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FRESH – Flexibility management and frequency containment reserve of heavy-duty vehicles at ports by the example of Hamburg Container Terminal Altenwerder (CTA)

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Abstract:
Within the logistical sector battery electric vehicles substitute more and more conventional vehicles. Due to shift work and volatile workload, idle times occur day by day. At the same time, the integration of renewable energy sources leads to fluctuations in power grid frequency (e.g., more energy is available on sunny days via solar plants). Virtual power plants offer an opportunity to counteract by bundling smaller energy sources.
When large fleets of heavy-duty electric container vehicles are deployed, container logistics is a promising field for smart grid applications. During idle times, their batteries can be used to support grid stability by providing Frequency Containment Reserve (FCR) for the grid. At HHLA Container Terminal Altenwerder a fleet of automated guided vehicles (AGVs) is set to provide the needed flexibility.

Keywords:
Electric Automated Guided Vehicles, Flexibility Management, Electromobility, Logistics

Introduction

The logistics sector is considered the second largest source of greenhouse gas emissions in the European Union (REN21 2020). Governments around the world are working on means to combat the anthropogenic climate change (Harmelink et al. 2006). Substituting electric for conventional vehicles is a promising change for the development of a more sustainable mobility sector (Valentine-Urbschat and Bernhart 2009) as this offers the additional opportunity of implementing smart grid concepts to support the integration of renewable energy sources (Watson et al. 2010). In the context of the transportation sector, container logistics offers a promising field for smart grid application as it is an energy-intensive endeavour.
To exploit the potential of renewable energies in container logistics, the electrification of heavy-duty container vehicles provides an important and impactful first step (BESIC-Konsortium 2016). Because AGVs are not on duty every hour of the day (Steenken et al. 2005), during idle times the AGV batteries can be used to support grid stability by rendering FCR for the grid (Han et al. 2012). FCR is important for the stability of the electrical grid as the integration of renewable energy sources leads to fluctuations in frequency (e.g., more energy is available on sunny days via solar plants) (Kahlen et al. 2014). Thus, incorporating AGV batteries into flexibility provision promotes the sustainability of all container logistics and subsequently opens up a new source of revenue.

Setting

At HHLA Container Terminal Altenwerder (CTA) AGVs operate the transport between the container gantry cranes at the berth and the storage area. In order to reduce the greenhouse gas emissions of the container terminal, the initially diesel-powered AGVs, are successively exchanged for battery-powered vehicles with lithium-ion batteries. Two thirds of the AGVs at the terminal are already powered electrically. By the end of 2022, nearly all 100 AGVs are going to be converted to the fast-charging battery electric vehicles.

FRESH – Flexibility management and frequency containment reserve of heavy-duty vehicles

The conversion of the AGV fleet at CTA, supported by Hamburg's Ministry for Environment, Climate, Energy and Agriculture with support from the European Regional Development Fund (ERDF) as part of the "Energiewende in Unternehmen" subsidy programme, is an important component of HHLA's sustainability strategy.

The publicly funded electric mobility project FRESH (Flexibilitätsmanagement und Regelenergiebereitstellung von Schwerlastfahrzeugen im Hafen) is realised in cooperation with OFFIS - Institute for Information Technology, Georg-August-University Göttingen and Next Kraftwerke GmbH. It serves as a business case to integrate the existing battery capacities of the AGVs into the energy grid as flexible storage units to contribute to grid stability and power supply. By now, renewable energies already account for around 40% of public net electricity (Frauenhofer ISE 2019). In comparison to fossil energy, renewable energy cannot reliably offer energy supply according to demand (Doleski 2017; Kroposki et al. 2017). This results in deviations in grid frequency that have to be compensated by FCR (Spieker et al. 2016). In this context, virtual power plants (VPPs) offer the opportunity to digitally linking various energy producers and consumers and bundle their offers in order to reach necessary thresholds for participation in the flexibility market (Kahlen et al. 2014). This can be implemented in the setting of CTA as the AGVs spend an average of 33 % of the time in an idle waiting position between transport orders. Therefore, as secondary exploitation, during these idle times the AGVs can be connected to one of the presently 13 electric charging stations, to provide or store energy by means of a VPP when the power grid requires it and thus provide FCR for the energy market. Five more charging stations will be added this year, so a total of 18 stations will serve the electric AGVs. Within the scope of the project, the CTA serves as a pioneer for how digitalization and electrification of the logistic sector can support the integration of renewable energies into the power grid and pioneer the goal of reaching "zero-emission" in the logistics sector.

The current logistical process is as follows: AGVs receive orders from the terminal management system that determines the fastest routes between gantry cranes and storage area for loading and unloading containers. Their routes are controlled via the interaction of more than 19,000 transponders embedded in the ground thus accounting for the positions of other AGVs and allowing for short-term changes in orders. Additionally, battery charging levels are monitored. If a defined state of charge (SOC) is reached, AGVs are assigned to an ACS to recharge. The recharging process is fully automated. An AGV is guided into a parking position next to an ACS, the charging device connects to the AGV and the recharging starts. After the recharging process, the AGV is assigned to new transport orders. Being equipped with bi-directional charging the ACS can also be used to discharge the AGV to provide energy to energy markets and power grid. This bi-directionality serves as a central functionality in the FRESH project. Furthermore, a flexibility management system is being developed in addition to the existing terminal operating systems that will take into account the operational terminal needs, provide an interface for monitoring and, if the situation should require, manual control, and implement interfaces to the VPP and the charging stations as well as to the AGVs and their control system. The flexibility management system determines the available flexibility of the individual batteries of the AGVs in a manner that allows for a maximum of battery capacity to be provided to the energy market and respectively be used for grid stabilisation while ensuring that the required transport capacity at CTA is always available. For the optimisation, the logistical requirements of the terminal and the state of charge of the batteries of the individual AGVs have to be continuously monitored and balanced. Thus, changing restrictions for the availability of power for the VPP occur. The amount of flexibility that can be provided by the AGV fleet has to be determined reliably taking into consideration that a pre-planned flexibility may be provided to the full extend (best case), not at all (worst case), or only partly, as some AGVs may not available as planned. Based on the varying availability of battery capacity, the VPP determines the capacity that can be used for the FCR market and integrates these capacities with the relevant restrictions into a pool of flexibilities. For the VPP interface, appropriate communication procedures, data formats and control constraints are defined and implemented to fit the application at CTA.

In addition, economic aspects of the provision of FCR especially with respect to the lifespan of the battery systems are being investigated. To this end various scenarios are being defined and with regard to their economic potential as wells as the changes in the lifespan of batteries (Harnischmacher et al. 2020).

FRESH aims at realising the entire process chain from offering flexibility to marketing of the flexibility to actual physical provision of energy. To this end, an IS-supported solution for the management of the flexibility potential of the AGV fleet is being developed and extensively tested in a field test.

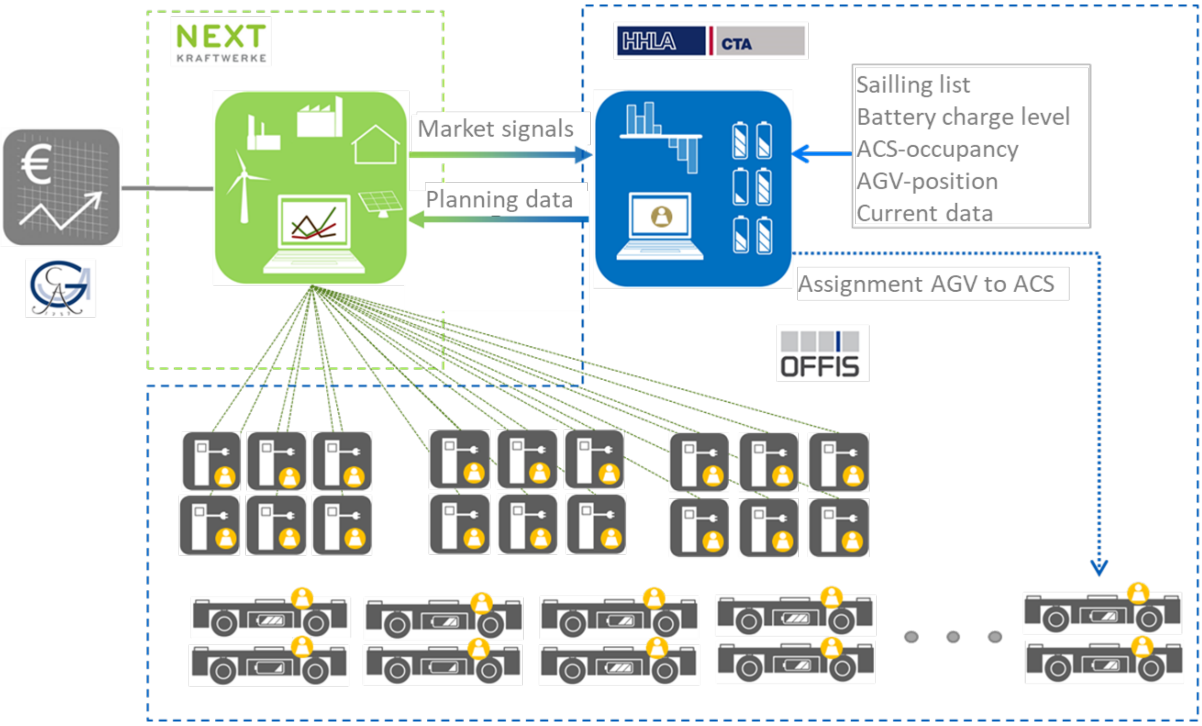

Figure 1: Integration of project partners

Use case

Due to the increasing proportion of renewable energies in power grids, grid frequency is more volatile than before. The amount of renewable energies is highly dependent on environmental impacts. On sunny days solar panels supply power, on windy day's power is provided by wind park. Fossil power plants have been switched on and off to balance frequency fluctuations. For renewable energies, new methods for stabilisation needed to be found.

One component are the VPPs. VPPs link decentral energy producers like solar-, wind-, hydro- or biogas plants, power storage units and customers. Many of them are small but their summed-up energy production / storage leads to a reserve and flexibility for power grids. Control systems in the single units are connected to a central control system that coordinates all electricity feeds and consumptions with the objective to balance the grid frequency at 50 hertz. The link between grid operator, energy exchange, producers and customers is shown in the following figure (Next Kraftwerke 2021).

Figure 2: Grid operator, energy exchange and producers in VPP by Next Kraftwerke (Next Kraftwerke 2021)

At CTA, the lithium-ion-batteries of the AGV fleet can supply a capacity of four megawatts (mathematically). The VPP calculates the energy-economical need of capacity for certain times and sells it accordingly. FCR processes are controlled by decentral control systems so-called Next Boxes that are installed at CTA. Just before an agreed time interval, an AGV is ordered to the ACS and a charging process will start automatically to set up a defined SOC-level. As soon this level is reached the charging / discharging control is handed over to the Next Box. According to the market needs monitored by the VPP control centre the battery is charged if the grid frequency is above 50 hertz and discharged if it is below. At the end of the agreed time interval control is returned to the battery charge management system of the AGVs. AGVs will be charged to a predefined SOC-level before they leave the ACS.

Flexibility management and FCR provision

In order to fulfill the presented use case, i.e., to provide FCR with the fleet of automated guided vehicles, we apply a two-phase process. FCR is tendered in a daily procedure, which takes place one day prior to provision. Thus, the flexibility of the fleet must be determined one day in advance to participate in the call for tender. Consequently, there is a day-ahead planning phase additionally to the intraday operational phase in which AGVs are actually scheduled and used for the provision of FCR. Figure 3 shows an overview of the tasks to be performed by the actors involved, namely CTA with its fleet as flexibility provider, the flexibility management system (FlexMan) as pre-aggregator and the virtual power plant of Next Kraftwerke as final aggregator with market access. In the following, we examine the procedures in the two phases in more detail.

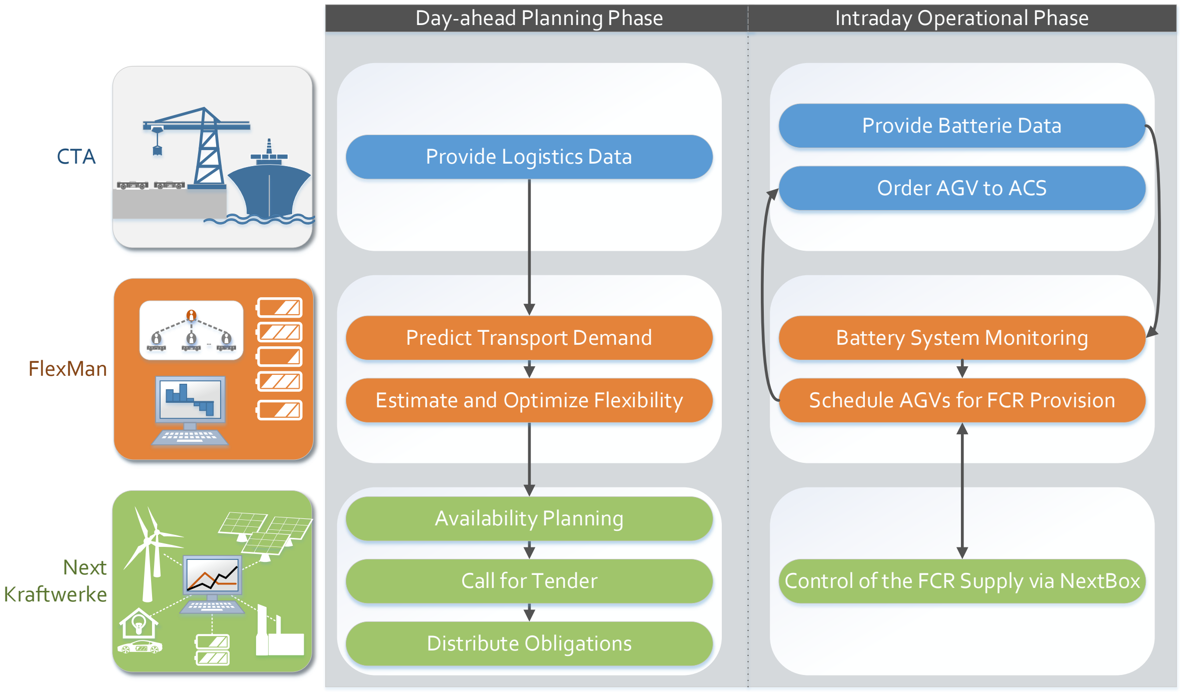

Figure 3: Overview of tasks of the involved actors in the two phases

Day-ahead planning

The day-ahead planning phase starts with FlexMan requesting the latest logistics data from CTA for the following day. This data provides information about the expected arrival times of ships, as well as the number of containers to be loaded and unloaded. Based on this information FlexMan uses a trained machine learning model to predict transportation demand throughout the day. Here, transport demand refers to the number of AGVs that will be needed during specific time periods. So far, machine learning with artificial neural networks and random forests has been tested and promising results have been obtained. However, the prediction performance is expected to be further improved by using more training data, tuning the model further and using additional input such as weather data (Holly et al. 2020). Additionally, FlexMan requests market signals from the VPP. These market signals show any differences in the pricing of the 4-hour blocks in which FCR is presently marketed. The predicted transport demand and the market signals serve as inputs to determine the flexibility. The flexibility of the fleet is defined here by how many ACS and AGVs can be withdrawn during the day for FCR provisioning without restricting the logistics process, i.e., the remaining AGVs can handle the predicted transport volume and there are still enough ACS to keep the fleet at a sufficient state of charge. The number of AGVs needed for transportation tasks is given by the forecast. Nevertheless, the number of required ACS can vary significantly depending on the allocation of transport orders to the AGVs. This affects the number of AGVs that need to charge at a given time. Therefore, we use an optimization heuristic. This heuristic selects a flexibility candidate, i.e., a certain number of AGV-ACS combinations to be used for FCR provisioning. For this candidate, expected revenues can be calculated using the market signals. In addition, a logistics model evaluates whether this candidate could lead to delays in the logistics processes. The resulting feasibility measure and the expected revenue result in the solution quality of the candidate. The candidate can then be adapted and reevaluated. We use a parallel cooperative metaheuristic to optimize the flexibility candidates until the candidate with the highest solution quality, hence with the highest revenue without impairing logistics, is found. The parallel execution of the heuristic leads to a reduction of the runtime. At the same time, information exchange between the parallel solvers aims at improving the solution quality without increasing the computational effort. This form of distributed artificial intelligence is implemented by a multi-agent system. The flexibility determined by the heuristic is once more checked for plausibility with a simulation model of the terminal logistics implemented in *Tecnomatrix Plant Simulation* (Siemens Digital Industries Software). If the flexibility fails this test, the optimization heuristic must be run again with modified parameters. Otherwise, it will be forwarded to the VPP. The VPP integrates the flexibility of the fleet into its pool. It conducts availability planning for its entire asset pool and then participates in the tender for FCR. After receiving the tender results, the VPP must allocate the obligations among the plants. The portion assigned to the AGV fleet is transmitted to FlexMan as marketed flexibility and serves as the basis for planning in the operational phase.

Operational phase
The operational phase is a continuous process in which specific AGVs must be scheduled for FCR provisioning. FlexMan again uses a multi-agent system for this task. Each AGV is represented by an agent that serves as its digital twin. FlexMan constantly updates its knowledge of the state of the AGV fleet, including SOCs. These current states are reflected in the AGV agents. The AGV agents can thus calculate schedules for the potential use of their AGV in FCR provision. The AGVs are all able to contribute the same amount of power but they differ in the amount of time they need before they are FCR-ready. This time span depends on the current SOC, the time an AGV needs to drive to the ACS and if it must finish an ongoing transport task beforehand. The possible usages of the AGV agents are integrated into an integer linear optimization problem by an optimizer agent. By solving this problem, the optimizer agent selects exactly one schedule for each AGV and thus determines which AGVs should be used for FCR provisioning and when they must be sent to an ACS to be FCR-ready in time. FlexMan must continuously check whether the current plan can still be maintained and reschedule if necessary. The planning process is performed for a 4-hour planning horizon. Therefore, FlexMan should be able to detect in time if the given flexibility cannot be met and then inform the VPP, which can compensate the deviation by other plants in its pool.
To execute the plans, FlexMan forwards charging requests to the terminal system, which generates driving orders to charging stations for the AGVs. When the AGVs arrive at the ACS, FlexMan can continue to track the current SOC. As soon as an AGV has a sufficient SOC and the time from which it is scheduled for FCR is reached, FlexMan sends an FCR ready signal to the responsible NextBox. As long as this signal remains, the NextBox takes control of charging and discharging the battery storage and can thus provide FCR. When an AGV is no longer designated for FCR provision, FlexMan withdraws the FCR-ready signal. The battery storage is automatically fully charged, and the vehicle can return to logistics duty.

Conclusion
FRESH is an ongoing project. The major challenge is to forecast the shortly needed transport capacities of automated guided vehicles in a logistical context characterized by high uncertainty and variability and provide the remaining capacity of the battery-electric fleet for frequency containment reserve.
In order to tackle these challenges, we

- use artificial neural networks to predict the availability of AGVs day-ahead,
- compute the marketable flexibility with a heuristic approach,
- rely on simulation for checking the plausibility of flexibility schedules,
- continuously supervise and control the AGVs with a multi-agent system and
- integrate the fleet’s flexibility into a larger pool of distributed energy resources within a virtual power plant.

A six-month field trial in 2021 enables verification, refinement, and performance analysis of the FlexMan system. Quality of prediction, simulation and optimization can be further improved.
Based on these results an assessment and transfer of the use case to other industrial sectors is feasible. All industrial sectors that operate with battery-electric vehicles and shifts or with fluctuating workload are feasible fields of application.
The economical use is examined as well taking into consideration total costs including a possible shorter battery life.

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