Smart Transportation Alliance

Durability of ports as a key path to their sustainability

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TABLE OF CONTENTS

1. Introduction: Sustainable Transportation 3
2. Sustainability of ports 3
3. Ports Design: Durability 4
4. Maintenance of port infrastructures, a decision taken during design 5
5. Predictive maintenance 6
   5.1. Indicators 6
   5.2. Monitoring 7
   5.3. Methodology 7
6. Example: Dynaport project 7
7. Conclusions 11

Bibliography 11

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1. Introduction: Sustainable Transportation

Sustainable development can be defined as a process for meeting human development goals while sustaining the ability of natural systems to continue providing the natural resources and ecosystem services upon which the economy and society depend.

In this sense, sustainable transportation can be also defined as the capacity to support the mobility needs of people, freight and information in a manner that is the least 'damageable' to the environment.

In the last decade, a number of voices have vehemently promoted rail and maritime transport as the two most sustainable modes of transport against road transport. The truth is that these authors mainly focus on environmental impacts, neglecting social and economic aspects (*Figure 1*).

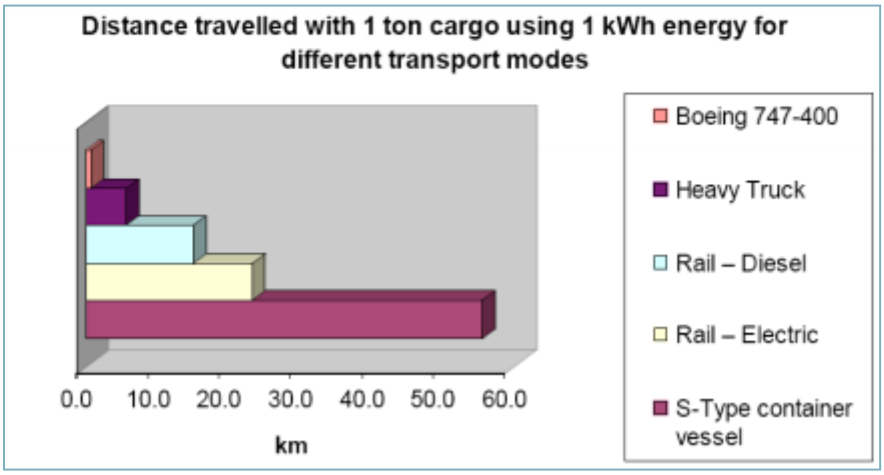

Figure 1: Energy consumption needed to transport 1 ton cargo depending on the mode of transport (source: Maersk Lines)

In practice, other socio-economic criteria such as accessibility, productivity, employment and added value must be assessed when analysing contribution of different modes to global transport sustainability. In short, referring to one mode of transport as more sustainable than others is inaccurate, since all of them are integral components of the same system and in this regards the term "sustainability of transport system" should be used.

Therefore, the purpose of this paper is not comparing the sustainability of ports with other transport infrastructure, or comparing maritime transport with other modes, but rather providing a specific view on how to increase the sustainability of ports.

2. Sustainability of ports

Building a harbour means not only a high economic investment, but also building a permanent infrastructure that will affect future generations -for both the better and worse-. Therefore, before undertaking such an investment, a thorough cost-benefit analysis should be carried out, leaving political criteria behind.

This cost-benefit analysis should compulsorily include an **Environmental Impact Assessment**. When doing so, two kinds of parameters should be considered:

- **Disqualifying variables**, which means that there are some environmental impacts that are *not acceptable*, and therefore the infrastructure is –or will be- environmentally unfeasible (for instance, the presence of endangered natural species that must be protected).
- **Regular environmental impacts**, which are unavoidable impacts that are considered as *acceptable*. These impacts must be addressed as externalities that can be economically quantified and added to the cost-benefit analysis.

If the cost-benefit analysis is favourable, the port will be built. At this point, the key issue is to understand the influence of design in the sustainability of the port along its service life.

A lot of literature exists regarding the sustainability of port operations. As a matter of fact, most of international sea Ports Authorities have developed guidelines for sustainable port development (for instance, the ports of Rotterdam, Antwerp, Los Angeles and Sidney have implemented policies to conduct their port operations in a sustainable and socially responsible way).

To the contrary, the relationship between port design and sustainability of port exploitation has not yet been studied in-depth.

3. Ports Design: Durability

Most of the decisions taken during planning and design stages of ports are irreversible and, consequently, each decision made during these phases will affect not only its construction but also its exploitation. Factors such as the size of the port, its room for expansion, its connection to other distribution 'hubs' or its capability to adapt to climate change will determine how sustainable the port exploitation could be.

Putting all these parameters together is somehow impossible, so it is important to study each parameter individually, analysing its impact to the whole.

In this context, **durability** is a key variable that has a great influence on sustainability and, unfortunately, it is sometimes neglected.

A more durable infrastructure has fewer impacts directly derived from repair and rehabilitation and, most importantly, it means less 'disruption' to exploitation activities.

In fact, durability is a key point in the EU Action Plan for the Circular Economy: *"The Commission will promote the reparability, upgradability, durability, and recyclability of products by developing product requirements relevant to the circular economy in its future work under the Ecodesign Directive".*

Transport infrastructures should not be indifferent to this general principle.

The opportunity cost of maintaining port facilities and structures are high, not only for the port authority but also to the private companies operating them. For this reason, it is essential to design and build durable ports and to develop management systems that support the reduction of maintenance operations.

4. Maintenance of port infrastructures, a decision taken during design

As previously mentioned, designing durable ports is a necessary condition, but not the only one. Maintenance needs must be also estimated and management systems must be implemented to increase the service life of the port.

It is highly important to define a **maintenance plan at the design stage**, preferably based on **predictive maintenance** through real-time measurements. Infrastructures evolve along time in an uncertain way, mainly due to the high variability of external conditions. Three strategies can be implemented to face this uncertainty:

- **Strategy based on a corrective maintenance system.** Corrective maintenance is carried out after failure detection and is aimed at restoring an asset to the conditions in which it performs its intended function. It is obviously the worst strategy among the three for two main reasons:
    - The repair cost is higher. As a rule of thumb, for every 1€ spent on preventive maintenance saves 5€ on corrective actions after ten years.
    - The impact on operation activities is also higher. Corrective activities are usually larger and they involve bigger equipment and machinery. As a consequence, it is highly probable that the exploitation of port installations is also highly impacted and the opportunity costs rise exponentially.
- **Strategy based on a preventive maintenance system.** Preventive maintenance is driven by time, metre, or event-based triggering. Maintenance tasks are pre-determined based on a number of factors including experience, age, recommendations, etc. It is assumed that the infrastructure will degrade within a time period that is common for its type. Under a preventive management approach, the relevant parts of the infrastructure will be replaced or rebuilt before the expected failure point.
    - The main issue with a preventive maintenance approach is that the way an infrastructure is used directly impacts on the operating life of the infrastructure. In many cases, maintenance tasks are undertaken when there is no need for them. Therefore, this approach can sometimes result into unnecessary maintenance.
- **Strategy based on a predictive maintenance system.** This is definitely the best strategy, since predictive maintenance is determined by the condition of infrastructure rather than average or expected life statistics. Essentially, this methodology tries to predict the failure before it actually happens by directly monitoring the infrastructure along its service life.

While **predictive maintenance** strategy generally has the **highest maintenance cost**, it will result into the **lowest repair costs**. To the contrary, corrective maintenance strategy has the lowest maintenance cost but the highest costs associated with infrastructure repairs.

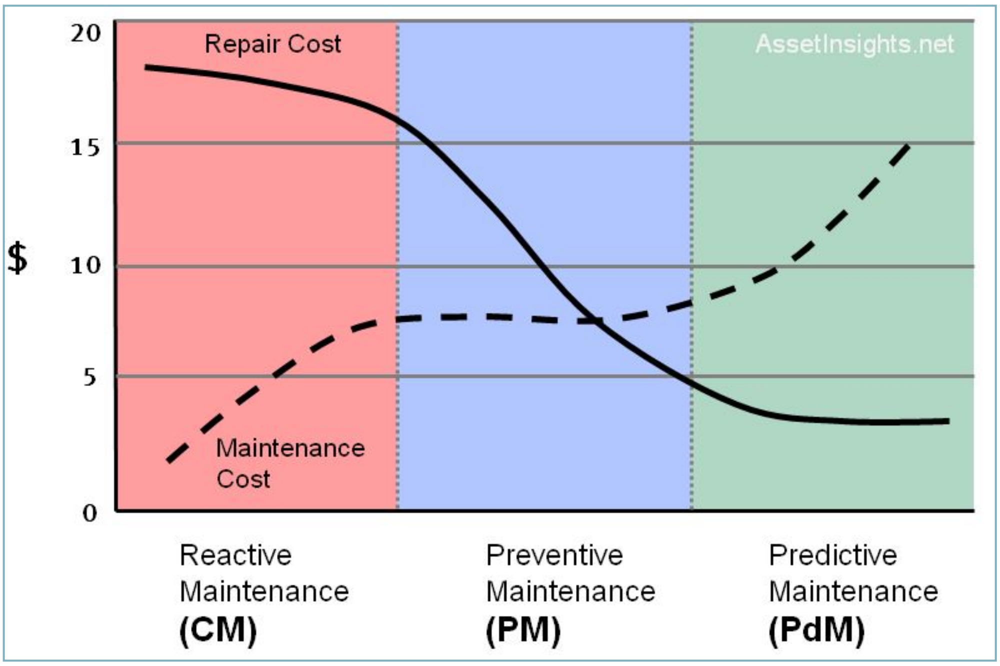

Figure 2: The correlation between the maintenance costs and repair costs associated with the three different maintenance strategies (Source: asset insights.net)

5. Predictive maintenance

The decision of following a predictive maintenance strategy must be made during the design stage and implemented during construction. This strategy is based on real-time information and it consequently requires monitoring systems. Sensors must be embedded inside the infrastructure to collect as much relevant information as possible.

The three steps that must be followed to implement a predictive maintenance strategy are:

i. Defining indicators that must be measurable tin order to allow making decisions.
ii. Choosing or developing the necessary sensors to measure previous indicators.
iii. Developing a methodology according to the available information.

Some common indicators and sensors can be defined regardless the port considered; however, as a general rule, it could be stated that each port would require defining specific indicators and sensors depending on their characteristics and situation.

5.1. Indicators

Durability indicators should be at least:

- *Relevant*: they should give information of key aspects of sustainability.
- *Measurable*: they should be quantifiable using available tools and methods; otherwise the information given is not comparable.
- *Robust*: they must be consistently measurable over time, done equally by different observers.

5.2. Monitoring

To define a strategy based on predictive maintenance, it is essential to have **real-time information available**. Continuous measurements are only possible by means of embedded sensors.

The use of sensors presents four main problems:

- **Cabling**: This has been overcome by the use of wireless technologies. However, wireless technologies have the inconvenience of the short duration of the batteries.
- The '**survival'** of the sensor to the construction phase of the structure.
- The **interpretation of the results**, due to the high amount of data collected by the sensors.
- Finally, sensors must be commercial products whose **performance** is already tested.

5.3. Methodology

After collecting and translating data from the infrastructure into useful information, the final step of the predictive maintenance strategy consists of building a decision-making tree where limit values and a number of actions are defined.

This methodology must be based on experience and it is nearly impossible to standardise it.

A classic methodology consists of setting limit values and triggering specific actions when those values are reached.

6. Example: Dynaport project

Dynaport is a research project carried out with the participation of the Spanish Institute of Cement and its Applications (IECA, the acronym in Spanish), that aims at developing a management tool to continuously calculate structural reliability and durability of port infrastructures by means of the definition of specific indicators and in situ monitoring of the infrastructure.

The system covers all different stages of the life cycle and could be applicable to other transport modes.

The management tool was customised to the specific characteristics of the Langosteira super-harbour in La Coruña (Spain).

Figure 3: Langosteira super-harbour (Spain)

For this particular case, the following indicators were defined.

Safety (S) and durability criteria (D)				Project	Construction	Exploitation	Repair
Concrete	Plain concrete		S	Compression strength	Compression strength Elastic modulus	Modulus	
			D	Resistivity	Thermal increase Shrinkage	Resistivity	Modulus Resistivity
	Reinforced concrete		S & D	Corrosion potential Corrosion rate			
Structural elements	Main breakwater	As a whole	S	Movement x, y, z	-	Movement x, y, z	Movement x, y, z
			D	-	-	-	-
		Blocks of the main armour	S	Porosity		Shape evolution	Shape evolution
			D	Thermal gradient	Internal and external temperature	Shape evolution	Shape evolution
		Breakwater crown wall	S	Cracking/m^2		Cracking/m^2	Cracking/m^2
			D	Reduction of steel section	Thermal increase Resistivity	Corrosion potential Corrosion rate	Corrosion potential Corrosion rate
	Docks	As a whole	S	Movement x, y, z	-	Movement x, y, z	Movement x, y, z
			D	-	-	-	-
		Caissons	S	Cracking/m2	Cracking/m2	Movement x, y, z	Movement x, y, z
			D	Reduction of steel section	Thermal increase Resistivity	Corrosion potential Corrosion rate	Corrosion potential Corrosion rate

Table 1: Set of indicators defined for Langosteira super-harbour (Spain)

Although many indicators were defined, only movements and corrosion were monitored due to the technical limitations of sensors.

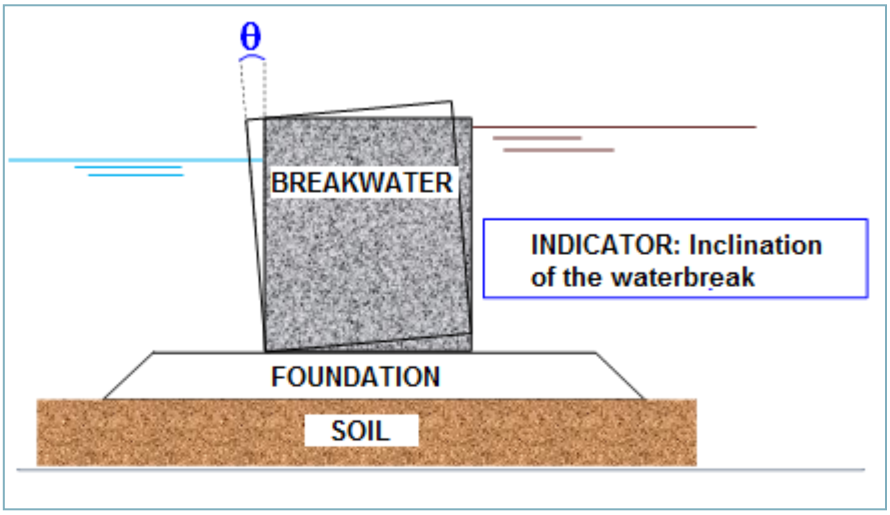

Figure 4: The correlation between the maintenance costs and repair costs associated with the three different maintenance strategies (source: asset insights.net)

Inclinometers were placed along the breakwater to monitor the movement of blocks and ‘caissons’.

For corrosion purposes, two kinds of sensors were used: i) passive sensors, which do not need any electrical current to work, and ii) active sensors, which need an electrical current for measuring.

Passive sensors:

- Corrosion potential: consisting in a Mn/MnO_2 reference electrode.

Active sensors:

- Corrosion rate: consisting of two coupons of reinforcing bar for measuring the Polarization Resistance, Rp. A connection to the main reinforcement is also made for the sake of comparing its potential to that recorded in the two small bar coupons.
- Resistivity: by means of a two parallel stainless steel bars

Figure 5: Installation of corrosion electrodes attached to the reinforcing bars of the caisson

Additionally, sensors for the detection of chloride anions were also placed. This device consisted of two bars with different covers, so that they begin to corrode (measured by detecting changes in the corrosion potential) at different time.

As the distance between both bars is known, measuring the lapse of time between the corrosion initiation between them, the rate of chloride penetration can be calculated.

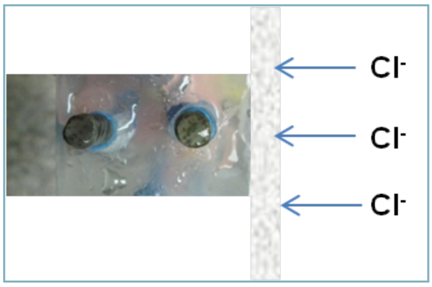

Figure 6: Sensor for chloride detection

Sensors were placed in two different positions within the breakwater:

Figure 7: Position of sensors inside the harbour

Two sensors of every type were placed in each position in order to guarantee at least one measurement for both points.

Finally, temperature of massive concrete blocks and caissons was also measured by means of commercial thermistors.

Although the project finished in 2012, data are still being collected and the methodology to develop a predictive maintenance strategy from the information gathered is now being analysed in another research project.

7. Conclusions

- Monitoring port structures is a complex task; a bad implementation of a predictive maintenance strategy could involve a high investment and a limited amount of information collected.
- Relevant indicators must be selected, and information gathered must be properly analysed to take the right decisions.
- Only when the two previous steps are overcome, a long-term exploitation strategy will be feasible for port infrastructures.

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