Virtual Intelligent Port "VIPort" – a Holistic Energy Approach

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1 ABSTRACT

The "Fit for 55 package" with the goal of reducing net greenhouse gas emissions by at least 55 percent by 2030 compared to 1990, requires a restructuring of the energy systems in the ports in order to supply ships with energy with as few emissions as possible. The virtual intelligent port takes a holistic approach to optimize the entire energy system of a port based on digitalization, data analysis, and artificial intelligence (AI). The optimization aims to maximize energy generation from renewable sources, minimize energy consumption, and keep investment and operating costs to a minimum through intelligent energy management. The digital twin of the port is created with the involvement of all participants relevant for the generation and consumption of energy. It is a very individual system for each port and can be further developed with future developments of the port. The digital twin is the basis for optimization and thus for intelligent investment decisions and efficient energy management.

Keywords: energy, greenhouse gas, digitisation, data analysis, holistic

2 THE CHALLENGES OF ENERGY SUPPLY IN PORTS

The optimal energy supply in the ports represents a very complex task due to the very individual requirements and boundary conditions. It has become considerably more complicated due to the requirements imposed by climate targets and the global political energy situation. The climate targets and the associated political requirements call for the minimization of emissions. This in turn requires a precise analysis of the energy demands as well as the potentials for renewable energies and the conversion and storage of these. The past few months have shown us all how important the topic of energy self-sufficiency is. The availability of renewable energies is subject to major fluctuations due to the influence of weather (wind, sun, waves, etc.), the annual and daily rhythm. This makes new concepts for energy storage and conversion necessary. What are the future energy sources? What storage requirements exist? How well equipped is the port for this? What is the connection to power plants and the public network like? Major changes are imminent, for which there is little or no experience to be resorted to. If there is a lack of experience, it is even more important to use new technologies such as digital twins, simulations and optimization algorithms to support investment decisions. This enables decisions to be made consciously and based on comprehensible data and facts.

3 THE METHODICAL APPROACH, DIGITALIZATION, DATA ANALYSIS AND ARTIFICIAL INTELLIGENCE

3.1 Generate added value from digitalization

Digitalization is much more than just a trend. Digitalization is the transformation from an analog environment to an environment in which physical objects and values are displayed in formats that are suitable for further processing or storage in digital systems. It will thus be possible in future to present, store and process real-time information of the systems. One approach to making this digitalization usable is the digital twin. The steps for an approach with a digital twin are explained below.

3.2 Analysis

The analysis phase deals with the collection and exploration of all information sources and data describing the system to be digitally represented. This refers to physical objects with their relevant data for the respective problem as well as the relationships between the objects, which are also described with data. The relevance of the data must be determined. Which objects and relationships, with which relevant properties are integrated into the digital system? Which data are available or must still be made available? Which interfaces are available to which data systems and/or must be created? What is the quality of the data in terms of completeness? Analysis of the data also means the development of new information from data fusion and correlation.

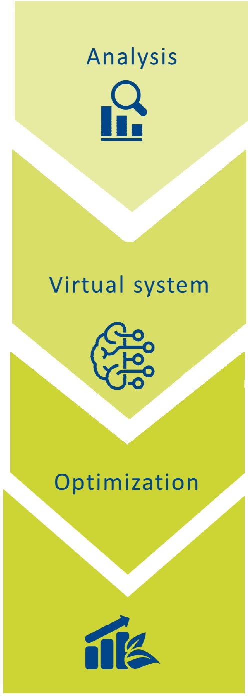


Figure 1: Procedure of the methodical optimisation approach

3.3 The digital twin

A digital twin is a digital representation of a real object using the data relevant to the respective objective, the so-called "data twin". Digital models expand this data twin into a digital twin. The term digital twin is not clearly defined and there are different expansion levels. For us, a digital twin is a system that is supplied with real-time data and is capable of simulation and learning, and that optimises itself. According to our definition, a digital twin can be used, among other things, to represent real-time states, to optimize operations, to reduce costs, but also for validation and verification in development or for investment decisions and predictive maintenance. A digital twin thus goes well beyond a simple virtual model or a simple visual representation! With the help of a digital twin, even complex relationships can be represented and understood. With the help of this fact-based procedure, it is possible to master complexity where even people with many years of experience reach their limits. The results can be documented transparently and comprehensibly.

3.4 Optimization

In most cases, optimization of very complex systems means larger solution spaces and, above all, the need for consideration of several (conflicting) targets that are often contradictory. This is often referred to as multi-criteria optimization. If there are several opposing goals, problem formulation becomes more complicated and increasingly complex with the increasing number of influencing factors and their interactions. Artificial intelligence methods provide us with the right tools for mastering such problems that are characterized by the fact that there is no global optimum. In this case, we speak of pareto optimization, or the search for a condition in which it is not possible to improve one of the criteria without having to worsen another. Here, the corresponding algorithms of the multicriterial systems provide the best solution for the specific situation to be selected. The following methods are available to select the best solution for the specific situation from this set of solutions:

(1) Expert interviews and decisions – Experts analyze the final solution quantity and make the selection based on situation-specific expert knowledge.

(2) Problem simplification through weighting – Individual target variables are given a higher weighting depending on the situation and are thus prioritized.

(3) Decision Support System - The decision making is achieved through machine learning or the solution quantity is further limited and connected with point 1, which combines expert decision.

3.5 Management

Intelligent energy management is made possible based on the digital twin and using a wide variety of AI algorithms. In addition to the topic of optimization, forecasts and anomaly detection also play an important role in the operation of the energy system.

4 THE CONCRETE IMPLEMENTATION FOR THE PORT

The theoretical approach described above is very well suited to efficiently master the current and future challenges of port energy supply.

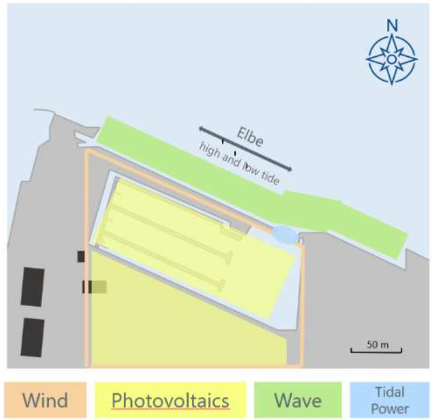


Figure 2: Result of the first area analysis

4.1 Energy potential analysis for ports

The aim of the energy potential analysis is to enable a maximum possible supply of renewable energy to the ports, starting from a purely physical consideration. This includes, on the one hand, the potentials of energy generation, but also the potentials of storage. In a first step, geo-information data are procured and the theoretically possible areas for energy generation are determined. In the case of ports, it is advisable to consider the following forms of energy: wind, sun, wave and possibly tidal energy. In this consideration step, no operational restrictions are considered. In the next step, the concrete usability of the individual areas regarding the possible forms of energy is analyzed. Now, restrictions such as shipping traffic, blocked areas, flood areas, possible shadowing in the case of PV installations, wind-reduced zones due to high buildings, compliance with distances to the security infrastructure (e.g., tank farm, radar stations, etc.). Once possible scenarios have been defined for the first time, the next step is data procurement. The following time-resolved (historical) weather data are of relevance:

- Wind speed and direction
- Temperature
- Solar radiation (global and diffuse)
- Information on tidal range and swell (depending on wind direction and thickness)

In addition, first technological decisions are made (e.g. performance and number of suitable wind turbines) and corresponding load curves are procured. After the data has been prepared, it is aggregated and the total energy yields are calculated for a calendar year. In this step, the individual regenerative yields can be considered independent, as there is practically no feedback to the overall energy system in the later real system. Through iterations and optimization algorithms, the regenerative energy yield is optimized in terms of energy demand. If the port's energy needs are known, initial estimates of the degree of self-sufficiency can be made on this basis. A similar procedure applies with regard to the energy storage. Here, too, the first step is to identify potential areas in the port area that can be used for energy storage, taking safety aspects into account. Storage types include battery electric storage, H_2, methane and ammonia storage, and heat/cold storage. A dimensioning of the storage requirement and the integration into the supply infrastructure takes place on a higher physical level and flows into the modeling of the digital twin.

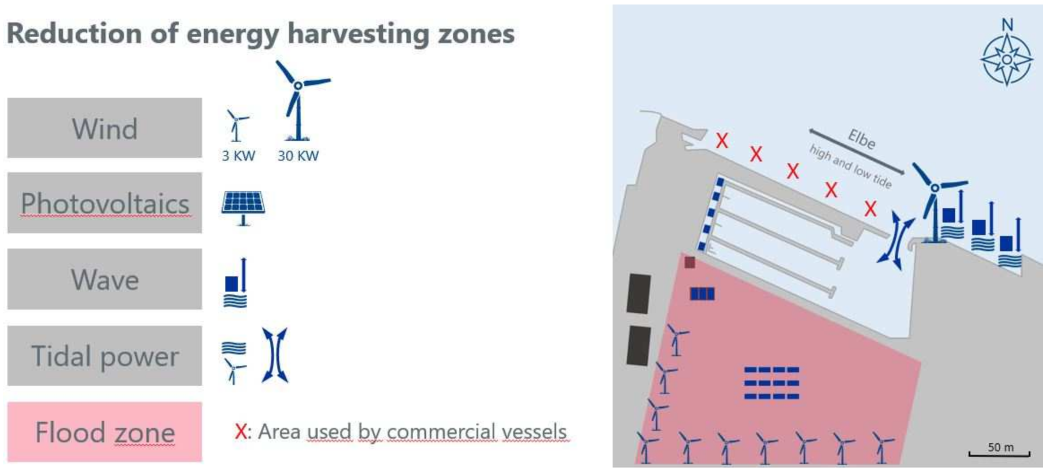


Figure 3: Result of area analysis including technological aspects

4.1.1 Energy sources

The energy transition will result in diesel fuel and heavy oil losing their role as an energy source in shipping. For this, H_2, ammonia, methanol, LNG and CNG will become more important. Since it is not yet clear whether one of these energy sources will play a dominant role in the future, both in shipping and in the processing industry, all these substances should be included in a new energy concept of ports.

	Unit	Diesel	Methanol	Ammoniak	LNG (liquid)	CNG (compr.)	H2
chemical formula		$C_{12}H_{23}$	CH_3OH	NH_3	CH_4	CH_4	H_2
Gravimetric energy density	kWh/kg	12,6	5,5	4,8	10,6-13,1		10,6-13,1 33,3
Volumetric energy density	kWh/l	10,5	4,3	0,003			0,003
General properties		toxic	toxic	highly toxic, explosive when heated	non-toxic, greenhouse gas, highly flammable, explosive in combination with air/O2		non-toxic, very reactive at high temperatures, highly explosive in combination with air/O2
Use		Internal combustion engines	chem. Intermediate, fuel cell	chem. Intermediate, storage and transport medium for H2	Internal combustion engines, heating		Internal combustion engines, fuel cell
Storage		Liquid tank	Liquid tank	Liquid tank	Freezer tank	High pressure tank	gaseous in high pressure tank

Table 1: Energy sources

Accordingly, appropriate storage facilities must be provided and simulated. In the case of H2 and LNG or CNG, storage must also be provided for the aggregate states gaseous, and liquid and the thermal behaviour must also be controlled. Electrical or electronic monitoring (functional safety) of the accumulators, since each material has specific critical properties (see table 1) and thus a corresponding safety must be guaranteed, which, as a rule, cannot be achieved solely through mechanical measures.

Ammonia as an energy source has a special dual role: on the one hand, it can be used directly as an energy source in marine engine combustion and on the other hand, it can be used as a liquid carrier material of H2. This transformation process must also be monitored and energetically optimized accordingly. There is no alternative to the use of a digital twin for the energy optimized orchestration and provision of all mentioned chemical energy sources.

4.2 Requirements Analysis

The collection and use of demand data is essential for optimum design and efficient operation of a port's energy system. The energy requirement has a direct influence on the required storage capacity, since the storage unit is intended to compensate for the time offset between energy generation and energy demand and to smooth out any peaks that occur. Since various forms of energy occur within a port, the first step is the collection of the relevant forms of energy. The following classification is recommended for systematic collection:

Propulsion energy of ships	**Auxiliary energy of ships (hotel)**	**Energy for port infrastructure**
Electric	Electric	Electric
Chemical	Chemical	Chemical
…	Thermal	Thermal
	…	…

Table 2:Classification of energy forms

In the next step, the energy demands are quantified and temporally resolved. As a rule, there are timetables for the ships from which the drive energy demand can be derived. For the planned waiting time, the ship-specific hotel demands will also be incurred. On the port side, the infrastructure requires energy. In addition to the base load, there are demands for the logistics applications that depend on the loading/unloading of the ships and thus correlate with the timetables.

Finally, the energy demands for each energy type are synthesized to form an overall demand profile.

The system design is based on the demand and generation profiles. Depending on the technology used, sectors or types of energy can be coupled. For example, the waste heat from electrolysis processes can be used to provide heating energy. Excess electrical energy can be stored in storage batteries or used to generate heat or cold. The storage of cold and heat is generally more favorable compared to electrical energy storage systems, assumed there is sufficient demand for cold and heat.

4.3 The digital twin of the port

The information and data collected during the analysis phases are now incorporated into the digital model of the port energy system. By modeling the physical behavior of the system as a digital twin, the interactions between the components are made transparent and the data collection effort is also reduced. Different system topologies are mapped, simulated, and evaluated using performance indicators such as total costs, energy efficiency or degree of self-sufficiency. The robustness and sensitivity of the system can also be evaluated by varying the input parameters.

After the design phase has been completed, the digital twin provides important information for the energy management of the real system. Decisions in storage management are simulated using the timetables and forecasts for energy generation and energy price development. The digital twin calculates the future energy storage levels. Charging and discharging as well as generation and conversion between different forms of energy are optimally regulated according to the requirements.

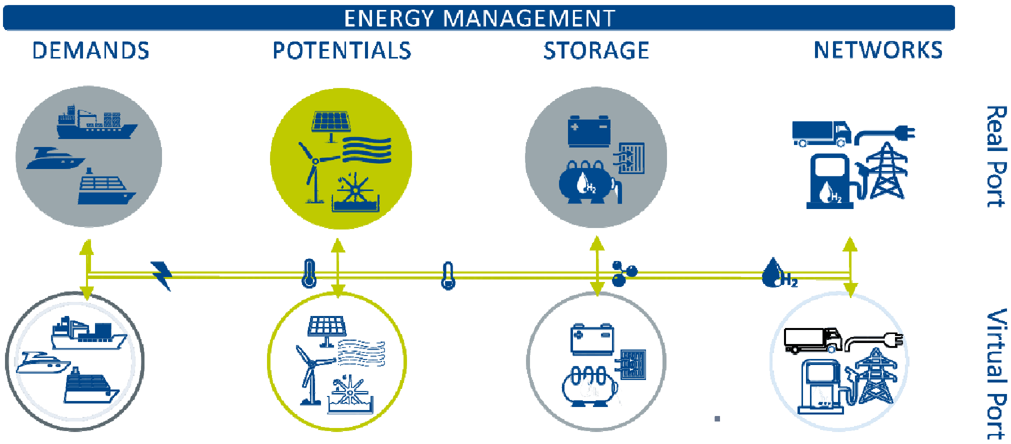


Figure 4: The digital port twin

Figure 4 shows the typical real and virtual objects and their diverse relationships and interactions of a port twin. The respective characteristics for a specific port are very individual, even if individual objects such as a PV system or an energy storage unit can occur repeatedly as a module in the modeling. A port is a complex system consisting of energy, goods and mobility flows and systems and can be controlled by a virtual system.

4.4 Use of the digital twin for optimization in all phases of the port life cycle

Our approach is a first step to use the digital twin in all phases of the life cycle of a port for optimization. The life cycle of a port can be easily divided into three phases.

Phase1: Planning of investments and structural measures => the decisive added value of the digital twin lies in securing the investments through previous simulation.

Phase 2: Operation of the overall system => Real-time data is used in the digital twin to optimize the overall system regarding energy efficiency and costs.

Phase 3: Continuous optimization and automation => through continuous expansion and optimization of the digital twin, the path from decision-making to automated operation of the energy system becomes possible.

The digital twin offers clear benefits in each of these phases. The following examples explain how we can use the digital twin profitably in the three phases.

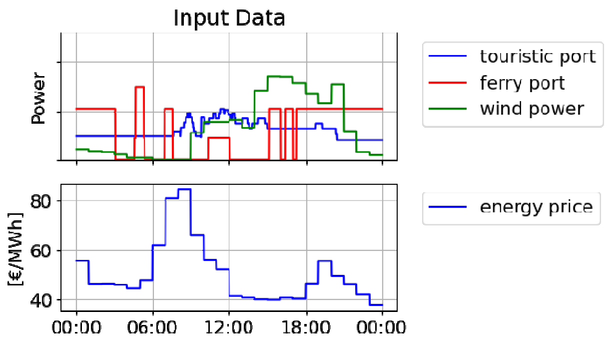
In planning, new technology and investment decisions can first be modelled with the digital twin and then their impact can be estimated thanks to AI prediction. “First modelling then investing” is quite easy with a digital twin, even with highly individual requirements. Different scenarios can be simulated, and the respective benefits shown. Not yet identified scenarios can be derived through such model-based data analysis and developed and prioritized in the form of use cases.

In the company, decisions must be made to ensure stable and economical operation. Experienced personnel usually make the decisions. The digital twin supports this by using real-time information. A digital twin can provide AI-based strategy and action recommendations for optimal operation and thus raise additional potential. The continuous further development of the digital twin with AI-supported algorithms offers the opportunity of automation and thus a far-reaching relief and Support.

In ports, for example, the smart use of stationary or mobile energy storage or land power units, the use of volatile energy sources as well as the flexible assignment of ship berths. By cleverly combining these areas, potential can be tapped to significantly reduce CO_2 emissions and air pollutants. Thanks to self-learning algorithms, the twin is constantly improving without neglecting stable operation.

4.5 Two modeling examples for the digital twin of the port

Using two concrete examples, we illustrate the added value of the digital twin in the planning and operation phase. By way of example, figure 5 shows the electricity demands for a small ferry port and a port with tourist excursion boats as well as the electricity yield of a wind turbine, supplemented by the electricity price profile of a day from the year 2020. It is already clear here that demand, income, and electricity prices differ considerably in size and timing depending on the scenario. In the current situation, electricity prices are once again more volatile and at a significantly higher level.



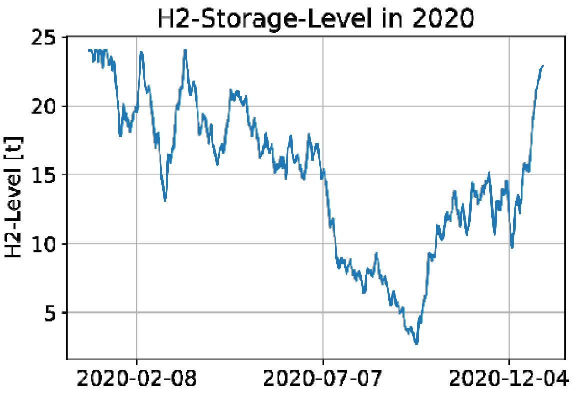


Figure 5 (left), Figure 6 (right).

In another scenario, a wind turbine feeds an electrolyser. The hydrogen produced is used to refuel ships. The demand for hydrogen is distributed quite evenly over the entire year, although there is a slightly higher demand in the summer. The average annual production of the electrolyser and the annual hydrogen demand are almost the same. Nevertheless, a large hydrogen tank is required, which is completely emptied during the calm months in the summer and filled up again in the autumn and winter months with lots of wind. The hydrogen tank level can be seen in figure 6. This illustrates the complex interaction between generation, storage and consumption.

4.6 Outlook

Ports will have to find further business models in the future to be able to compete, but also to identify new sources of income. A digital twin can be used to work out complex interrelationships and new correlations, if required also derive cross-domain business models. AI-based algorithms are used to detect even the most complex correlations, based on which new business models can then be developed.

5 CLASSIFICATION, OPPORTUNITIES AND MATURITY LEVEL OF THE APPROACH

The presented concept represents an important contribution in the context of digitalization with the aim of a CO_2-neutral port. Digitalization has already found its way into energy systems and their management in many areas. There are several projects that have overcome the first important hurdles and thus established a basis for use through the collection and monitoring of data. We see our approach as a holistic method that can build on these foundations, if available.

In addition to the holistic approach, our approach is characterized by the combination of AI and physical modeling. This combination is the important basis for stable energy management. Compared to purely AI-based approaches, our approach is less dependent on existing training data.

In principle, neural networks are very well able to map the relevant relationships. In practice, there is often a lack of quality and quantity of training data. In addition, in practice, edge cases for instability should be avoided as far as possible so that even fewer measurement data are available for these operating statuses. At this point, the combination of AI and physical modeling plays out its strengths. On the one hand, the training effort decreases because the neural network does not have to learn more things that are already implemented in the physical model. On the other hand, the physical model can also be specifically stimulated in order to generate virtual measurement data for the edge cases, with the help of which e.g., the neural network can be trained.

The presented approach is based on a series of methodical elements such as data analysis, physical modeling, optimization algorithms and other AI methods that have been tried and tested at ITK Engineering GmbH for many years. We can build on an ITK-own and proven modelling and optimization framework.