Enhancing Energy Efficiency and Dynamic Carbon Footprint Calculation at Container Terminals

Ignacio Benítez[1], José A. Giménez[1], Francisco Blanquer[2] and Ángel Martínez[3]
1.Fundación Valenciaport, Valencia, Spain
2.CMA CGM, Marseille, France
3.Prodevelop, Valencia, Spain
Corresponding author: nbenitez@fundacion.valenciaport.com

Abstract: *The paper presents the results of the proof of concept (PoC) developed in the scope of the iTerminals 4.0 Project, to achieve a real-time calculation of the carbon footprint generated in port container terminals. iTerminals 4.0 is an innovation project co-funded by the Connecting Europe Facility Program (CEF) of the European Commission, with the objective of deploying and implementing the necessary concepts, tools, and systems to enable digital*

comprises a study with pilot deployments in real operations at European port-container terminals, focused on digitization of port operations and adoption of Industry 4.0 technologies within the container-handling sector. A wide range of transversal benefits is expected from the digital transformation of container port operations, like operational efficiency increase, safety and (cyber) security improvement, costs reduction and carbon footprint decrease, to name only a few.

Keywords: *Port Container Terminals, Process Standardization, IoT, Big Data, Carbon Footprint, Key Performance Indicators, Energy Efficiency*

Conference Topic(s): *Communication, networks; interconnected freight transport; logistics and supply networks; material handling; ports, airports and hubs; technologies for interconnected logistics (5G, 3D printing, Artificial Intelligence, IoT, machine learning, augmented reality, blockchain, cloud computing, digital twins, collaborative decision making).*

Physical Internet Roadmap *(Link): Select the most relevant area for your paper:* ☒ *PI Nodes,* ☐ *PI Networks,* ☐ *System of Logistics Networks,* ☐ *Access and Adoption,* ☐ *Governance.*

1 Introduction

Port container terminals and their logistic infrastructures are essential to keep the European Union (EU) in the leading position of world-developed areas. The impact of this strategic sector in the quality of life of European citizens and in the EU competitiveness is crucial, as freight transport is a powerful key driver for job creation and economic growth. Promoting innovation on efficiency, sustainability and safety of the port-container industry is a fundamental issue.

The significant economic growth before the global financial crisis and the increase of cargo volumes have driven maritime ports into developing their capacities in unexpected ways. Infrastructures, services, and equipment have achieved a significant development of capabilities and complexity. This evolution has provided remarkable benefits for the performance of container handling and logistics. However, operational missing links and bottlenecks remain, resulting in significant negative effects like performance inefficiencies, labor accidents, increased energy consumption as well as pollutant and greenhouse gas emissions.

In parallel, the development of the 4th Industrial Revolution in the last decade (Industry 4.0) has progressively deployed new concepts that, with different degree of adoption, are currently adopted in strategic sectors (automotive, heavy industries, energy, health, etc.) (Madsen, 2019). The adoption of concepts like Internet of Things, Big Data, Artificial Intelligence, Cloud Computing, Robotics and Automation is transforming the industry and society. The port industry, however, is not taking advantage of the benefits and impacts derived from the digital transformation due to the low degree of implementation of such technologies and digital solutions.

Fast advances in information technologies and in particular, digitization, machine learning and Internet of Things have created new possibilities for the cargo handling industry, that could improve processes by connecting all equipment and systems in real time, thus enabling seamless data exchanges. Under these new conditions, more automated and inter-operable solutions could be achieved by the sector with less risk, at a lower cost and faster lead-time, thus allowing universal connectivity of port equipment regardless of the type of manufacturer.

iTerminals 4.0 (Application Of Industry 4.0 Technologies Towards Digital Port Container Terminals) is a project awarded in mid-2018 by the **Connecting Europe Facility Programme** of the European Union that has studied and tested the implementation of the 4th Industrial Revolution concepts in the Port Container Terminal Industry. The iTerminals 4.0 project addresses this gap and comprises the study and pilot deployment in real operations at European port-container terminals of Industry 4.0 technologies within the container-handling sector. The Pilot described in this article is a Proof of Concept (PoC) of how the data can be used to provide this added value regarding energy efficiency and carbon footprint monitoring at TEU or container granularity level and in real time.

Addressing the CO2 emissions and carbon footprint at a container terminal is not an innovative concept. Previous research in this sense can be found in the literature. There is, for instance, the work of Van Duin and Geerlings (2011), that provide a methodology to predict CO2 emissions on a yearly basis at container terminals, based on estimates of energy consumption patterns for each type of machine used in container handling. Vasanth et al. (2012) performed a study of CO2 emissions by type of machinery and Scope (1, 2 or 3) for a complete year. Prayogo (2019) proposed an approach of dynamic modelling and optimization of CO2 emissions in container handling operations for one year, based on estimates of carbon footprint per handled container for each type of machine at the terminal. More recently, Budiyanto et al. (2021) have developed a methodology to estimate CO2 emissions at a container terminal, based on data of energy consumption and estimates of consumption per move or cycle for each type of machine. The article presented is built on the same foundations as these previous works, having as the objective in this case **the carbon footprint for each identified handled container** within the terminal, **in near real-time**, thanks to the development implemented in the context of the iTerminals project. With this information, a terminal operator can devise specific KPIs to aggregate the information and observe its evolution through time, with a granularity of seconds, if needed. The information is processed and served directly from the data being monitored from all the machines involved in container handling, therefore it is not a statistical value, nor a monthly average based on energy bills, but an actual, dynamic and real measurement.

2 The TIC 4.0 model. Definition and objectives

The iTerminals 4.0 project has developed its Proof of Concepts (PoCs) applying the common data model and semantics defined by the Terminal Industry Committee 4.0 (TIC 4.0[1]). The TIC

[1] https://tic40.org

4.0 initiative aims to bring together representative companies from both the Terminal Operators Industry, Port Equipment Manufacturers and Digital Solution Providers to collectively work on the elaboration of port terminal standards, with the objective of defining and agreeing on a **common language** and process definitions among the agents involved in the cargo handling industry. Moreover, this initiative has facilitated the **interoperability** of different information sub-systems of a cargo handling facility in a seamless way.

Due to separate development in the first decades of containerization of terminal operation solutions in several regions around the world, there is not a single definition for processes or machine movements at the terminal. A multitude of varying descriptions can be found with different words, sentences, protocols, languages for the same unique physical element, making it unusable for virtual representation and use of new technologies. For example, the word “Move” is used in all areas of terminal operations and can refer to certain parts of the process and certain units being handled i.e. at the Berth, STS, Yard, Gate, Port or Terminal and Box, TEU, Reefer, Over height Load etc. With Port Equipment the word “Cycle” has different meanings depending on the equipment and brand i.e. for STS, ASCs, RMGs, RTGs, Straddle Carriers, Reach-stackers, Spreaders, Terminal Trucks, AGVs, etc.

This challenge has been taken up by the industry stakeholders with the foundation of the Terminal Industry Committee 4.0 (TIC 4.0) to properly define unique physical elements using a common agreed language/vocabulary for virtual transformation, as can be seen in the conceptual image depicted in Figure 1.

In the context of the iTerminals 4.0 project, the TIC 4.0 communication architecture (see Figure 2) has been implemented and tested in different port container terminals in the EU, such as Malta Freeport, Thessaloniki, Dunkirk and Montoir terminals, as well as PSA Antwerp, Sines and Genoa. In this architecture, the IoT gateways deployed at each Container Handling Equipment (CHE) gather and circulate real-time information to a central node where a Big Data platform is located, so that specific Key Performance Indicators (KPIs) can be computed in real-time and visualized in different dashboards in order to deliver to the container terminal staff useful insights regarding the cargo handling performance.

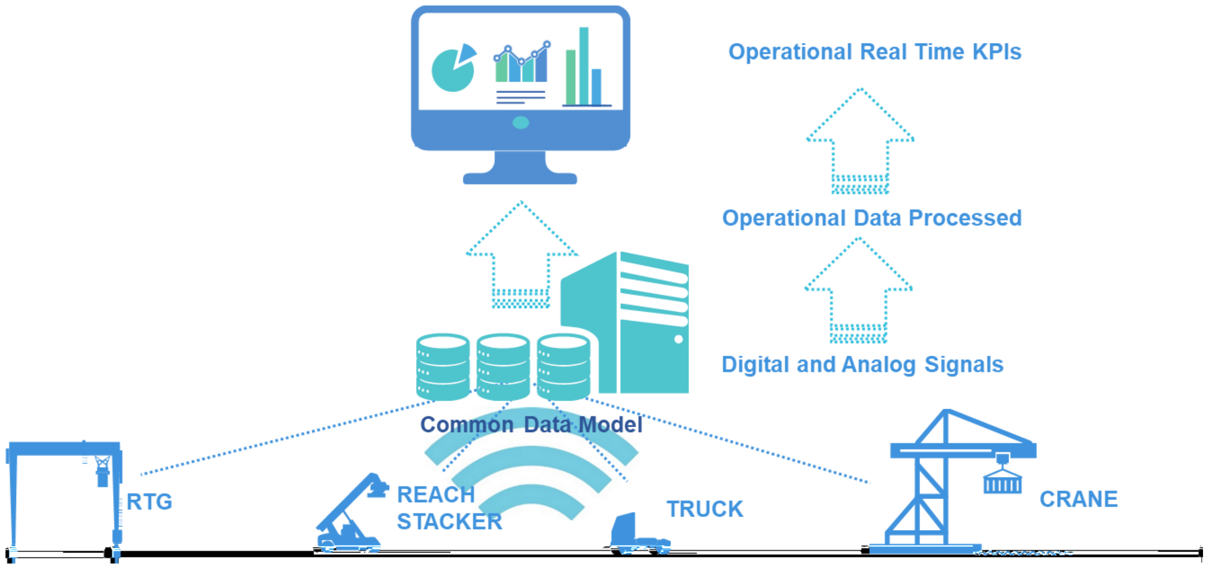

Figure 2. iTerminals 4.0 communication architecture

3 Energy Efficiency and Carbon Footprint Pilot

Besides the improvement in the operational processes, thanks to highlighting bottlenecks and idle times in the CHEs, the TIC 4.0 communication architecture in a container terminal opens a wealth of opportunities for the development of new value-added services. In the context of a transition at the EU to a zero-emission maritime transport and a carbon neutral economy by year 2050, one of the most promising ones is to estimate and compute a real-time **dynamic carbon footprint per each specific handled container**. The carbon footprint (in gCO2 per kWh), the total energy used (in kWh), and the total energy cost (in €) can be calculated in a straightforward way, assigning to each manipulated container a unique carbon footprint value generated during its handling. The data is provided by the iTerminals 4.0 communication architecture, and it is the real-time data monitored by each CHE handling the container, therefore it is the real energy used in handling each specific container. The diagram in Figure 3 illustrates this approach.

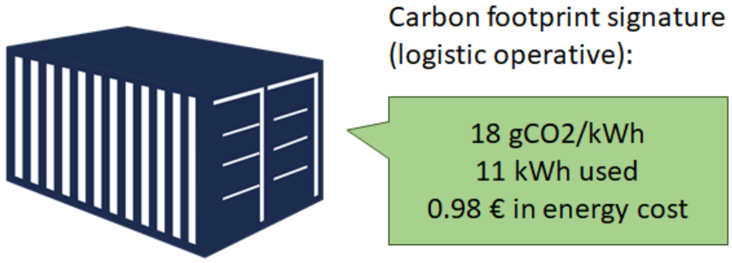

Figure 3. Example of container carbon footprint signature.

A key variable in these analyses is the value of the carbon footprint of all the energy sources used in the terminal. In most of the cases, this input is limited to two main sources of energy: diesel combustion engines, usually used by Rubber-Tyred Gantries (RTGs), Terminal Tractors (TT), Reach Stackers (RS) and other machinery used for container handling; and electricity supply from the grid, mainly for Ship-To-Shore (STS) cranes and minor consumers as offices and lighting. Identifying the carbon footprint for these sources of energy is the core of all the subsequent KPIs related to energy efficiency and carbon footprint being analysed.

Regarding diesel fuel, the carbon footprint will be a fixed, constant value, that may vary as a function of the Port, the machine, or the fuel supplier. Regarding the electricity supply coming from the grid, however, the carbon footprint may vary through the day, depending on the following factors:

1. Typically, the electricity production mix of a territory will match the variable demand through the day, switching on and off fossil-fuelled production plants considering the variability of the intermittent renewable energy plants (such as wind and solar). The carbon footprint of the electricity consumed will therefore not be constant, varying as a function of the contribution to the energy being produced from these pollutant production plants.
2. If the terminal has contracted an electricity supply with a green certificate from a retailer, it could be assumed that the carbon footprint is zero, although this may not be the case, unless the energy has a unique, direct supply coming from a renewable energy production plant nearby.
3. The port or the terminal may have a renewable energy production plant located at their premises, feeding the port's electricity grid with renewable energy. In this case, given that the electricity grid at the port is not isolated from the distribution grid, how this production plant contributes to lower the carbon footprint of the energy mix should be studied.

Given that the carbon footprint of the electricity grid varies with time, the platform should be prepared to input variables that may change their values dynamically through the day. It is therefore necessary to address whether this dynamical information regarding the carbon footprint is available or not. In some countries, such as France, the information of the carbon footprint is available in real time through an API[2] and can also be visualised by means of a web interface[3]. This value is computed for each fifteen-minutes step, having therefore 96 different values available per day. It must be noted, however, that these carbon footprint values are calculated from fuel consumption of energy sources only in French territory, therefore international interconnections are not considered.

Spain, for instance, implements another API[4] that gives carbon footprint and total emissions from each pollutant source, allowing as well to visualise the data by means of a web interface[5]. The carbon footprint value provided in this case is a daily average, computed as the quotient between the total emissions from pollutant sources in the day, by the total energy produced by energy sources (both renewable and non-renewable) in the Spanish territory. It can be noted, again, that the computation is not including international interconnections.

Regarding Malta, one of the Pilot locations, no information on the carbon footprint is available in real time. The Maltese Distribution System Operator (DSO), Enemalta, publishes an annual

[2] https://opendata.reseaux-energies.fr/explore/dataset/eco2mix-national-tr/information/?disjunctive.nature
[3] https://www.rte-france.com/eco2mix/les-emissions-de-co2-par-kwh-produit-en-france
[4] https://www.ree.es/es/apidatos
[5] https://www.ree.es/es/datos/generacion

report with the average carbon footprint in the electricity supply, calculated for the whole year, being the last provisional value available for the year 2019[6]. Malta's electricity supply has a mix of around 68% coming from natural gas plants, 7% from renewables, mainly photovoltaic plants, and 25% imported from a high voltage interconnection with Sicily (Italy).

3.1 Proof of Concept of Dynamic Carbon Footprint and Energy Cost per Container

3.1.1 Carbon footprint per container

In order to compute the carbon footprint, the platform must be able to group all the cycles from all the machines (CHE) that have operated a given container. Each cargo (i.e. container) has a unique ID, and has been identified using the following variable from the TIC4.0 data model: **che.cycle.cargo**. Once grouped under a same cargo ID, the energy or fuel consumption from each cycle and machine that participated in moving the cargo is read, including the energy used while these machines were idle in the cycle. The energy used is available in the TIC 4.0 data model, with the following notation: **che.cycle.energy.consumed**. Different units can be found (see Figure 4).

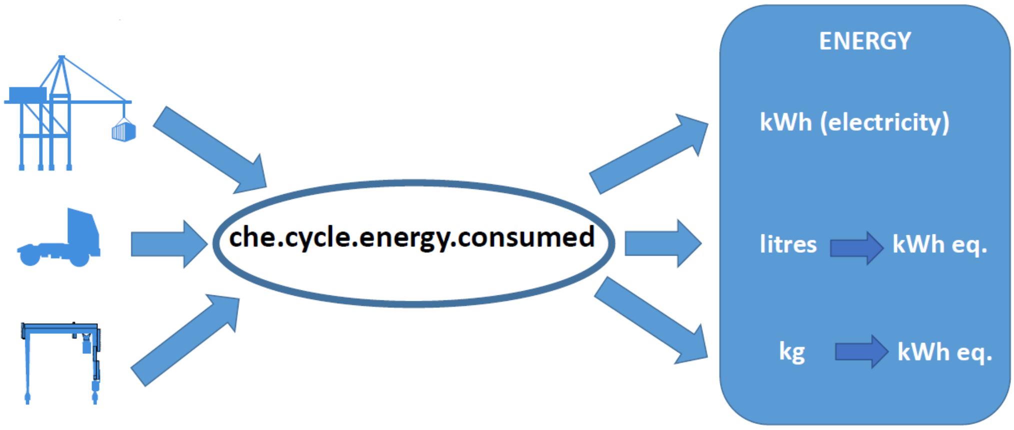

Figure 4. Measure of energy consumption using TIC 4.0 data model.

Once the energy consumption needed by each machine to move a single container is obtained, the following steps are followed:

1. A cost to each energy source (€/kWh and € per litre of gasoil) is assigned.
2. Litres of diesel used are converted to equivalent kWh.
3. Total emissions from each energy source (g CO2) are computed.
4. The following values are calculated:
    a. Total energy used (kWh)
    b. Total emissions (g CO2)
    c. Total cost (€)
    d. Carbon footprint (g CO2 / kWh)

This way, the carbon footprint for each cargo (container) is obtained. Besides, the information can be even more disaggregated if it is considered of interest. For instance, **per operative**, i.e., a carbon footprint could be calculated only for loading/unloading operation, or for

[6] https://www.enemalta.com.mt/environment/fuel_mix_for_energy_distribution/

housekeeping operations. The different moves, in the case of cranes, are also measured using TIC 4.0 data model, therefore it is possible to apply the same steps commented to calculate the carbon footprint per container only for the targeted operation.

3.1.2 Key Performance indicators

From the individual carbon footprint signatures of all the containers, some key performance indicators and other variables have been computed. In the context of this Pilot, different indicators and variables have been grouped in three different levels: terminal, service or container. Indicators at **terminal** level indicate the overall progress of the terminal in terms of energy efficiency and carbon footprint:

1. KPI on **global carbon footprint per physical container**. Computed as a rate, obtained as the quotient between the sum of total carbon footprint signatures of all the containers, divided by the number of containers passing through the terminal.
2. KPI on **global carbon footprint per weighted Tonne**. Similar to the previous one, in this case the rate is obtained per weighted tonne, given that the weight of all the containers is being measured and the data are available.

The first KPI is obtained from the information previously calculated of the carbon footprint per container. This information should be available for the desired time interval for this KPI (e.g. the last day, the last month, the last year…). There is an additional variable needed, the number of containers, to compute the average. Therefore, for the time interval, the number of containers must be extracted from the Big Data platform.

Further segmentations of the containers can be performed, for data mining purposes. For instance, containers can be classified in categories such as import/export, transhipment, or hinterland. The global carbon footprint can then be calculated and evaluated separately for these three groups.

Regarding the KPI per weighted tonne, in this case the procedure is slightly modified. For each single container, its weight is needed. This information is available in TIC 4.0 from the cycle performed by each CHE, making use of any of the variable **cargo.weight.net,** available in the TIC 4.0 data model.

The **service** refers to the regular lines of container vessels, following regular routes of container transport. With the carbon footprint signatures from all the containers, classified into the different services at the terminal, **global carbon footprint signatures per service** can be computed (see Figure 5), allowing to differentiate between ECO from non-ECO lines, and providing the hints to further investigate on the reasons behind the rank obtained by any specific service.

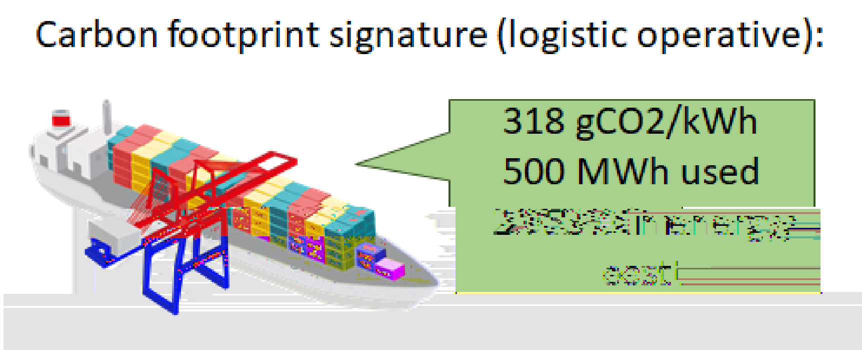

Figure 5. Example of real-time service level carbon footprint signature

In order to compute this KPI dynamically, **all the different containers (cargo) should be linked to a specific line or service**. Once the carbon footprints are obtained, the containers are aggregated by service, and the KPIs is obtained for each group. An average carbon footprint per container belonging to the same service can be also calculated and visualized. This information is available in the following TIC 4.0 variables: **cargo.line** and **cargo.service**.

3.1.3 Energy Label at Container level

Indicators at container level can have, as previously indicated, an individual **real-time carbon footprint signature**, that comprehends the dynamic carbon footprint, the energy used in each container handling and the cost associated to that energy.

Besides this result, however, this indicator can be used to compute a different variable with an added value, which is the **real-time energy efficiency label per container**, regarding its transport and logistics chain, very similar to, for instance, domestic appliances, with the main difference that, in this case, the labels are calculated continuously and can vary through time, allowing a number of future uses and applications (see Figure 6 as an example).

Figure 6. Example of real-time container logistics energy efficiency labelling.

The EEI (Energy Efficiency Index) for appliances, as defined by the European Commission, is usually obtained as a ratio between the annual energy consumption and a standard annual energy consumption from an appliance or load of the same type[7].

In this case, however, the time required to move each container varies; therefore, the first step is to obtain an equivalent measure of the work used to move each container per unit of time. This means that the total duration of the cycle for each cargo or container is needed. The following variables contain this information: **cycle.start.time.timestamp** and **cycle.end.time.timestamp**. Having the duration available, the procedure to compute the labels is the following:

1. Set the temporal window to compute the labels (e.g. the last day, the last month, the last year…)
2. Obtain from each container (cargo) the following information:
    a. The total energy consumed in its logistics operative.
    b. The total duration of the logistics operative (i.e. the total duration of all the cycles needed to move the container).
3. Obtain, for each container, the ratio of power per unit of time, as the quotient between energy consumed and duration.

[7] European Commission. (2021). About the energy label and ecodesign. Retrieved from https://ec.europa.eu/info/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and

As a result, values of power needed per unit of time for each container are obtained. These power ratios can now be compared among them and translated into specific energy labels, based on minimum and maximum values of power obtained, or on historical records of these values at the terminal.

3.1.4 Visualization

The strength provided by a common semantics language to describe movements and processes, serves as the basis to calculate and compare KPIs for any container or groups of containers at the terminal. Adding some extra information, such as the energy sources' carbon footprint and costs, allows operators to obtain a clearer view of what is really happening at the terminal in terms of energy efficiency and usage, giving not only the overall picture of the terminal in real-time, but also allowing to discriminate and compare among services and containers. Figure 7 depicts a visualization example of a dashboard with these KPIs, calculated in real-time for groups of containers segmented by areas in the yard.

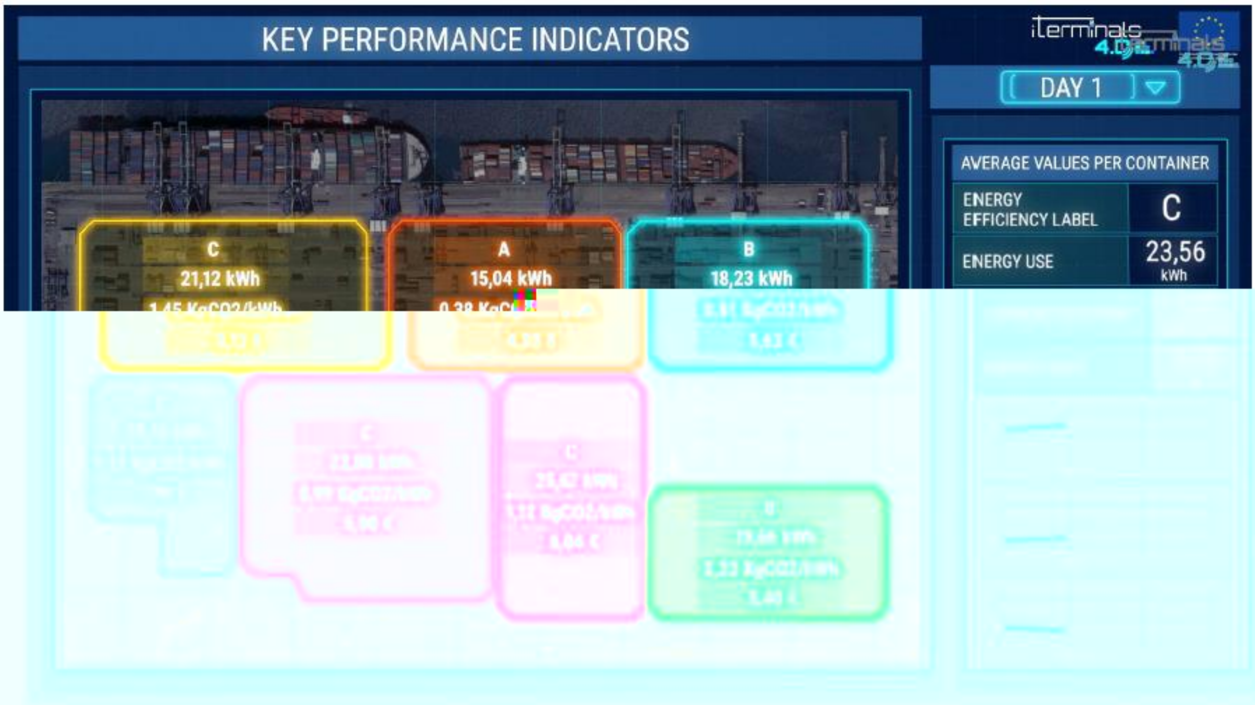

Figure 7. Dynamic Carbon Footprint KPIs grouped by areas at the yard, Malta Freeport container terminal. Dashboard Example.

4 Conclusions

The information on the carbon footprint of the processes that can be currently obtained is restricted by the availability of the data, being these usually scarce, or an average, or available on a monthly or yearly basis. This approach allows a detailed view of the insights of the processes machine by machine, having therefore a better understanding of the CHE behaviour. Thanks to the real time visualization of energy use and cost per cargo and per machine, terminals can derive conclusions on the real energy costs and carbon footprint incurred to each TEU and observe how the indicators evolve with time, evaluating trends and the impact of operational and activity-based cost allocation management decisions. Another benefit of the implementation of the dynamic carbon footprint calculation is the possibility of forecasting energy demand with a variable time horizon.

The iTerminals4.0 project has enabled the standardization of operational data and its implementation in port equipment through IoT technologies and digital platforms, especially developed to fulfil the needs and requirements of a Port Terminal. Having this IoT deployment connectivity, it is possible to study and develop new services and functionalities that provide a higher level of abstraction, built above a common semantics and ontology for container terminals operations, thanks to the telemetry systems that serve the data, and the middleware systems that convert them to uniform, standard and interoperable information. These new functionalities are provided to the terminal operators, allowing them to have an overall view of the container logistic operations in real time, helping them in decision making and providing an insight to the processes and operations that was not available before. This IoT & Big Data ecosystem is the basis which will help the terminals to build on top of this added value services like the dynamic calculation of carbon footprint presented in this paper.

References

- Budiyanto M.A., Huzaifi M.H., Sirait S.J., Prayoga P.H.N. (2021): *Evaluation of CO2 emissions and energy use with different container terminal layouts*. Scientific Reports, v11, 5476.
- Madsen D.Ø. (2019): *The Emergence and Rise of Industry 4.0 Viewed through the Lens of Management Fashion Theory*. Administrative Sciences, v9, no3, 71. https://doi.org/10.3390/admsci9030071.
- Prayogo D.N. (2019): *Carbon emission modelling in container terminal operations planning using a system dynamics approach*. International Conference on Informatics, Technology and Engineering. IOP Conference Series: Materials Science and Engineering, v703.
- Van Duin J.H.R., Geerlings H. (2011) : *Estimating CO2 Footprints Of Container Terminal Port-Operations*. International Journal of Sustainable Development and Planning, v6, no4, 459-473.
- Vasanth M., Chowhan S., Hiremath A.M., Asolekar S. (2012) : *Carbon Footprinting of Container Terminal Ports in Mumbai*. International Conference on Impact of climate change on Food, Energy and Environment.