NON-PEER-REVIEWED PAPER

Exploring and modeling the impact of supply chain-related decisions in production and logistics on energy efficiency – lessons learnt from the E²Log project

Andreas Pastowski
Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19
DE-42103 Wuppertal
Germany
andreas.pastowski@wupperinst.org

Dr. Frank Ellerkmann
Fraunhofer Institute for Material Flow and Logistics
Joseph-von-Fraunhofer-Str. 2–4
DE-44227 Dortmund
Germany
frank.ellerkmann@iml.fraunhofer.de

Dr. Kathrin Hesse
Fraunhofer Institute for Material Flow and Logistics
Joseph-von-Fraunhofer-Str. 2–4
DE-44227 Dortmund
Germany
kathrin.hesse@iml.fraunhofer.de

Dorothea Schostok
Wuppertal Institute for Climate, Environment and Energy
Döppersberg 19
DE-42103 Wuppertal
Germany
dorothea.schostok@wupperinst.org

Jan Cirullies
Fraunhofer Institute for Material Flow and Logistics
Joseph-von-Fraunhofer-Str. 2–4
DE-44227 Dortmund
Germany
jan.cirullies@iml.fraunhofer.de

Emanuel Fuss
Fraunhofer Institute for Material Flow and Logistics
Joseph-von-Fraunhofer-Str. 2–4
DE-44227 Dortmund
Germany
emanuel.fuss@iml.fraunhofer.de

Keywords
logistics, productivity, energy efficiency assessment, modelling

Abstract
Most strategies for increasing energy efficiency in industry and logistics are heavily based on improvements of related technologies. As opposed to this, organisational approaches are often overlooked or only play a role as a complementing factor, once new technologies applied in production or logistics require some organisational change. Likewise there is not much evidence on the interrelation of decisions focused on production or logistics and their effects on energy efficiency.

While technological change is an important determinant and well-established strategy for energy efficiency in industry and logistics there is a lack of demonstrated organisational strategies. It requires in depth data collection on energy use and profound modelling exercises at the plant, company or a certain supply chain partner level to make the case for substantial organisational impacts and interdependencies that otherwise most likely remain invisible.

This contribution briefly describes the background, scope, methodology and selected results obtained from the E²Log project. E²Log was designed to better understand organisational causes of energy efficiency and to shed some light on likely interactions of decisions with a focus on either organisation of manufacturing or logistics as well as for coherent concepts for the both. Contrary to the extensive body of evidence on technical strategies there are much less insights available concerning the organisational causes of and strategies for improving energy efficiency.

The project E²Log has taken stock of three case studies to explore some of the mentioned causes and interdependencies. This has provided the basis for modelling exercises that may help to better understand interrelated organisational variables and to design them in a way that the system-wide energy efficiency can be optimised. The three case studies cover plant-related logistics, a local production cluster and a particular branch of a global distribution network.

Energy efficiency and the E²Log project
Energy efficiency is one of the major strategies that many governments want to see more extensively deployed for the mitigation of climate change. E.g. the 'Action Plan for Energy Efficiency' of the European Union states the importance of this. The objective of the Action Plan is to reduce energy use to achieve savings of 20 % of primary energy use by 2020 as opposed to forecasts (European Commission 2006). This translates into an average 1.5 % saving per year up to 2020. Moreover, expected shrinking availability of fossil fuels and likely price spikes have made it as important issues into the boardrooms of many companies. Thus in future, in-depth analyses into the causes and interdependencies associated with energy efficiency will gain even more importance than previously experienced.

In the last decades, energy efficiency has improved in many economies and certain sectors of OECD countries. However, this did not necessarily translate into an overall reduction in energy use and related emissions, but was counterbalanced by growth in economic activity and by some structural change (e.g. higher shares of energy intensive modes in freight transport activity). Figure 1 depicts that the overall energy productivity of the German economy has improved by roughly 40 % in the period considered, while the sector commerce, trade and services (CTS) has performed at a significantly faster pace. However

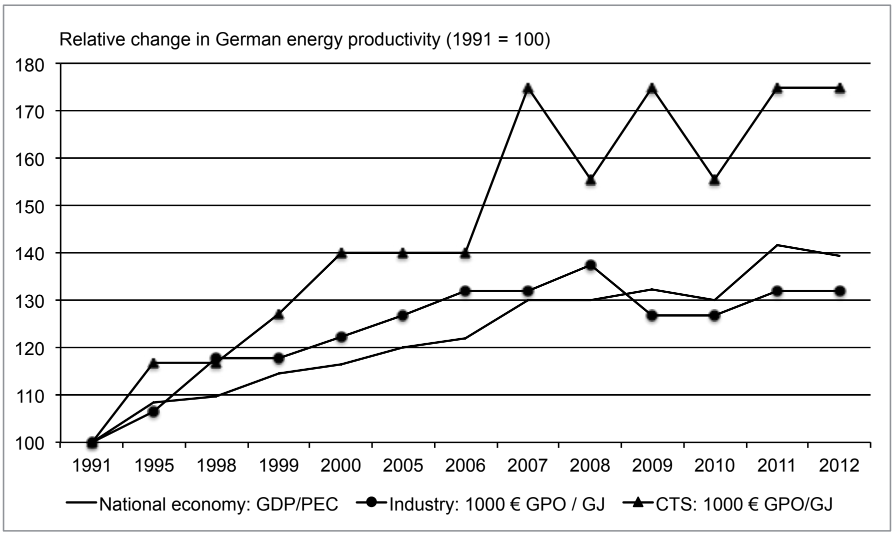

Figure 1. Relative changes in energy productivity. Based on observed nominal energy consumption data, not adjusted for temperature and changes in inventory; gross domestic product (GDP) primary energy, gross product originating (GPO) for industry and CTS final energy consumption; own calculation and representation based on Arbeitsgemeinschaft Energiebilanzen (2011, 2013).

CTS is a somewhat diverse sector which includes the provision of logistics services. Owing to the heterogeneous composition of this sector, its performance cannot be interpreted in such a manner as if it were representative for logistics services.

Since there is no specific data available on logistics-related energy consumption, it is difficult to provide a clear overall picture of the energy efficiency performance of those activities that are usually associated with the provision of logistics services. Industry – more or less in line with the overall economy in terms of energy productivity for some time – has seemingly de-coupled starting from 2008. The causes of increasing energy productivity at the levels considered are varied but the general expectancy is that the deployment of new technologies plays a major role in this.

In contrast with technology, there is much less evidence on the impact of organisational changes at the micro level on the development of energy productivity, its causes as well as suitable strategies for improvement of energy efficiency. This is particularly valid in the closely interrelated sectors manufacturing industry and logistics services. This lack of evidence was one of the main reasons why the E^2Log project has been initiated.

A concept that allows to determine the impact of certain drivers on changes at the aggregate level in e.g. energy efficiency is decomposition analysis (see e.g. Greening et al. 1997). Most recently, this concept has gained more importance as an approach to identify the impact of single causes of greenhouse gas emissions using a top down perspective. One of the strengths of the concept is that it allows to identify some important drivers which may translate into effective strategies.

One of the major shortcomings of this methodology is that it can only be applied to measureable explanatory variables for which data is available. An early but good example of making this approach fruitful for identifying major drivers of emissions from freight transport has even included organisational drivers (Schipper et al. 1997). However this was only possible because freight statistics often provide data on the modal split of freight activity which were ready to be used for the decomposition analysis.

In the case of energy efficiency data availability is very much dependent on the character of drivers considered. Data on economic activity and energy use at various aggregate levels is widely available. Drivers of energy efficiency that are not uniformly measureable prove much more difficult to be included and thus for the most of it are simply not taken account of. Usually decomposition analyses are focused on technology and structural change of the sectoral composition of economic activity (see e.g. Cian et al. 2013). Thus there is not much to be expected from a top down perspective in terms of organisational approaches for the enhancement of energy productivity. As opposed to this, it is necessary to take a closer look at the micro level and what lessons can be learnt from that perspective.

Structural trends in logistics and energy efficiency

When the question is raised whether organisational change may have a substantial impact on energy efficiency in industry and logistics and the both combined, it is helpful to provide examples that demonstrate this in practice. Such examples may showcase in which ways and to what extent particular organisational changes have influenced energy efficiency under certain circumstances. However the following examples have emerged as highly visible general trends which may not always be the case with organisational changes. In order to provide some examples at least from logistics, we take a look at empty trips and utilisation of capacity of vehicles in use for road freight. Both have been influenced in German logistics by trends that are significant well beyond this country.

One of the substantial results of structural changes in freight transport and logistics has been the reduction of empty trips on the road. On the one hand, this has been triggered by a fundamental trend of outsourcing of logistics services on own account. On the other hand, the liberalisation of freight transport within the internal market of the European Union has allowed to increase capacity utilisation of vehicles used for border crossing road freight transport. Both trends differ in that the reduction of freight transport on own account has mainly emerged within the industry itself while the deregulation of cabotage resulted from policy making.

Figure 2 shows to which extent freight transport on own account has shrunk in the period considered. It is obvious that such a substantial change in the context of growing demand for freight transport services in general depicts a trend which necessarily needs to be based on a high level of organisational change. While the reasons for this might primarily have been based on costs and the requirement to keep up a certain level of know-how for logistics services that do not have much in common with what is required for the core business activity of manufacturing companies.

Approaches to changes in energy efficiency in economic sectors and logistics businesses can be explained with reference to structural and organisational trends. The declining share of empty trips describes such a structural change. Figure 2, shows a decline by 30 % of the absolute proportion of empty trips in the period under observation. Although empty runs in 2010 have increased, a downward trend associated with an increase in energy efficiency can clearly be seen. But what triggers structural change at the organisational level? This will be illustrated by the following examples on own-account transport, 24-hour-delivery and tailored delivery.

In the past, plant-related freight transport on own account has often been characterized by imbalances, which on average has led to poor average utilization of vehicle capacity. Manufacturing companies have increasingly set the focus on lean production. One of the results has been that they have become more concentrated on their core business activities. Resulting from this, logistics services on own account have been outsourced by manufacturing companies to the providers of logistics services. As opposed to manufacturing companies, logistics service providers may have far more opportunities to consolidate shipments. In a larger pool of shipments logistics service providers can reduce unnecessary empty runs and by that increase utilization of capacity. Furthermore, the handling of empty trips has improved and economies of scale were achieved. Overall, the outsourcing of freight transport on own account brought about an increase in energy efficiency for shippers as well as for logistics service providers.

A somewhat disadvantageous side-effect of this development is, however, the much more limited access to related data on energy consumption. Thus manufacturing companies that have outsourced their former own-account transport have to rely on energy consumption data delivered by their logistics service providers.

An example of a trend of changing organisational patterns with most likely detrimental effects on energy efficiency in the context of logistics is the introduction of 24-hours-delivery in retailing. Logistics service providers have introduced 24-hours-delivery with the aim of greater differentiation in quality competition. Originally 24-hours-delivery was designed as a premium logistics product, intended to secure a unique selling proposition. Though, from the envisaged premium product it has become a standard product. By now an almost universal geographical coverage of 24-hours-delivery has solidified. Combined with short-term disposals, these services have turned into an almost general expectation of consumers that is difficult to turn around. The advantage of increasing flexibility on the side of consumers, which usually is not associated with additional cost, keeps 24-hours-delivery running. For logistics service providers however, this translates into a reduced flexibility in the provision of logistics services, since the consolidation and creation of optimal tours is more difficult with tight delivery windows. The result is a decreasing utilisation of vehicle capacity and/or an increasing use of smaller vehicles. Overall, 24-hours-delivery is an example of organisational change that on average reduces the energy efficiency on the part of logistics service providers.

For shippers and logistics service providers another organisational change can be identified as tailored delivery that is not limited to effects on energy efficiency in logistics but may also impact on energy efficiency in production. Companies

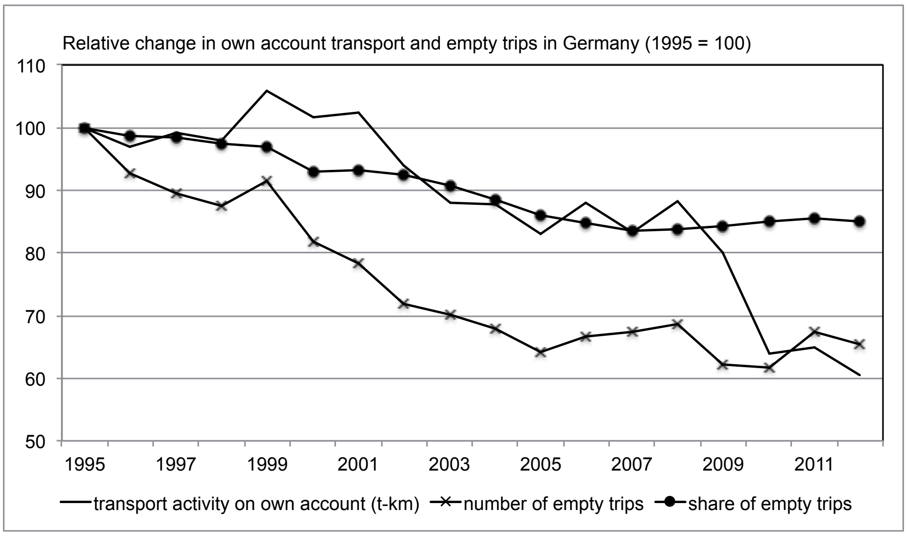

Figure 2. Own-account transport and empty trips in Germany. Expansion of the scope of the data starting from 1999; own calculation and representation based on Kraftfahrt-Bundesamt (2013) and Statistisches Bundesamt (2014).

pursuing the principles of lean production, have aimed at the reduction of lead times and the capital commitment for storage with increasing product variants. However, smaller inventories require precisely timed delivery of parts from the suppliers. Accordingly, suppliers must decide whether to take over the storage or to manufacture in smaller batches. Smaller batches extend the share of set-up times and thus the proportion of energy consumption in non-productive standby mode, which most likely reduces energy efficiency.

Of course the evidence presented by these examples does not suggest that the potential of organisational change at the micro level will necessarily be similarly large as e.g. the reduction of transport on own account. However it can be demonstrated by the mentioned general trends that impacts of organisational change do exist and that those can be substantial.

While organisational change as a strategy to increase energy efficiency can be expected to be rather context specific at the micro level, it is very difficult to provide an assessment concerning its full potential at the meso or macro level. Even more so, the existing focus on energy efficiency through the deployment of new technology also means that systematic evidence on organisational drivers of energy efficiency is for the most of it non-existent. In order to shed some light on what is going on at the micro level and to which extent organisational change can bring about increases in energy efficiency, it is necessary to take a closer look at specific areas of interest. This was done in the three case studies of the E²Log project which will be dealt with in detail in what follows.

Properties of technical and organisational approaches towards energy efficiency

As Figure 3 shows, energy efficiency in consumption, production and logistics is influenced by a multitude of factors residing in separate areas. Some of those are related to decisions of the consumers and their expectations regarding features of products and delivery. Others appear as side effects of concepts of manufacturing and logistics or the both combined. However so far, the focus of efforts to increase energy efficiency has been on the application of technology in nearly all the other areas mentioned.

The focus of the E²Log project is mainly on production and logistics. Preferences of customers along the supply chain are primarily treated as given complementing factors even though they may play a role once energy efficiency is considered beyond the system boundaries of individual companies or plants together with supply chain partners. Technologies may have implications also for organisational matters, but are not the focus of the E²Log project and considered as given.

Figure 4 depicts the specifics of the individual case studies of the E²Log project. While it was not possible to include the whole variety of possible configurations in one project, it was decided to focus on a limited set of three case studies with typical properties regarding their scope in terms of focus on production, logistics or the both combined as well as the included actors and supply chain partners. Even though the number of case studies had to be kept limited, the ones considered cover a fairly wide range of somewhat typical configurations and issues that play important roles in today's supply chains.

The E²Log approach

Based on the dynamic market environment as a fluctuating trend of demand and hardly predictable disturbances, an evaluation of the effectiveness and the required resource management of production networks with pure statistical examinations is insufficient. Evidence from industry-oriented research as well as from basic research has shown that these two dimensions are not even sufficient for pure economic evaluations.

Performance parameter of logistics as adherence to schedules, delivery time, delivery capacity or replacement time have a strong impact on resource management (Kuhn 2006; Kuhn 2008). Dynamic modelling and simulation tools determine the time dimensions and have to form the basis for a coequal economic and ecologic evaluation as well as for the optimisation of complex production networks in a dynamic market environment. The continuous and event-discrete simulation can be distinguished (Law et al. 2000; Hrdliczka et al. 1997). Discrete

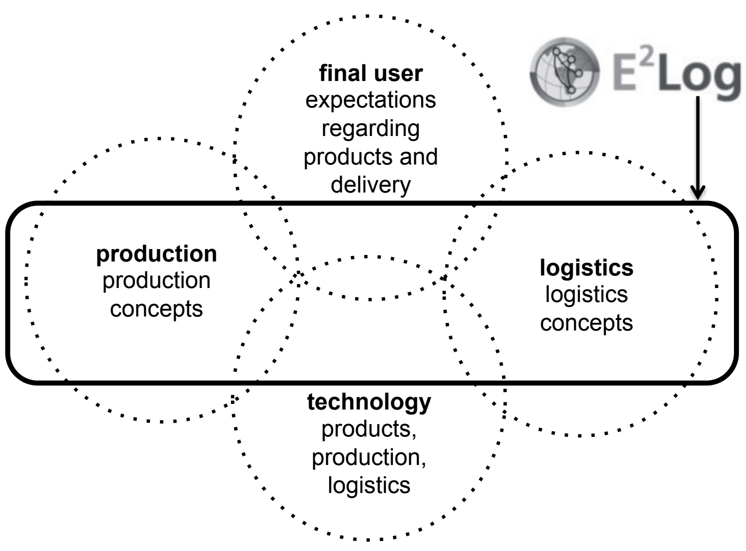

Figure 3. Drivers of energy efficiency in production and logistics and the focus of E²Log.

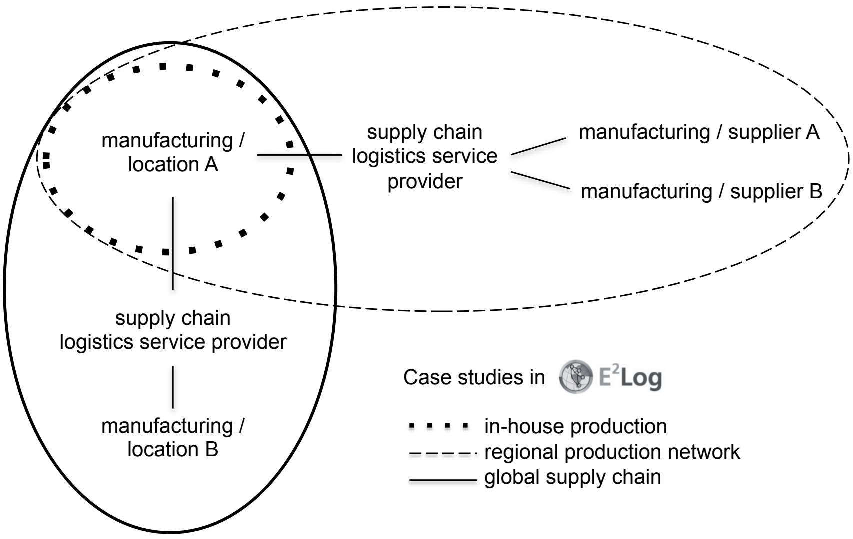

Figure 4. System boundaries of the E²Log case studies.

simulations will cover changes of state only if certain events happen, whereas in continuous simulations unlimited changes of state per period are covered. Simulation will always be required if certain criteria are met:

1. The system that will be analysed is very complex (Norm VDI 3633, Blatt 1).
2. Characteristics of time flow are the subject of the investigation (Hrdliczka et al. 1997; Wenzel et al. 2008).
3. Stochastic effects must be considered (Wenzel et al. 2008).
4. Particular requirements in communication, visualisation and transparency of the results as well as in the documentation of the approaches are claimed (Wenzel et al. 2008).

At least for the economic evaluation, the Fraunhofer Institute amongst others developed firmly anchored simulation methods that are already acknowledged by industry and network-wide production planning respectively logistics planning. These methods for example provide information about which supplier network endures a long term efficient supply of parts with high reliability. For the companies it is hereby possible to create and control a production network that offers an economic optimum at given basic conditions, as for example a delivery time that is required to fit consumer needs.

The diversification of the supplier selection has gained increasing importance which includes to simultaneously manage costs and the delivery of services in terms of energy efficiency and environmental performance as additional and coequal objectives for companies.

The project consortium and especially the Fraunhofer IML have chosen one tool for the evaluation and design of production networks (OTD-NET) and another tool for the investigation within internal system boundaries (Plantsimulation). These tools belong to the pool of simulations tools which are used at the Fraunhofer Institute and the evaluation and design dimensions of energy efficiency has been added to them. The ambition was the development of an Eco-Toolsuite that basically consists of two consecutive tools:

- **Plant Simulation:** A multiplicity of tools that are suitable for the simulation of production and logistics systems for performance measurement and strategies for optimisation is available on the market. In the context of this research project, simulation studies were performed with regard to the production planning and control system by means of the simulation tool Plant Simulation. This component-oriented and event-discrete material flow simulator is particularly suitable because the intended modelling of condition-based profiles for energy consumption could be implemented. Plant Simulation supports the development of libraries with changed and self-developed components, which can be integrated in the Eco-Toolsuite.
- **OTD-NET^{ECO}:** A demonstration version of this tool with its multiplicity of parameters allows to develop a holistic and dynamic design and evaluation of production systems in their full complexity. OTD-NET^{ECO} generates a dynamic assessment solution based on the simulation tool OTD-NET developed by Fraunhofer IML. Existing production structures and modifications can be detailed in scenarios. Afterwards an estimation of the alternatives for the configuration takes place. For that purpose it is dynamically simulated how the alternatives for the configuration would act in the operations. Detailed parameters for energy efficiency, performance and costs can be obtained from the simulation and generate the basis for the evaluation of the alternative configurations. The dynamic assessment solution can be used for the support of planning and control decisions in the operations. Operational decisions can be simulated – also assisted by the developed valuation method – to take energy efficient and cost-efficient planning decisions.
  - **Ecoleano**: The Encapsulation of the research results in a manageable tool was sought in this research project, because the application of full-fledged simulations is too ambitious for many small and medium-sized companies while at the same time the integration of energy efficiency in operational practices is urgently required. The demonstration version of the tool Ecoleano which

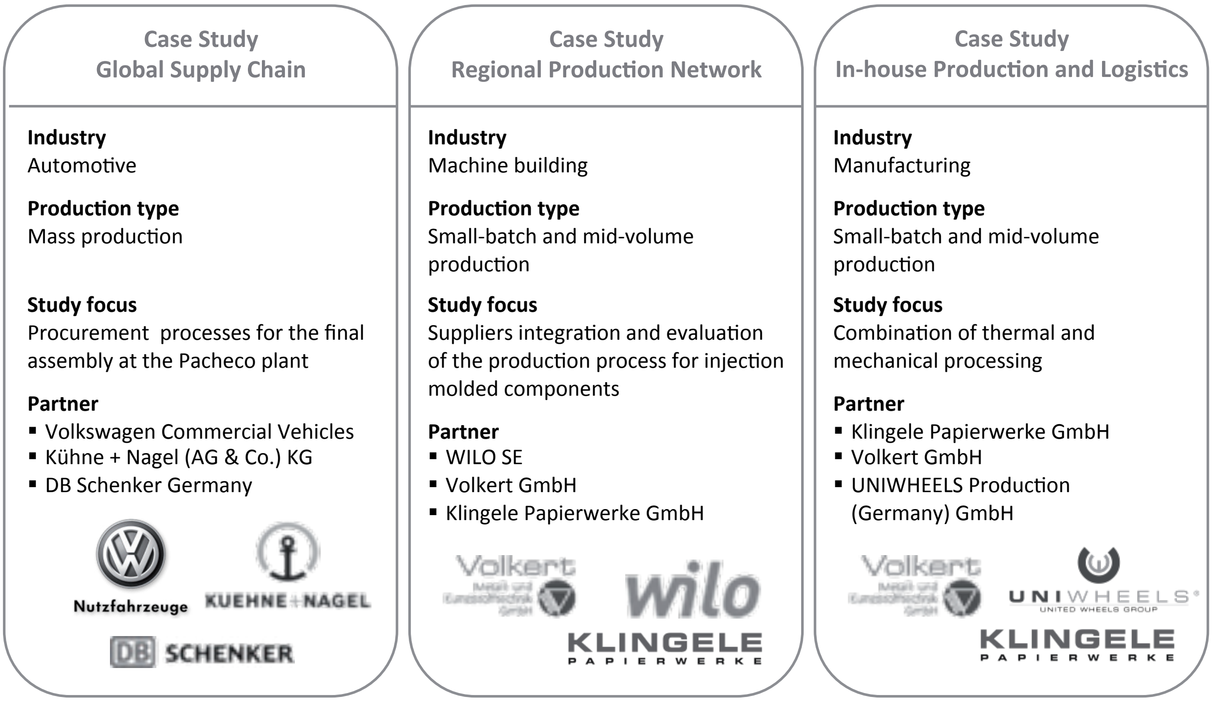

Figure 5. Description of the three case studies of the E^{2}Log project.

is especially designed for the requirements of small and medium-sized companies was developed in order to overcome this barrier. Ecoleano uses the technical functionality of OTD-NET^{ECO}, but it emphasizes the easy access to expert knowledge and the applicability for the special problems of small and medium-sized companies.

– **ECO$_2$LAS:** In support of the parts supply as described below in the case study of VW Utility Vehicles, the demonstration version of OTD-NET^{ECO} was enhanced to an assistance system to support the planning and control of the logistics network. The cause for this process was the multiplicity of logistical challenges in global procurement processes, which occur because of the absorption of resources in the supply chain, particularly in the form of inventory, insufficient transparency associated with late identifiable supply shortfalls and at lastly air freight as a final option which is classified as critical from the environmental point of view. ECO$_2$LAS integrates software functionality and concepts from the fields of typical logistics software and supply chain management with its four core modules "Supply Chain Monitoring", "Demand and Capacity Planning", "Supply Chain Simulation" and "Transportation Planning" (Klingebiel et al. 2014) to cope with these challenges.

The aim of the research project was to achieve a wide coverage of likely configuration options in order to optimize the energy efficiency in production and logistics networks and to allow for an evaluation of their influence on economic and logistic target figures. On this account the project relies on three applications, which enable a broad base for the obtainment of sectoral as well as intersectoral design recommendations for an environmentally and economically optimized design of production and logistics networks depending on the choice of the examination area, the represented industries and the applied technologies. Figure 5 classifies the case studies with regard to represented industry and production type, the area of examination as well as the represented companies. The case studies will be described in more detail in the following sections.

E^{2}Log case study global supply chain[1]

Global logistics networks are complex systems due to plenty of supply chain partners, long transport lead times and stochastic influences such as unexpected delays. As energy prices are increasing and emission trading schemes were introduced, energy balances must be included into the holistic assessment of the supply chain besides costs and logistics performance (Cirullies et al. 2011). Whereas the very most of the present research approaches implement a post-simulative assessment approach (i.e. subsequently to the simulation run), the E^{2}Log approach favours an intra-simulative assessment method, i.e. the calculation of energy demand and emissions at simulation runtime (Cirullies et al. 2012a). As former transport scheduling was exclusively based on costs and performance (e.g. acceptable lead times), this method is able to consider emissions and the remaining GHG quota as a decision base. For instance, although transatlantic shipping by sea freight might cause delays and penalties, energy efficiency improvements compared to air freight could still make this a more reasonable option. In order to allow such decisions dynamically, the energy or GHG balance has to be available during simulation.

This concept of intra-simulative assessment was implemented into the supply chain simulation tool OTD-NET^{ECO},

1. This section has been contributed by Jan Cirullies.

an environmentally enhanced version of OTD-NET (Cirullies et al. 2012b; Cirullies et al. 2013). The original tool combines information and material flow in a unique way. This feature is particularly relevant in the automotive sector, which necessitates a complicated long term planning process (Wagenitz 2007). OTD-NET has proven its suitability in various logistics research and industry projects (Cirullies et al. 2013).

The innovative simulation concept and the enhancement of OTD-NET were validated in the case study "global supply chain" of the E²Log project (Cirullies et al. 2012c). The automotive OEM VW Utility Vehicles produces the pick-up Amarok in Pacheco, Argentina, a place close to Buenos Aires. Since 2012, the car is also manufactured in Hannover, Germany. Suppliers are spread worldwide, but are located mainly in Europe and South America. Hence, about 1,000 parts, components, modules and aggregates are consolidated, packed and scheduled in Wedemark, Germany, and Anchieta, Brazil. Multi-sourcing strategies allow in time-critical cases to procure parts from the nearest supplier. If a part can only be obtained from Europe, a distance of about 13,000 km (approx. 8,000 miles) will have to be covered by a multi-modal transport chain. Typically, the main carriage is performed by maritime shipping. In the case of sudden demand changes and unavailability of parts at nearby suppliers, the demand is fulfilled by express transport, e.g. by airfreight, causing higher energy demand and transportation costs.

The concept of OTD-NET^{ECO} and the case study were considered on different levels of supply chain management (SCM) and with different scopes in three major work packages of the E²Log project:

1. Strategic network design (Cirullies et al. 2012c): as the strategic level of SCM, the supply chain design (SCD) offers the greatest lever for energetic improvement and several scenarios of the case study grouped by three major variants were investigated. The focus lay on the spatial and process-related positioning of consolidation points.
2. Tactical-operative supply chain planning (Klingebiel et al. 2014): in contrary to SCD, supply chain planning and execution comprise decisions regarding transport routes and stock levels with a 2-month horizon. In order to integrate energetic matters into this planning level, an energy-oriented decision support system (DSS) called ECO$_2$LAS (combining economic and ecological objectives in a logistic assistances system) was developed and implemented as a demonstrator for the case study.
3. Encapsulation for SME: simulation methods offer great opportunities for a profound planning basis. However, simulation required a lot of methodological knowledge as well as time resources for data collection, validation and modelling. While SMEs are typically not able to handle simulation, the light-weight, Microsoft-Excel-based wrap-around tool Ecoleano was developed and validated in other case studies.

ECO$_2$LAS, which was subsequently introduced as a productive system by VW Utility Vehicles, is a highly innovative SCM planning tool and received the elogistics award 2011 (AKJ Automotive 2011). ECO$_2$LAS offers two major benefits (Bockholt 2012): Firstly, monitoring of the current supply chain situation and, secondly, assessment of decision options. For this purpose, the system consists of four modules: (1) Supply Chain Monitoring, (2) Supply Chain Simulation, (3) Demand Capacity Planning and (4) Transport Planning.

As the global supply chain is highly complex and involves innumerous sets of data, the first key benefit of ECO$_2$LAS is to automatically import data from both corporate (e.g. orders, stock levels) and public (e.g. vessel tracker, ELCD) sources. The system intelligently stores all import data in the supply chain database (SCDB) and aggregates them for a user-specific supply chain monitoring. Based on this holistic view, both the real network status and user scenarios with adapted parameters can be simulated by OTD-NET^{ECO}. The results allow for evaluating performance measures regarding production supply (daily part availability in comparison to demand, called Demand Capacity Planning) and transportation costs and energy demand (module Transport Planning).

Based on these modules, DCP responsibles can easily compare scenarios of different order configurations and scheduled transports. The system comes with all relevant features, e.g. to modify capacity-critical orders for testing purposes and express transport to evaluate the behaviour of production supply and transport balance. The energy-related result is presented in a scalable chart.

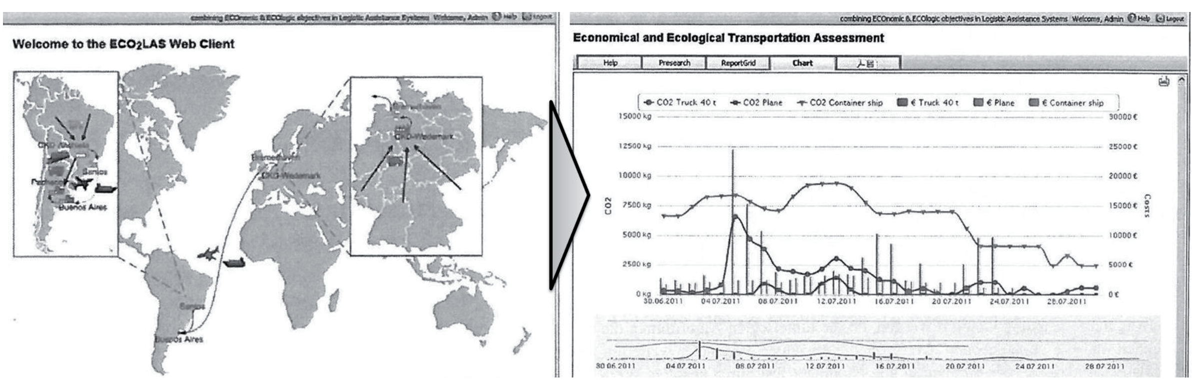

Figure 6. The decision support system ECO$_2$LAS. Start screen of the web-based decision support system as well as the ecological and economic assessment report (Bockholt 2012).

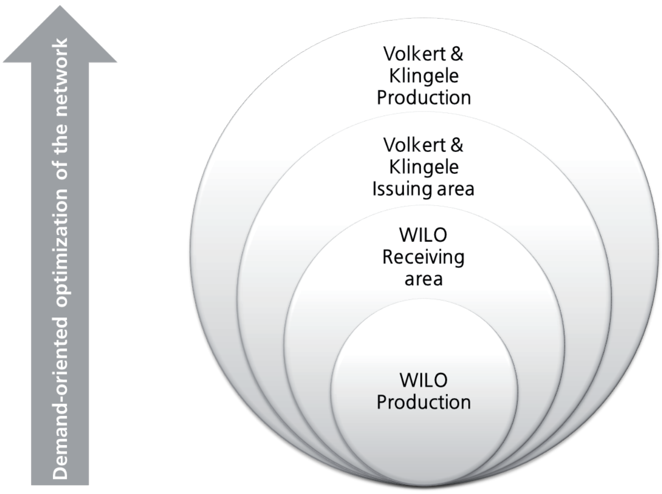

Figure 7. Background and goal of the WILO case study.

Both the advanced features for a holistic and transparent DCP and the estimation of potential energy demand lead to a significant decrease of the already energy-saving world-wide supply chain: within the first three months after the introduction of ECO_2LAS, the number of air cargo deliveries could be reduced by 18 % (Bockholt 2012). Further qualitative evaluations document e.g. that the entire DCP process became steadier and more reliable.

E²Log case study regional production network

In the case study WILO "Regional Production Network" the system boundaries cover the energy-efficient design of the cross-company value-added chain for the production of pumps of the 'STRATOS' series. Starting from two selected small and medium-sized suppliers to the WILO production in Dortmund the effects of different production and supply strategies on energy efficiency as well as to the classical logistic target variables have been analysed.

KLINGELE supplies the cardboards and packing material for the manufactured pumps and VOLKERT produces, amongst others, the plastic injection molding parts of the pump housings. Figure 7 shows the background and goal of the WILO case study.

In the course of the research project, the following issues turned out as especially relevant:

- Identification of energy drivers and starting points for a new organisational design of processes;
- Effects of the design principles of lean manufacturing on internal energy efficiency: one piece flow principle versus batch operation; and
- Energetic importance of the external transports (production supply) in the context of a regional production network.

In the first step it was necessary to energetically assess the specific behaviour of production and logistic plants in different operating states within the defined system boundaries. This was a prerequisite to be able to holistically evaluate the complex interaction of machine scheduling and the resulting internal and external transport and storage requirements with regard to energy use. In case of the project partner KLINGELE, the connection between the production rate and the energy consumption of the corrugator was examined to find approaches for energy-optimised system control. The corrugator is the largest energy consumer in the production of cardboard boxes and cardboard packaging. This relationship is illustrated in Figure 8.

In contrast to previous assumptions it turned out that a reduction of the production rate has a negative impact on energy efficiency and thus represents an unsuitable lever.

A considerably greater potential provides the WILO SE production plant in Dortmund. Due to their consumption, the main energy consumer spray varnishing and cathodic dip-paint coating (see Figure 9) are providing approaches for organisational energy efficiency measures during the start-up and shut-down operations. Through batch operation, the unproductive phases (start-up and shut-down operations) can be minimized.

For example, 9.3 % of the cathodic dip-paint plant's energy consumption could be saved by the plant being switched on and off only once a week instead of every day. However, it is important to notice that such a measure has a negative impact on stocks and lead times. Other effects on energy efficiency, for example due to increased internal transports and additionally required storage and retrieval processes have been examined by the simulation experiments carried out. It turned out that the internal transports only have very little effect on energy efficiency. The same also applies for the external transport processes in a regional production network, those amounting to approx. 60,000 MJ per year for the defined system boundaries (tank-to-wheel consumption). The annual consumption of the cathodic dip-paint coating plant amounts to approx. 3.9 Mio MJ (final energy) per year. Thus improving energy efficiency is contrary to the principles of lean manufacturing (especially of the one piece flow principle and by reducing inventories).

E²Log case study in-house production and logistics[2]

UNIWHEELS is a leading European manufacturer of premium alloy wheels operating a production site with a foundry at Werdohl (Germany). For the process of the casting production within the foundry the effects of different organisational measures such as scheduling have been evaluated by simulation regarding the efficiency in logistics and energy consumption. The case study is focusing on energy intensive processes in the foundry. Machines and equipment used in these processes account for over 20 %[3] of energy use at the production site.

The aim of the case study was an in-depth investigation of in-house production and logistics material flows to identify potentials of energy efficiency improvements. Therefore, it required the use of simulation technique to model the complex processes and their interdependencies in detail. In the beginning a holistic methodology for energy models of complex production systems was developed. The objective of the case study, the data availability and the system inherent characteristics of the production plant were taken into consideration. In case

2. This section has been contributed by Emanuel Fuss.

3. Determined with energy bills as well as connected loads and estimated runtimes of production machines and equipment.

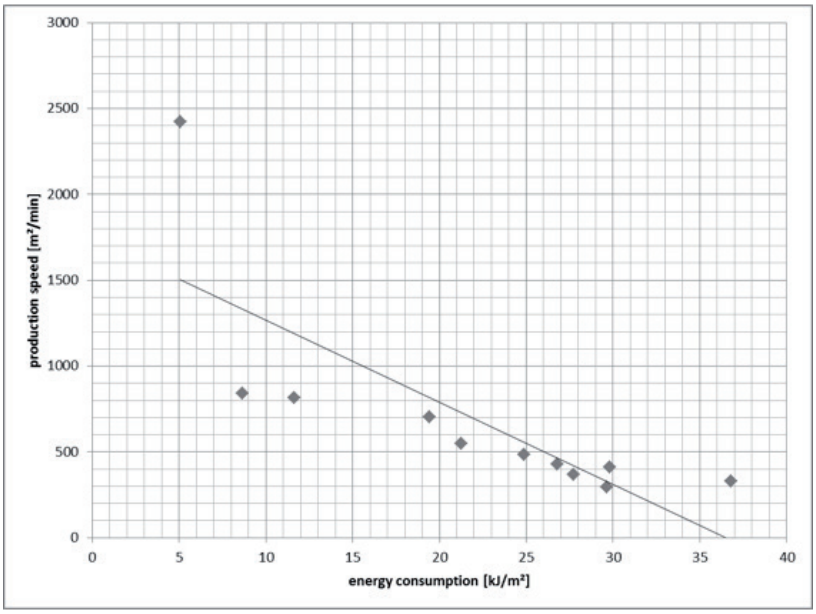

Figure 8. Link between production rate and energy consumption of the corrugator for the same produced cardboards.

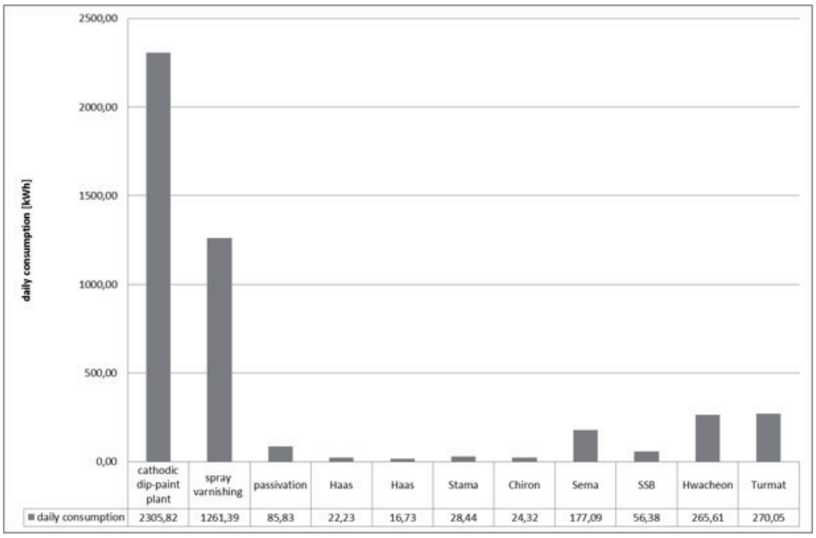

Figure 9. Driver of energy use in the production of WILO SE in Dortmund.

of the thermo processing systems, e.g. the transport crucible or holding furnaces, the thermodynamic dependencies were modelled with differential equations.

In the numerical formulation these were replaced by discrete approximations. Other production systems like the low-pressure casting machines were modelled using state based energy profiles[4, 5]. The verification of the energy models was successfully carried out by means of regression analysis (model error <5 %). The necessary process data e.g. temperature and energy profiles, failure data, process times etc. were gathered via production data acquisition and measurements. The necessary machine data like geometrical and physical properties etc. were taken from plant data sheets as well as from technical literature.

Figure 10 shows the screenshot of the developed simulation model on the top level with its 24 low-pressure casting machines and the overhead gantry with a transport crucible. Using the model allows the evaluation of a broad range of measures on different levels and in different fields of action of the foundry.

The simulation study was performed using a representative system load for two succeeding weeks provided by UNIWHEELS. Thereby, in total over 70 different alloy wheel blanks with varying batch sizes from 200 to 1,500 had to be completed. First the current status situation was simulated. Afterwards various design alternatives attached to different in-plant activity sectors were analyzed (see Table 1). Using integrated analysis options different parameters were evaluated like production

4. The details of this approach can be found e.g. in references (Weinert, 2010), (Dietmair, Verl, & Wosnik, 2008) and (He, Liu, Zhang, Gao, & Liu, 2012).

5. An adaptable module which can be connected to any kind of already existing model to define its energetic states and their energy input or output functions to model easily the different energy and energy-related material flows (e.g. electricity, gas, compressed air, water etc.) was developed within the research project.

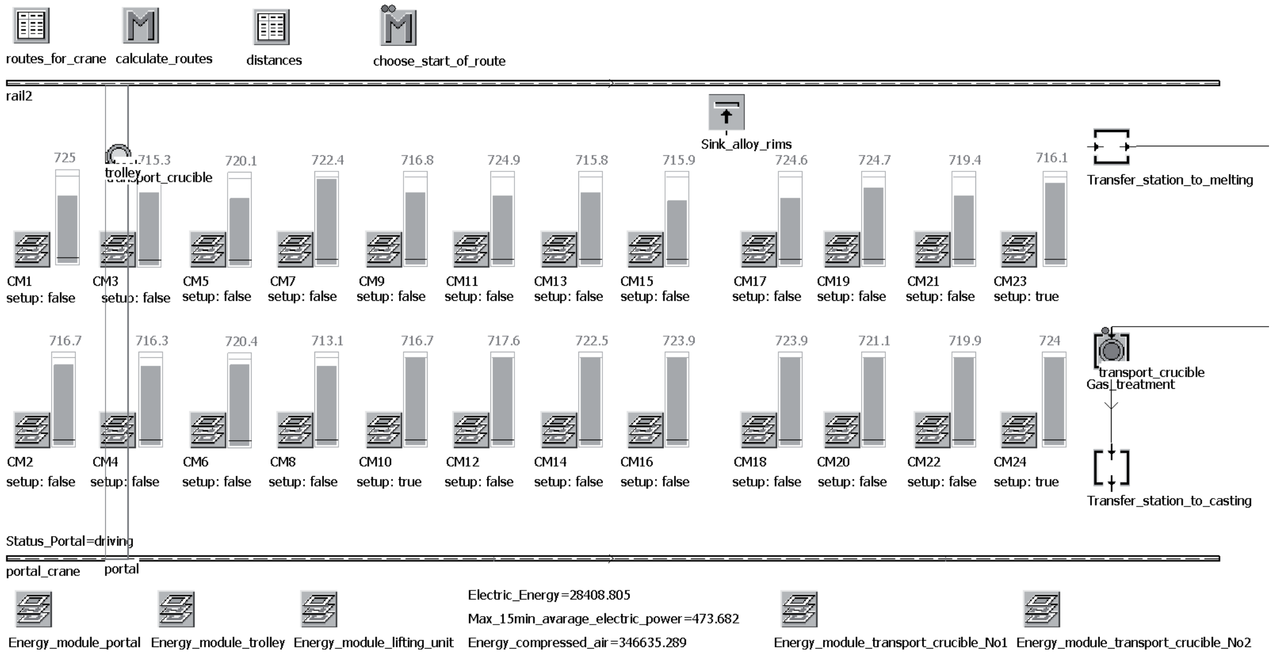

Figure 10. Foundry model. Screenshot of the graphical user interface in Plant Simulation.

Table 1. Selected design alternatives of the simulation study.

Production planning and control	Machinery and process parameter setting	Energy engineering
(1) Optimization of machine utilization	**(2) Increasing the filling temperature of transport crucibles**	Optimizing the compressed air/ compressor regulation
Widening the planning horizon	**(3) Optimizing the control temperature of the holding furnace during machine downtime**	**(4) Implementation of a peak load management system**
Energy focused filling strategy of casting plants		

planning and control, machinery and process parameter setting as well as energy management. In this paper only some of the analyzed measures and the corresponding simulation results are briefly introduced.[6]

The design alternative (1) *optimization of the machine utilisation* was evaluated from an energy focused point of view. Thereby, the goal was to minimize the number of utilized casting machines during the production period of a week to achieve a reduction of energy demand. Every machine run up goes along with high energy consumption. The number of utilized casting plants could be reduced by one with redistribution of orders for a typical planning period of one week. As a result electric power use was reduced by more than 5 % (saving of €260 per week), while at the same time the average order fulfilling time was reduced by 7 %.

Secondly, the alternative (2) *Increasing the filling temperature of transport crucibles* was investigated. Thereby, the savings through increased melting temperature during the staging of materials from the smelter were elicited. The transport crucibles provide the melting to the holding furnace of the casting plants during multiple rounds of transport. The melting temperature has a significant influence on the energy consumption of the holding furnace that ensures the necessary material temperature with an on off controller with hysteresis (Fuss et al. 2013). The results of the simulation indicate that in case of a 20 °C higher melting temperature the electric power of the casting can be decreased by around 6 %. This corresponds to savings of around €320[7] per week.

By analyzing the design alternative (3) *optimisation of the control temperature of holding furnace during machine downtime,* durting weekends and throughout other non-operation periods, even higher potentials were identified. Usually, the temperature of the holding furnace is held at 720 °C ± 20 °C, even during non-operation as during weekends. A complete

6. All evaluated measures are illustrated in detail in the final report of the research project.

7. The additional power demand respectively the costs of energy for the necessary restructuring of the operating mode of the smelter were not simulated in the context of the research project. According to first estimations these costs do not exceed the prognosticated saving of costs. Primarily, this is determined by the difference between electricity and gas price.

shutdown of the holding furnace is not possible from a procedural point of view. However, a lowering of the temperature down to 450 °C is feasible without violating procedural and machinery regulations. This design alternative of the holding furnace was implemented in the simulation model: All machines without further jobs decrease their temperature. A well-timed, progressive machine run up has to be considered in the implementation of this design alternative due to the risk of peak loads. As a result, compared to the as-is-procedure, weekly electric power use can be reduced by 11 %. This reduction corresponds to savings of around €580 per week.

At last, the alternative (4) *Implementation of a peak load management system* was implemented, motivated by unsteady electrical power use of the foundry. The management system restricts the maximum power of the holding furnaces. For this purpose single holding furnaces are shutdown or their run up is decelerated. This strategy ensures that the maximum allowed power consumption of the 24 holding furnaces is never exceeded. As a result the model provides a forecast quarter-hour power value reduction by 32 %. This corresponds to savings of around €980 in the accounting period of one month (€245 per week).

All four presented design alternative lead to a significant reduction of power demand and hence to a cost reduction. While little changes in the job assignment to machines only result in minor savings, the third strategy is a promising one. It brings about major cost savings while the order fulfillment time is not affected.

The extracts of the case study results presented in this paper demonstrate the dimension and the potential of an energy-oriented simulation study based on discrete event and continuous machine and equipment modeling being performed in a complex production system. Using a practical example, the achievable cost savings are evaluated by means of concrete examples. For the team it became obvious that even the use of a state-of-the-art simulation tool leads to high efforts to carry out the study. Especially by taking energy flows into consideration, minor parts of the simulation study took several weeks to be performed.

At first sight, these facts seem to prohibit the consistent application of energy-oriented simulation in complex production systems and seem to make cost improvements hardly achievable. But, given a user's certain knowledge in energy-related topics, the presented holistic methodology to build energy models for production facilities allows to develop models that are appropriate for a given problem with a justifiable amount of work. Likewise, the generic energy-modules for Plant Simulation that have evolved from the study alleviate the potential user's simulation activities. Concluding, the performed simulation study in cooperation with UNIWHEELS led to valuable findings and can be described as a success.

Lessons learnt from the E^{2}Log project

This paper summarizes the major objectives and goals of research project 'E^{2}Log – Energy Efficiency in Logistics and Production'. As opposed to the well-established body of evidence on technical strategies for increasing energy efficiency, this project was meant as a contribution that considers technology as given and that places a strong focus on major organisational matters in production and logistics.

During the three year project duration the co-operating research institutes and partners from industry worked on different scenarios to integrate energy as an equivalent target into daily planning scenarios. In order to achieve general valid statements regarding derivation of measures and effects on energy efficiency and state of the art logistics targets three case studies were chosen that guarantee practical relevance.

The three case studies can be labeled as ***global supply chain***, ***local production cluster*** *and* ***in-house production and logistics***. Planning and execution of efficient supply and transport processes in a global, multi-modal procurement network was focused on in the case study **global supply chain**. The assessment of energy efficiency of production and supply alternatives and the interactions between production and logistics was analysed in the case study **local production cluster**. The estimation of different scenarios of production planning and control depending on workload, order structure and energy costs were considered in the case study **in-house production and logistics**. In all case studies simulation models were used to evaluate the complex interactions between material- and energy-flows. Those were analysed on appropriate strategic and operative levels to develop energy efficiency design alternatives and to show interdependencies between logistics output and energy demand.

Additional to the modeling, **energy measuring concepts** for logistics and production sites as well as the **environmental transport data sheets** were developed to determine energy use in transport processes. A combination of basics, methodological knowledge and tools were integrated into the **Eco-Toolsuite.**

To evaluate energy efficiency in supply chains, the supply chain simulator OTD-NET was extended to **OTD-NET^{ECO}.** For in-house logistics and production processes **Plant-Simulation** was enhanced to evaluate state-based energy consumption profiles. For operative planning the logistics assistance system **ECO$_2$LAS** was developed to assess the energy demand of planning alternatives. According to the requirements of SMEs, the methodological knowledge and software tools were transformed to **Ecoleano** to ensure an easy and simple way to evaluate the energy demand of transport processes. As a result, the objectives of the research project were achieved.

References

AKJ Automotive (2011): Verleihung des Elogistics Award 2011 im Rahmen des Jahreskongresses AKJ Automotive in Saarbrücken.

Arbeitsgemeinschaft Energiebilanzen (2011): Ausgewählte Effizienzindikatoren zur Energiebilanz Deutschland. Daten für die Jahre von 1990 bis 2010. Berlin: Arbeitsgemeinschaft Energiebilanzen.

Arbeitsgemeinschaft Energiebilanzen (2013): Ausgewählte Effizienzindikatoren zur Energiebilanz Deutschland. Daten für die Jahre von 1990 bis 2012. Berlin: Arbeitsgemeinschaft Energiebilanzen. http://www.ag-energiebilanzen.de (2014-01-05)

Bockholt, F. (2012): Operatives Störungsmanagement für globale Logistiknetzwerke. Ökonomie- und ökologieorientiertes Referenzmodell für den Einsatz in der Automobilindustrie. Dissertation. Dortmund: Praxiswissen.

Cian, E. De; Schymura, M.; Verdolini, E.; Voigt, S. (2013): Energy Intensity Developments in 40 Major Economies: Structural Change or Technology Improvement? ZEW Discussion Paper No. 13-052, Mannheim: Centre for European Economic Research.

Cirullies, J.; Klingebiel, K.; Scavarda, L. F. (2011): Integration of Ecological Criteria into the Dynamic Assessment of Order Penetration Points in Logistics Networks. In: Burczynski, T.; Kolodziej, J.; Byrski, A.; Carvalho, M. (Ed.): Proceedings of the 25th European Conference on Modelling and Simulation. Krakow, pp. 608–615.

Cirullies, J.; Klingebiel, K.; Scavarda, L. F. (2012a): A Conceptual Framework for Green Supply Chain Design. In: Proceedings of the International Conference on Industrial Engineering and Operations Management. The XVIII international conference on Industrial Engineering and Operations Management. Guimarães.

Cirullies, J.; Schwede, C.; Toth, M. (2012b): Intra-Simulative Ecological Assessment of Logistics Networks. Benefits, Concepts, and Tool Enhancement. In: Laroque, C.; Himmelspach, J.; Pasupathy, R.; Rose, O.; Uhrmacher, A. M. (Hg.): Proceedings of the 2012 Winter Simulation Conference. Winter Simulation Conference 2012. Berlin.

Cirullies, J.; Toth, M.; Holtz, A. (2012c): Auf dem Weg zur Energieeffizienz in Logistiknetzwerken. Stand der Integration energetischer Größen in die simulationsgestützte Analyse globaler Lieferketten. In: Industrie Management 28 (5), pp. 20–24.

Cirullies, J.; Klingebiel, K.; Scavarda, L. F.; Ceryno, P. (2013): Integration of Environmental Criteria into Simulation-Based Postponement Decisions. In: International Foundation for Production Research (Ed.): Challanges for Sustainable Operations. Proceedings of the 22nd International Conference on Production Research. Iguassu Falls, pp. 336–342.

Dietmair, A.; Verl, A.; Wosnik, M. (2008): Zustandsbasierte Energieverbrauchsprofile: Eine Methode zur effizienten Erfassung des Energieverbrauchs von Produktionsmaschinen. Werkstattstechnik online (7/8), pp. 40–45.

European Commission (2006): Communication from the Commission – Action Plan for Energy Efficiency: Realising the Potential. COM/2006/0545 final, Brussels: European Commission.

Fuss, E.; Krewald, A.; Drvendzija, S. (2013): Transparenz als Schlüssel zur energieeffizienten Produktion: Ablaufplanung in Schmelzerei und Gießerei mittels planungsbegleitender Energie- und Materialflusssimulation. ProductivITy Management, Vol. 18, No. 3, pp. 35–38.

Greening, L. A.; Davis, W. B.; Schipper, L.; Khrushch, M. (1997): Comparison of six decomposition methods: application to aggregate energy intensity for manufacturing in 10 OECD countries. In: Energy Economics, Vol. 19, No. 3, pp. 375–390.

He, Y.; Liu, B.; Zhang, X.; Gao, H.; Liu, X. (2012): A modeling method of task-oriented energy consumption for machining manufacturing system. In: Journal of Cleaner Production Vol. 23, No. 1, pp. 167–174.

Hrdliczka, V.; Jakobi, H.A. (1997): Leitfaden für Simulationsbenutzer in Produktion und Logistik (ASIM Mitteilungen, 58).

Klingebiel, K.; Hackstein, L.; Cirullies, J.; Parlings, M.; Hesse, K.; Hohaus, C.; Jung, E. N. (2014): Ressourceneffiziente Logistik. In: Neugebauer, R. (Ed.): Handbuch Ressourcenorientierte Produktion. München: Carl Hanser, pp. 719–748.

Kraftfahrt-Bundesamt (2013): Verkehrsaufkommen durch Leerfahrten deutscher Lastkraftfahrzeuge seit 1995. http://www.KBA.de/ (2014-01-05).

Kuhn, A.; Hellingrath, B.; Keller, M. (2006): Bewertung und Verteilung von Kosten und Nutzen in Wertschöpfungsnetzwerken; in: Wissenschaft und Praxis im Dialog, 3. Wissenschaftssymposium, 30.–31. Mai 2006, Dortmund, pp. 378–394.

Kuhn, A.; Keßler, S.; Vornholt, C. (2008): Ergebnisse des Sonderforschungsbereiches SFB 559: Modellierung großer Netze in der Logistik. In: Jahrbuch Logistik 2009, pp. 255–261.

Law, A. M.; Kelton, W. D. (2000): Simulation modeling and analysis. 3. ed., Boston: McGraw-Hill.

Norm VDI 3633, Blatt 1, p. 12.

Schipper, L.; Scholl, L.; Price, L. (1997): Energy use and carbon emissions from freight in 10 industrialized countries: An analysis of trends from 1973 to 1992. In: Transportation Research Part D: Transport and Environment, Volume 2, Issue 1, March 1997, pp. 57–76.

Statistisches Bundesamt (2014): Straßengüterverkehrsstatistik Deutschland. Beförderte Gütermenge und Beförderungsleistung (Straßengüterverkehr): Deutschland, Jahre, Verkehrsart, Verkehrswege. http://www-genesis.destatis.de (2014-01-05).

Wagenitz, A. (2007): Modellierungsmethode zur Auftragsabwicklung in der Automobilindustrie. Dissertation. Technische Universität Dortmund, Dortmund.

Weinert, N. (2010): Vorgehensweise für Planung und Betrieb energieeffizienter Produktionssysteme. Stuttgart: Fraunhofer Verlag.

Wenzel, S.; Collisi-Böhmer, S.; Pitsch, H.; Rose, O.; Weiß, M. (2008): Qualitätskriterien für die Simulation in Produktion und Logistik. Planung und Durchführung von Simulationsstudien. Berlin, Heidelberg: Springer.

Acknowledgements

The E²Log Project has been co-funded by the German Federal Ministry for Economic Affairs and Energy and supervised by Project Management Jülich (PTJ).