

Fig. 3 Warehouse functions

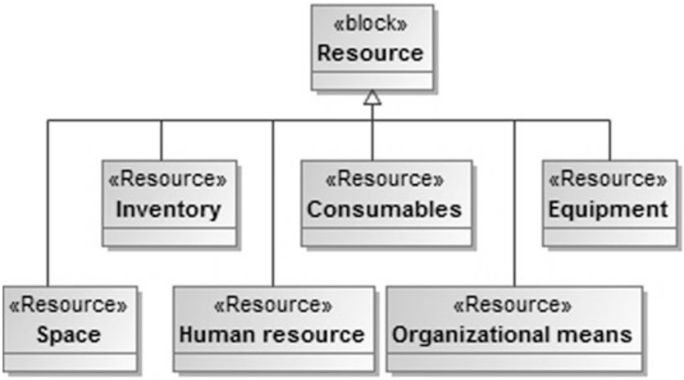

Fig. 4 Defining resource categories

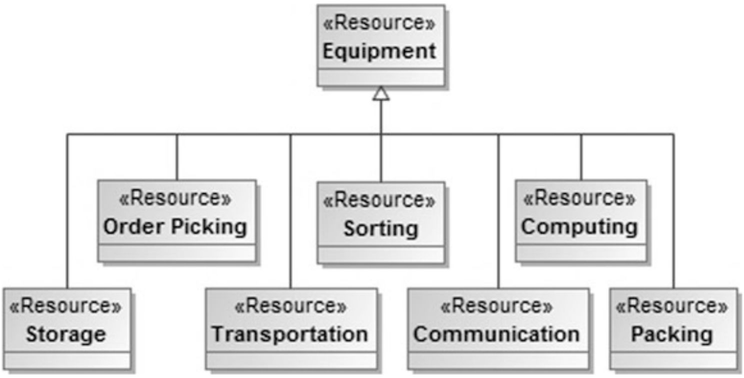

Fig. 5 Refining equipment category

is important is that the library contain those technological options that are likely to be useful.

Other aspects of warehouse semantics can be captured as well, such as the definitions of units of handling, standard data schema for product definitions, customer orders, warehouse transactions, etc.

3.2 SysML, MBSE and Design Workflow

A classic text on engineering design [16] recommends a general design workflow that includes: (1) establishing the requirements of the artifact to be designed; (2) identifying the functions necessary to meet the requirements; (3) developing a solution architecture, in which functions are aggregated into system elements; and

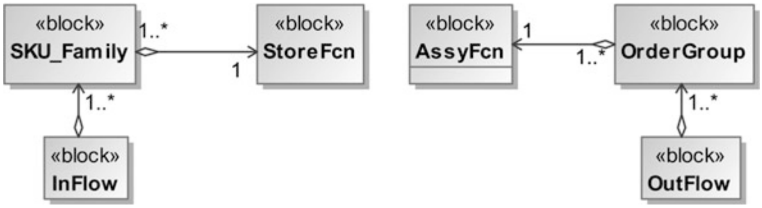

Fig. 6 SKU family and order group

(4) specifying the embodiment of each system element. Clearly, alternatives at each step are considered, and iteration between steps as appropriate. This classical engineering design approach can be applied to the design of warehouses, in the context of MBSE.

A fundamental requirement for a warehouse is that it "consume" the arriving goods, and that it "produce" the required customer orders. Thus, it is suggested in [16] that a starting point for warehouse design is the definition of SKU families and order groups, i.e., a partition of SKUs based on how the goods will be initially stored in the warehouse, and a classification of customer orders based on how the orders are assembled. This is illustrated in Fig. 6. Note that both the storage and order assembly are specified as functions, rather than as specific systems, and that there is a specific store function for each SKU family, and a specific order assembly function for each order group.

It further is suggested in [17] that there is a limited set of primitive warehouse functions, as illustrated in Fig. 3. By appropriately defining SKU families and Order groups, and by appropriately specifying the primitive functions that connect them, a complete *functional requirements graph* can be specified for a warehouse.

The primitive functions defined in the functional requirements graph can be used to define a *solution architecture*, i.e., a set of systems which together implement all the required functions and support the transformation of the warehouse InFlow to the warehouse OutFlow. Once this solution architecture has been defined, the selection of specific technologies for each system, the sizing and configuration of the system can be determined based on the magnitudes and characteristics of the flows into, through, and out of the associated functions.

3.3 SysML and Design Semantics

SysML not only supports the creation of both the warehouse domain semantics and the warehouse design semantics, it supports the use of these semantic reference models in the development of specific warehouse designs, in an iterative manner. In SysML, the block definition diagram, or bdd, allows the user to specify the types of "parts" of a system. For example, once the InFlow has been characterized in terms of SKU families and the OutFlow in terms of order groups, the user can specify for the particular warehouse, the primitive functions required to consume the InFlow and produce the OutFlow.

Figure 7 below is a bdd defining an initial set of functions for a warehouse which receives cartons in containers, palletizes the cartons for storage, and assembles two kinds of orders—“push” orders which are shipped LTL and “pull” orders which are shipped via parcel carrier. This example is taken from the 2005–2006 CICMHE design competition case (http://www.mhi.org/cicmhe/competition).

The SysML internal block diagram, or ibd, for the block named “Dragon-DudsWarehouse” allows the user to specify how the functions are connected, i.e., how goods flow between the functions. The ibd for the DragonDudsWarehouse specified in Fig. 7 is shown in Fig. 8, which illustrates how the flows between functions can be specified. While not shown on the diagram, information about the magnitude of the container inflow carries through the diagram to the storage function, and information about the flows that go out to parcel orders and LTL orders carries through the diagram from the storage function to the corresponding outflows.

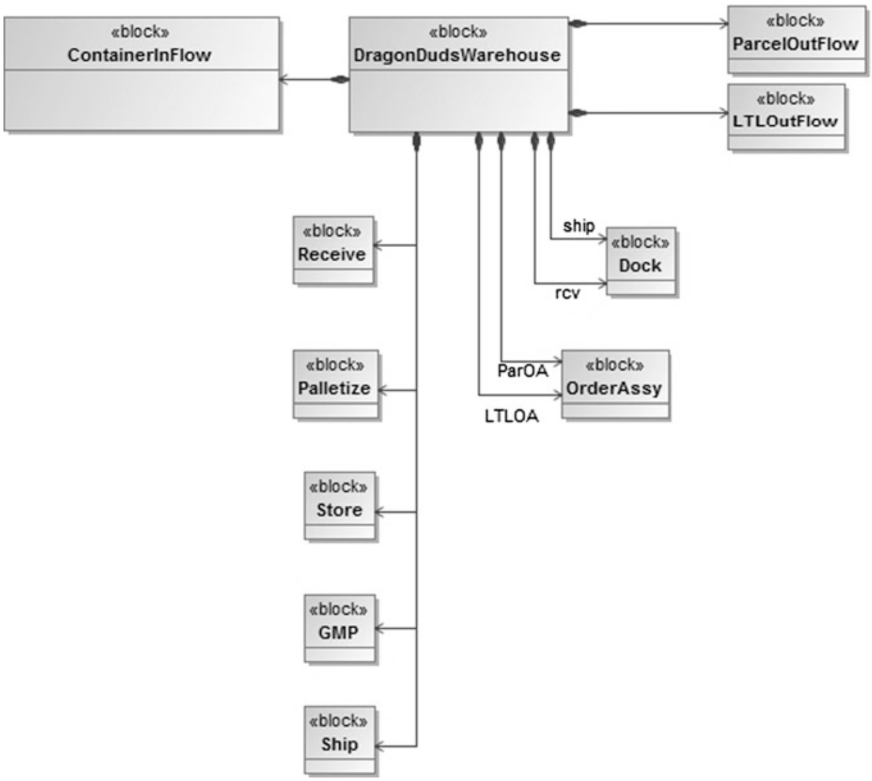

Fig. 7 Primitive functions for a specific warehouse, specified in BDD

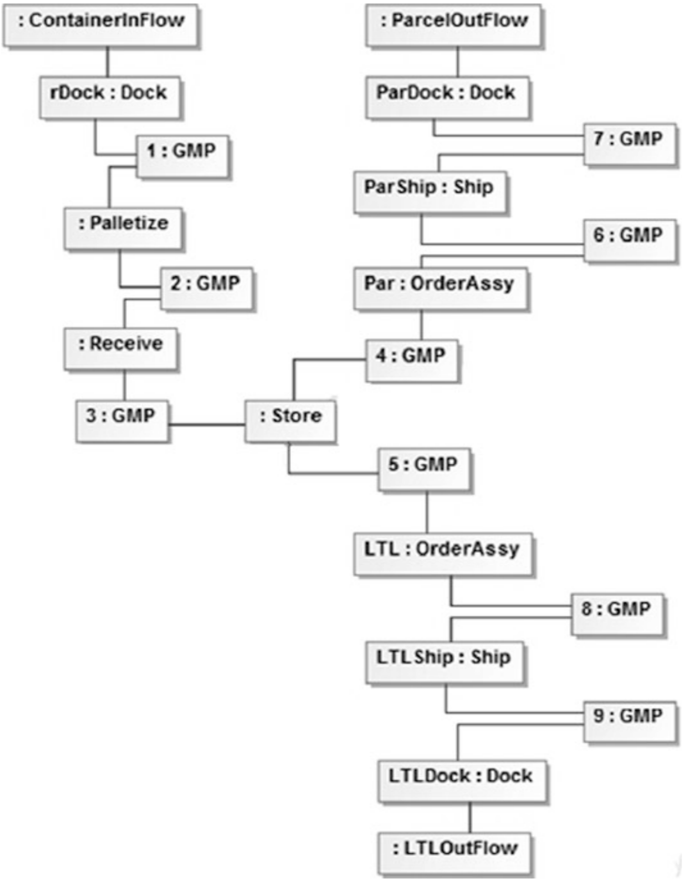

Fig. 8 Functional requirements graph example, specified in IBD

Note that in the ibd, there are three instances of the "dock" function, one for receiving the containers, one for LTL shipments, and one for parcel shipments. Subsequent embodiment decisions might add details, such as the number of dock doors. Also, note the numerous instances of the GMP, or "get-move-put" function. Subsequent architectural decisions might group some of these together, for example if several could be implemented using pallet jacks or lift trucks.

In a similar fashion, the bdd and the ibd can be used to specify a solution architecture for the warehouse. The functions identified in the functional requirement graph, e.g., the ibd shown in Fig. 8, can be specified as "generalizations" of individual warehouse "systems" or "departments" or function embodiments in an augmented bdd, as in Fig. 10, which for clarity shows only the receiving department, which incorporates a palletizing operation, a receiving operation, and the receiving dock itself. Then the corresponding ibd can show how the functions are incorporated into departments, as illustrated in Fig. 9.

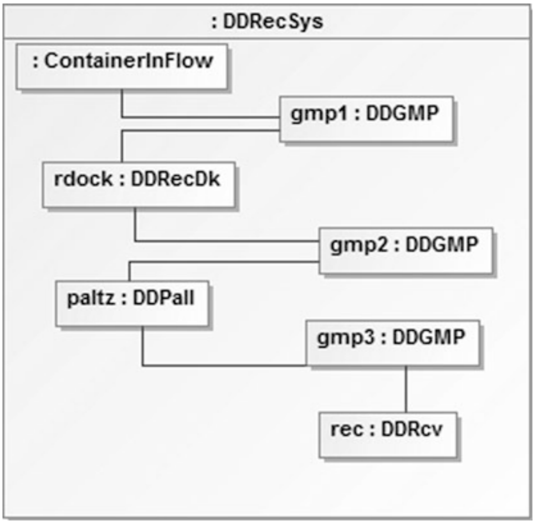

Fig. 9 Warehouse receiving system

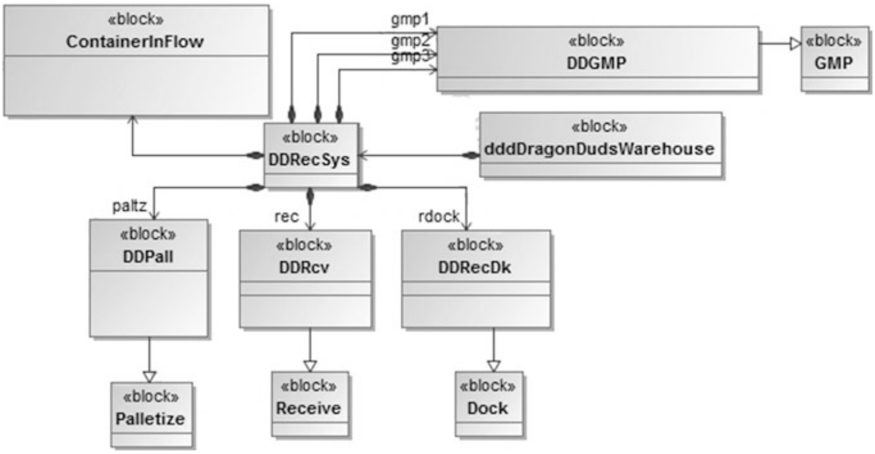

Fig. 10 Partial BDD showing embodiment of receiving

Provides a platform for not only defining the domain and design semantics for warehouse design, but also for specifying the warehouse design as it evolves from basic requirements to functional requirements to system architecture. As should be apparent, taking the systems descriptions, as in Fig. 9, to an embodiment specification essentially is one more iteration of the use of the bdd and ibd. Thus, SysML does provide the capabilities needed to apply the principles of MBSE to warehouse design, namely, using SysML, it is possible to create a unified comprehensive system model which captures all aspects of the design, from the early conceptual phase to the embodiment phase. The one aspect of warehouse design which will not be captured directly in SysML is the physical layout of the warehouse.

4 Warehouse Design Decision Support

A great deal of the decision support for warehouse design comes in the form of data analyses, specifically looking at data describing the incoming orders from suppliers, the outgoing orders to customers, SKU-specific characteristics, and inventory-related data. Fundamentally, these kinds of analyses seek to determine sets of SKUs which are sufficiently alike that they can be treated in the same way, and large enough so that they justify their own storage, handling, or picking system treatment.

Any individual or firm doing warehouse design on a regular basis will have a suite of "tools" to support data analysis, including:

- Rectifying the data—finding and correcting errors, dealing with missing quantities, detecting and deleting obsolete data
- Making future projections
- Classifying SKUs using a variety of Pareto analyses

The particular forms of analysis will be dictated by the specific situation, but also by the accumulated domain knowledge and experience of the warehouse designer and the data analyst.

In a similar fashion, once the data analyses have been completed, domain knowledge and experience play a key role in identifying a small set of alternative treatments that are likely to be appropriate.

A worthwhile question is "Is it possible to capture this domain knowledge and experience in a manner that makes it re-usable?" Apple et al. [11] suggest the answer is "Yes". For example, they suggest a tabular format for capturing "reasonable" solution architectures, specific to an industry and to a mix of handling units, which is reproduced in Fig. 11. Of course, this is simply an illustration; in practice one might well imagine that there might be more than one set of solutions for a particular industry, depending upon the ranges of values for the units of handling. For example, it is not hard to imagine a "Consumer direct apparel" warehouse with only a small fraction of "carton in/units out" and a large fraction of "pallet in/units out", which might dictate two columns for that industry segment.

In a similar fashion, the Fraunhofer IML characterizes SKUs by picking volume and picking frequency, as illustrated in Fig. 12. Within each cell, rules of thumb, based on experience, suggest a set of potential technology solutions.

These kinds of decision support are *suggestive*, i.e., they suggest possible alternatives that the designer might consider. Two other kinds of decision support

Handling unit conversion	Retail apparel	Consumer direct apparel	Packaged foods manufacturing	Grocery distribution	Service parts
Pallet in/pallet out			100%	10%	
Pallet in/cartons out	20%			80%	
Pallet in/units out	70%	5%			
Cartons in/cartons out					
Carton in/units out	10%	90%			
Units in/units out		5%			
Scale of facility					
Small					
Medium					
Large					

• Batch pick for multiple orders in each zone, convey to packing and "put" to order pigeonholes
• Wave pick for 1000-2500 orders in each zone, convey through buffer and induct pieces onto unit sorter and pack at chute

Fig. 11 Industry unit handling matrix (Fig. 3 in Apple et al. [11])

		Picking frequency		
		A	B	C
picking Volume	A	number of different sku number of UoH in total number of UoH per article ...		
	B			
	C			

Fig. 12 Fraunhofer IML scheme for classifying SKUs

are *normative*, i.e., suggesting what should be done in a particular scenario, and *evaluative*, i.e., assessing the *result* of a particular decision. An example of a normative analysis is one that optimizes the configuration of an AS/RS in terms of number of aisles, length and height. Examples of evaluative analysis include estimating the labor cost for a particular picking system configuration under a particular order picking load, or detailed simulation of total warehouse operations.

All three kinds of decision support—suggestive, normative, and evaluative—require as input some description of the system being designed, either a characterization of the flow in the warehouse, or the specification of a particular technology and performance requirements.

5 Integrating Design and Decision Support

SysML not only provides a platform for defining and using the warehouse domain and design semantics, it also provides multiple mechanisms for integrating the design specification with appropriate decision support. The SysML *parametric diagram* is key to several of these mechanisms, as is the SysML *constraint block*.

The *constraint block* is a special kind of block that allows the user to define value properties and an equation that uses the value properties. So, for example, a constraint block could define the computation of the travel time of a crane as a function of the acceleration, velocity, and distance traveled. The *parametric diagram* allows the user to link together multiple constraint blocks to define a more complex computation, such as a dual-command cycle time.

There are a number of add-ons to SysML which use the *parametric diagram* to gain access to external solvers, making the *parametric diagrams* executable. If the analysis requires only solving a system of equations, then InterCAX (http://www.intercax.com/) provides a product, which for the MagicDraw™ SysML tool is called ParaMagic™. The ParaMagic™ plugin creates an additional window in which the user can identify the givens and the target variables (those to be computed), and launch the computation, which can be completed using commercial solvers like Mathematica™ or MatLab™. Thus, any warehouse design decision support model which can be structured as a solution to a system of equations can be directly integrated into the SysML platform.

Many types of warehouse design decision support analysis are more complex; they may involve an iterative procedure or perhaps a "black box" analysis implemented as a piece of proprietary code. Phoenix Integration (http://phoenixintegration.com/) provides the ModelCenter™ tool which can be integrated with SysML, allowing SysML *parametric diagrams* to be linked to ModelCenter. ModelCenter then provides integration to a wide variety of analysis components, which can be in the form of spreadsheets, Java code, simulations, optimizations, etc. The primary requirement is that the analysis can be viewed as a "black box", i.e., it has a well defined set of inputs and a well defined set of outputs. ModelCenter then enables the mapping between the inputs/outputs of this analysis black box and the parameter values of the associated SysML *parametric diagram*.

Figure 13 is a fragment of a SysML model in which an AS/RS has been modeled and a *parametric diagram* has been created to provide the interface to ModelCenter. In this particular case, the AS/RS analysis actually is performed by a web-based analysis tool hosted on a Fraunhofer IML server, illustrating the capability for ModelCenter to provide access to analyses that are local to the user's computer, on other computers on the user's local network, or located anywhere on the internet.

The use of high-fidelity animated simulations has become fairly common as a way to validate a proposed warehouse design. A major concern is the time and expense of developing these simulation models, and so typically they are the last

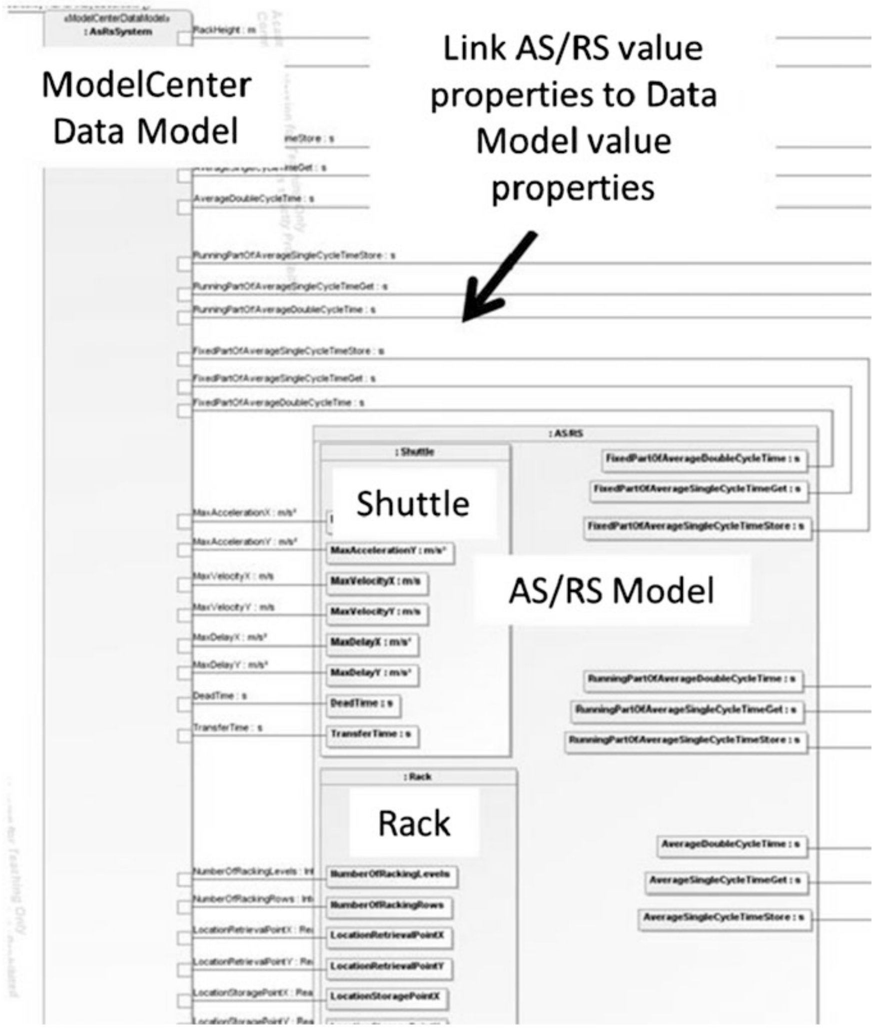

Fig. 13 Parametric diagram fragment showing integration to ModelCenter™

step in a warehouse design study, rather than a source of continuous decision support. Adapting MBSE and SysML to warehouse design could significantly change this.

In the context of electronics assembly and test, Batarseh and McGinnis [18] describe how a domain-specific profile can be created in SysML and used to develop descriptive models of specific electronic assembly production scenarios. A corresponding model-to-model transformation script automatically generates the associated Arena simulation model, achieving an order of magnitude reduction in the simulation model development time.

6 Broader Impacts

Adapting MBSE, SysML, and the rapidly emerging software tools that support them to warehouse design moves us very close to having true computer-aided engineering of warehouses. It enables both the development and use of a comprehensive semantic reference model for both warehousing and warehouse design, and the syntactical framework for its use in designing warehouses. It enables the integration of warehouse design models with a broad array of knowledge and analyses to support warehouse design decisions. When fully realized, these developments will transform the research, teaching and practice of warehouse design. However, warehouses are but one example of discrete event logistics systems, which include factories, supply chains, hospitals, call centers, and many other commercial activities. We should ask, “Can the same approach be applied to these other systems?”

There are good reasons to answer in the affirmative. These all are large-scale complex systems with many different decision makers and a number of well-understood analytical models for decision support. They are systems that are being pressured to be more efficient and effective, when all the interaction effects are not completely understood.

There also should be concern over the difficulty of the undertaking. Based on experience to date, one of the most challenging hurdles will be the development of a widely accepted, comprehensive domain semantic reference model. What should not be a concern at this point is the capability of the technical software tools to support the endeavor.

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