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MarRINav

MARITIME RESILIENCE AND INTEGRITY OF NAVIGATION

# D8 Cost Benefit Analysis

21st February 2020

MarRINav is a project delivered on behalf of the European Space Agency

# MarRINav – Maritime Resilience and Integrity in Navigation
# Work Package 5 Cost Benefit Analysis

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## Executive summary

This report outlines the findings of the cost benefit analysis of the MarRINav system-of-systems. It is the output deliverable of *work package 5 – Cost Benefit Analysis* (**WP5**). It integrates the findings from **WP1** – *Maritime Context*, **WP3** - *PNT R&I Technologies and Integration* and **WP4** - *Conceptual PNT Architecture* in an economic model.

The aim of **WP5** is to analyse the economic rationale for investment in the resilient system-of-systems (SoS) identified in the technical analysis in previous work packages.

The CBA considers the central economic case of maritime transportation and assumes that one 5-day wide area outage of GNSS (Global Navigation Satellite System) will take place within the next 10 years, with certainty.

The analysis focusses on container ships only. The economic assumption is drawn upon a selection of **10 major ports** which handle **90.5% of the economic value** attributable to maritime transport of containers. The resilient technologies are selected in order to fully enable maritime traffic around these ports in the absence of GNSS.

The benefits are computed by taking the difference of economic loss from an outage of GNSS between a situation with a resilient SoS based on non-satellite-based sources of position, navigation and timing, and no change from the current scenario.

Costs are estimated with respect to the selected technologies, the amount of necessary infrastructure, and the number of ships considered.

The CBA output is a conservative estimate of the total economic impact of MarRINav using realistic worst-case assumptions. Overall, the net present value is **£221m** and the benefit-cost ratio is **2.2**, suggesting that the solution would be recommended under these assumptions.

Importantly, this result only relates to maritime container transport. This means no other type of vessels and no other transport sector is considered, and no terrestrial users of the timing signals required to deliver MarRINav are considered.

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## Glossary

| | |
|---|---|
| AIS | Automatic Identification System |
| ASF | Additional Secondary Factor |
| BCR | Benefit-Cost Ratio |
| Bn | Billion |
| CAPEX | Capital expenditure |
| CBA | Cost benefit Analysis |
| DfT | Department for Transport |
| DGPS | Differential Global Positioning Systems |
| DLoran | Differential LOng RAnge Navigation |
| ECDIS | Electronic Chart Display and Information System |
| eLoran | Enhanced LOng RAnge Navigation |
| ESA | European Space Agency |
| GIS | Geographical Information System |
| GMDSS | Global Maritime Distress and Safety System |
| GNSS | Global Navigation Satellite System |
| IMU | Inertial Measurement Unit |
| MSF | Three letter code designation of the UK National Physical Laboratory's radio time signal broadcast from Anthorn, Cumbria, UK |
| NAVISP | Navigation Innovation and Support Programme |
| NAVTEX | NAVigational TEleX |
| NPL | National Physical Laboratory |
| NPV | Net Present Value |
| OPEX | Operating expenditure |
| PNT | Position, Navigation and Timing |
| PPU | Portable Pilot Unit |
| PV | Present Value |
| SoS | System of Systems |
| TEU | Twenty-foot Equivalent Units |
| UK | United Kingdom |
| UTC | Coordinated Universal Time |
| VDES | VHF Data Exchange System |
| VHF | Very High Frequency |
| WP | Work Package |

# 1 Introduction

This report presents the findings of a Cost Benefit Analyses (CBA) of the resilient system-of-systems (SoS) defined in other work packages (WP) of the MarRINav project undertaken on behalf of the European Space Agency (ESA) as part of NAVISP (Navigation Innovation and Support Programme) Element 3.

The objective of MarRINav is to define a resilient SoS that can mitigate against the maritime sector's vulnerability to a loss of Global Navigation Satellite System (GNSS) signals as identified in London Economics' 2017 study on the *Economic impact to UK of a disruption to GNSS* and *Satellite-derived time and position, a study of critical dependences* (the Blackett review) from 2018.

The objective of the present report is to investigate whether the SoS offers an economically viable mitigation.

## 1.1 Scope of the analysis

The analysis provides a Cost Benefit Analyses (CBA) for a range of SoS options aimed at mitigating the maritime sector's vulnerability to loss of Global Navigation Satellite Systems (GNSSs), their contributory technologies and conceptual infrastructure.

The CBA considers the central economic case of the wider UK socio-economic benefits. On the one hand, the benefits account for the difference between the loss of economic value resulting from a disruption of the GNSS signal and the loss reduction attributable to the resilient SoS. On the other hand, costs represent the upfront investments necessary to develop and deploy the SoS, annual maintenance costs and other recurring costs.

The CBA builds upon the foundations laid by the previous London Economics study[1] ("the GNSS loss report") and use the same scenario in which a single significant, 5-day GNSS outage occurs over a 10-year period with certainty. **WP1**, **WP3** and **WP4** constitute the core supply of inputs and are supplemented by secondary research.

The maritime sector cannot, however, be viewed in isolation as it depends on land transport operations to move the goods to the end-user (or, symmetrically, to the vessel). For this reason, the CBA must consider the land transport system as part of the analysis. Disruptions to land transport mean there is a (lower) upper limit for the benefits that can be saved by the MarRINav SoS. However, WP4 has identified that the MarRINav SoS, in particular the inclusion of eLoran, can also contribute to resilient PNT solutions for land transport and Timing applications.

[1] London Economics. (2017) *Economic impact to UK of a disruption to GNSS*.

## 1.2 Methodology

In this analysis, we estimate the costs associated with the creation of a resilient navigation system-of-systems (MarRINav) and compare it with the benefit it would provide to the maritime industry and wider UK society. The benefits are the loss avoided due to a GNSS outage, whilst the costs are those of implementing and maintaining such SoS.

In the GNSS loss report, the economic impact of a 5-day outage was estimated at £5.2bn for the UK, of which the maritime industry accounts for **£1.1bn**. If an alternative solution to GNSS is provided to mariners, some of the economic loss is likely to be alleviated.

A **scenario-based approach** is used to estimate the costs and avoided loss of economic value.

Given that benefits and costs are distributed over time, it is necessary to discount their value. We use a discount factor of **3.5%** per year (following standard UK Government practice as specified in The Green Book[2,3]) to compute the net present value (**NPV**). The NPV is the difference between discounted benefits and discounted costs. If the value obtained is positive, it means the project will be recommended. However, if the result is negative, the investment opportunity is not recommended.

$$PV\ Benefits = \sum_t \frac{1}{(1+r)^t} \times B_t$$

$$PV\ Costs = \sum_t \frac{1}{(1+r)^t} \times C_t$$

$$Where: B = benefits\ (£m);\ C = costs\ (£m);\ t = time\ (years); r = discount\ rate\ (\%)$$

The results also include the benefit-cost ratio (BCR) which can be used to compare the relative profitability of projects. A BCR greater than one indicates an economically worthwhile project and a BCR of less than one indicates a project the opposite. In the latter case, it is recommended to look at other alternatives.

## 1.3 Definition of the scenario(s)

**WP1** provides the scenario of a single container on a container vessel in transit from the mid-ocean phase to a port in which a truck picks it up and leaves the port. The scenario is split into 10 activities within which GNSS applications are used to support the navigation. Table 1 summarises these activities.

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[2] Note the discount factor is UK specific. In the case of a broader, European analysis of the costs and benefits it is recommended to apply the EC derived discount factor, 4%.

[3] HM Treasury (2108). *The Green Book.* Available at: https://bit.ly/18GEvvR

| Activities |
| --- |
| Activity 1 – Vessel is making way in ocean phase |
| Activity 2 – Vessel approaches UK coastline, entering coastal voyage phase |
| Activity 3 – Vessel arrives at anchorage, or a pilot station (if pilot required) |
| Activity 4 – Vessel enters port approach voyage phase (w or w/o pilot) |
| Activity 5 – Vessel enter port phase and manoeuvres |
| Activity 6 – Vessel arrives at berth |
| Activity 7 – Vessel's cargo is cleared and unloaded by crane |
| Activity 8 – Container is collected and transported to the stack |
| Activity 9 – Cargo container is loaded onto truck for departure from port |
| Activity 10 – Truck makes way through port and exit port gate |

***Table 1 – Activities of the scenario***

The activities can be grouped by phases of applications:

- **Ocean phase:** activity 1;
- **Coastal phase:** activities 2 and 3;
- **Port approach:** activities 4 to 6;
- **Port operations:** activities 7 to 9; and
- **Road operations:** activity 10.

Each phase has different Position, Navigation and Timing (PNT) requirements and GNSS applications can satisfy these requirements in a different way.

GNSS applications are technologies and systems that ships and stations ashore rely on to ensure safe and efficient navigation. The importance of each application varies throughout the voyage and a failure of applications could compromise its successful completion.

In total, **17** GNSS applications have been identified as critical to complete the voyage in the scenario.

| GNSS applications |
| --- |
| Electronic Chart Display and Information System |
| Global Maritime Distress and Safety System |
| Automatic Identification System |
| Voyage Data Recorder |
| Gyrocompass |
| Radar |
| Engine Management System |
| Satellite Communications |
| Dynamic Positioning Systems |
| VHF Data Exchange System |
| Portable Pilot Unit |
| Ship Clocks |
| Track Control |
| NAVTEX (NAVigational TEleX) |
| Vessel traffic services |
| Cranes and other automated loading systems |
| Road Navigation |

***Table 2 – GNSS applications***

When the GNSS signal is lost, these applications do not function (properly), which puts the voyage at risk. It is necessary to identify alternative PNT technologies that will constitute a resilient solution to overcome the outage.

Several candidate technologies have been introduced in the previous work packages. The table below lists the different PNT technologies selected for analysis in **WP3**.

| PNT technologies |
| --- |
| eLoran |
| Radar absolute positioning |
| Satelles |
| VDES R-mode |
| MF R-mode |
| Locata |
| ePelorus |

***Table 3 – Alternative standalone PNT applications***

Not all these technologies are required in the resilient SoS to maintain maritime operations as normal. But the difficulty to provide a one-size-fits-all SoS arises when taking into account all characteristics of the UK coastline, ports and technical constraints (for instance, time synchronisation methods, bathymetry data, signal coverage, etc.). Due to these differential characteristics, there are several ways of combining technologies at each port.

The major ports in the UK have been identified based on the economic value of the goods loaded and unloaded. We use these locations as references for the analysis. The complexity to deploy resilient SoS increases with the traffic management requirements, the congestion, complexity, size of vessel, topography, etc. It is likely that implementation would be cheaper at smaller ports, so the cost estimation based on major ports represents a conservative, or realistic upper-bound estimate of the total cost.

In 2016, MDS Transmodal published an economic analysis of the ports in the UK.[4] The report presents the total value of imports and exports in British ports. By analysing the value of unitised cargo (Twenty-foot-Equivalent Units – TEU), we can identify the leading ports.

| Port | Import / export value | Share of total import / export value |
|---|---|---|
| Felixstowe | 74.5 | 17.6% |
| Dover | 69.0 | 16.3% |
| Southampton | 58.5 | 13.8% |
| Grimsby | 52.2 | 12.4% |
| London | 45.3 | 10.7% |
| Liverpool | 30.8 | 7.3% |
| Hull | 10.3 | 2.4% |
| Tees | 8.7 | 2.1% |
| Medway | 7.4 | 1.8% |
| Harwich | 6.4 | 1.5% |
| **Total top 10** | **422.5** | **90.5%** |

***Table 4 – UK major ports (unitised import / export value)***

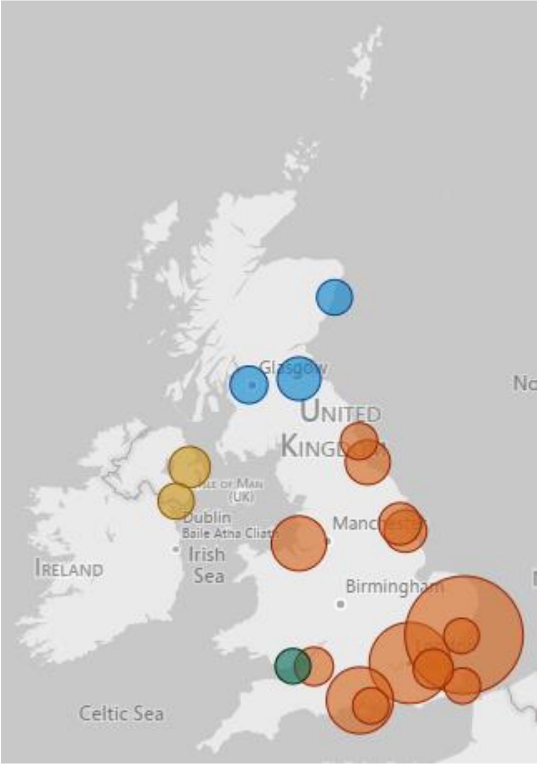
*Source: MDS Transmodal, 2016*

The table shows that the **top 10 ports** handle **90.5%** of the total import / export **value** in the UK.

Interestingly, the data from 2018 (in volume) shows that most of the major ports handling the largest volume of unitised cargo also appear in the table above (in value).

[4] MDS Transmodal. (2016) *The value of goods passing through UK ports.* Final Report

| Major port | Volume (millions) |
|---|---|
| Felixstowe | 2.2 |
| Southampton | 1.2 |
| London | 1.0 |
| Liverpool | 0.5 |
| Tees & Hartlepool | 0.2 |
| Grimsby & Immingham | 0.2 |
| Hull | 0.2 |
| Forth | 0.1 |
| Belfast | 0.1 |
| Medway | 0.1 |
| Bristol | 0.1 |
| Clyde | 0.1 |
| Tyne | 0.0 |
| Portsmouth | 0.0 |
| Dover | 0.0 |
| Warrenpoint | 0.0 |
| Aberdeen | 0.0 |
| Cardiff | 0.0 |
| Harwich | 0.0 |
| Manchester | 0.0 |




***(Left) Table 5 – Volume of unitised cargo by port (units)***
***(Right) Figure 1 – Graphical representation of volume of unitised cargo by port***
*Source: DfT. UK port freight annual statistics*

Therefore, analysing major ports as case study provide a good proxy for the assessment of aggregate costs and benefits.

## 1.4 Caveats and limitations

The study has been carried by independent economists, engineers and specialists of the maritime sector using best practice and expert judgement to build the assumptions of the CBA. We describe the assumptions transparently. The reader should bear in mind the following limitations and caveats:

- Not all the economic value is captured by the scenario. It is approximated using container ships as they carry the largest economic value in and out of the UK. Due to the specific management requirements of containers it was decided to work exclusively with container vessels. For this purpose, we also restrict the loss of economic value to a share less than the £1.1bn estimated in the GNSS loss report. The non-container value like bulk (liquid and dry) or passenger navigation is not included in this study.

- A national, resilient system is difficult to establish as each port and maritime zone have different characteristics and, therefore, one-size does not fit all. We identify one major port as a proxy for the whole UK. The estimation of costs will represent an upper bound since larger ports are expected to require larger capital investments and incur higher operating costs.

- The knowledge about the readiness of some alternative PNT technologies is uncertain. The CBA assume that the technology is ready when it is required.

- We assume that the total economic value at stake is constant over time and that the probability of the disruption to occur is uniformly distributed over time.

# 2 Criticality and adequacy assessment

In mid ocean, in bad weather conditions and without GNSS-based equipment, it is riskier to navigate at full speed without knowing whether there is a ship in the surrounding area. In a port approach situation, the congestion increases and without radar information or AIS systems it can be difficult to navigate accurately and safely.

In both situations, GNSS outage puts the crew and the environment at risk as well as economic value. GNSS applications play different roles in each of the two situations.

The criticality assessment presented in this chapter aims to identify the applications which are critical to navigation at different steps of the voyage. Every GNSS application is assigned a qualitative indicator to measure the impact against each activity.

- A high (**H**) importance means that a loss of GNSS would severely impact the efficiency of the **activity** as the **application** is of high importance and requires GNSS as a critical or sole input, and no alternative of adequate performance is available.

- A medium (**M**) importance means that a loss of GNSS would bring considerable disruption to the activity, however, a) the application (while important) is not essential, or b) non-GNSS assisted ways of achieving the activity are available with difficulty and/or substantially reduced performance and/or significant cost increase.

- A low (**L**) importance means a loss of GNSS in the activity would be easy to cope with as a) the application is of limited (non-zero) importance for the activity, or b) non-GNSS assisted ways of meeting the needs of the use case at adequate performance levels are readily available.

- **0** means the application has no importance for the activity at all.

The efficiency loss (**%**) is therefore estimated by taking into account the importance of every application and has been validated by the consortium's experts in maritime transportation. The total economic impact (value loss) is calculated by applying the efficiency loss (%) to the overall economic loss (€) for containers, based on the estimates in the GNSS loss study[5] (see section 3).

We use a similar approach to assess the **adequacy** of the alternative resilient SoS in the situation **with MarRINav**. The objective is to quantify the economic impact, by estimating the degree to which the resilient SoS can mitigate against the loss of GNSS. A similar qualitative assessment is used, gauging the adequacy of the technology to support the completion of the activity.

[5] London Economics. (2017) *Economic impact to UK of a disruption to GNSS*.

Given the inputs from **WP1**, **WP3** and **WP4** and additional research, we have established the 'heatmap' of the criticality assessment of GNSS applications and the alternative SoS throughout the scenario.

## 2.1 Criticality assessment of GNSS applications. Without MarRINav.

Table 6 present the assessment of GNSS applications against the activities of the scenario.

| | Activity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **GNSS apps** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Electronic Chart Display and Information System | M | H | H | H | H | H | 0 | 0 | 0 | 0 |
| Global Maritime Distress and Safety System | L | L | L | L | L | L | 0 | 0 | 0 | 0 |
| Automatic Identification System | M | H | H | H | L | L | 0 | 0 | 0 | 0 |
| Voyage Data Recorder | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Gyrocompass | M | L | L | L | L | L | 0 | 0 | 0 | 0 |
| Radar | L | M | M | M | M | M | 0 | 0 | 0 | 0 |
| Engine Management System | L | L | L | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Satellite Communications | H | H | H | H | M | M | 0 | 0 | 0 | 0 |
| Dynamic Positioning Systems | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| VHF Data Exchange System | M | H | H | H | L | L | 0 | 0 | 0 | 0 |
| Portable Pilot Unit | 0 | 0 | 0 | H | H | H | 0 | 0 | 0 | 0 |
| Ship Clocks | H | H | H | H | H | H | 0 | 0 | 0 | 0 |
| Track Control | H | M | L | L | L | L | 0 | 0 | 0 | 0 |
| NAVTEX | L | L | L | L | L | L | 0 | 0 | 0 | 0 |
| Vessel traffic services | 0 | 0 | M | M | M | M | 0 | 0 | 0 | 0 |
| Cranes and other automated loading systems | 0 | 0 | 0 | 0 | 0 | 0 | H | H | H | 0 |
| Road Transport Network | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | M |
| **Efficiency loss (without MarRINav)** | **15%** | **60%** | **40%** | **70%** | **70%** | **70%** | **100%** | **100%** | **100%** | **30%** |

***Table 6 – Criticality assessment of the GNSS applications***

Given this assessment, an internal workshop with maritime experts has determined the efficiency loss incurred by a GNSS disruption if MarRINav is not available. Each activity is estimated independently from the others. However, as GNSS disruption would have a bottleneck effect, we consider the total loss of efficiency in the scenario as the **maximum** efficiency loss between activities. In this case, without MarRINav the efficiency loss is total (100%) since activities 7 to 9 cannot be completed.

**Activity 1** is the only activity in ocean phase. Despite being highly reliant on five applications and moderately on three, the loss of efficiency in ocean phase is not substantial. Most of the efficiency loss will materialise in slower, less efficient steaming but the delay incurred is not likely to severely impact the economy. Therefore, we estimate the impact of GNSS disruption to have minimal impact on the efficiency: **15%.**

**Activities 2 and 3** can be grouped under the coastal phase. In this phase the AIS system has greater importance due to increasing congestion as ships approach coastlines. The shallower water will also impact navigation. In case of a disruption, critical navigation tools like radar will likely not be available and captains will rely on visual techniques and charts, which is likely to reduce the efficiency. In **activity 2**, the efficiency loss will be higher than in ocean phase and we estimate it to reach a maximum value of **60%** reduction. **Activity 3** carries an efficiency loss of **40%**. The difference between the two is that the coastal voyage is a challenging task due to proximity with the coast, the shallower waters obliging the vessel to follow a specific path, as well as increased congestion. Activity 2 represents the transit in coastal phase while activity 3 is the transition between coastal and port approach.

**Activity 4** is a pivotal activity. At this point, the ship commencing port approach is likely to require a pilot. Pilots are mandatory if the size of the ship exceeds a certain threshold. Given the scenario, most container vessels will require a pilot, hence we consider a pilot would be needed for this step. Without Portable Pilot Units (PPUs), experts have stated that a second pilot is likely required to assist with manoeuvres and berthing. The efficiency is halved in this case but given the loss of GNSS, it is also likely that a greater proportion of ships will require pilotage, increasing queueing at port entrance. We estimate this efficiency loss to be as high as **70%**.

**Activities 5 and 6** are also grouped under port approach. The ship has now entered the port and is manoeuvring to the berth. These activities do not rely on the same applications as activity 4 but we still consider the reduced efficiency to be of the same magnitude. This is due to similar reasoning. Twice as many pilots are required than with functioning PPU and the congestion within ports is likely to affect the berthing. We estimate these activities to have **70%** impact on the efficiency.

**Activities 7, 8 and 9** are the container handling activities. In this case, the reduction of efficiency is total. Without alternatives, automated cranes will not be able to operate, and the containers will not be unloaded from the ships. The reduction in efficiency is **100%**.

**Activity 10** represents the operations of road haulage. In the GNSS loss report,[6] it was estimated that road transport efficiency would be reduced by **30%.**

In summary, if the GNSS signal is lost, the complete activity of container ships would shut down due to the inoperability of cranes.

## 2.2 Adequacy assessment of resilient SoS. With MarRINav.

In this section we assume that the PNT applications presented in Table 3 are available. As elaborated in the MarRINav Roadmap, **D10**, not all solutions are currently available. The results presented in this report should therefore be viewed as representative of a fully implemented SoS with consideration for the transition period omitted.

Each application has been selected for its ability to provide a resilient solution in the event of a GNSS outage. **WP3** and **WP4** provide good inputs on the technologies and their capacity to support the safe and efficient completion of each voyage phase.

[6] London Economics. (2017) *Economic impact to UK of a disruption to GNSS*.

To assess the avoided economic loss, we need to replicate the efficiency loss estimation from the situation without MarRINav and compute the difference between the two situations with and without MarRINav.

The difference is that, instead of analysing the criticality of the selected PNT technologies, we need to determine the degree to which the technologies can be used as alternative navigation support technologies. Here we gauge the adequacy of the technologies to support the completion of all the activities of voyage.

We define the qualitative indicators as follow:

- High adequacy is understood as a robust technology that meets all the requirements of the relevant applications within the activity.
- Medium adequacy is understood as a technology that does not fully meet the requirements of the relevant applications within the activity.
- Low adequacy is understood as a technology that does not meet the requirements of the relevant applications within the activity.
- 0 means that the technology is not useful in the given activity.

| | Activity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **PNT technologies** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| eLoran | H | M | M | M | M | M | 0 | 0 | 0 | 0 |
| eLoran + DLoran | L | M* | M* | H | H | H | 0 | 0 | 0 | 0 |
| Radar absolute positioning (incl. IMU**) | L | M | M | M | M | M | 0 | 0 | 0 | 0 |
| VDES R-Mode | L | M* | M* | H | H | H | 0 | 0 | 0 | 0 |
| MF R-Mode | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Satelles | M | M | M | M | M | M | 0 | 0 | 0 | 0 |
| Locata | L | L | L | M | M | M | H | H | H | 0 |
| ePelorus | M | M | M | M | M | M | 0 | 0 | 0 | 0 |
| **Efficiency loss (with MarRINav)** | **0%** | **0%** | **0%** | **0%** | **0%** | **0%** | **0%** | **0%** | **0%** | **30%** |

***Table 7 - Adequacy assessment of PNT technologies***

Note: *: individually, the technologies cannot feasibly be implemented to serve the entire country, however, wide area eLoran and DLoran with local supplementing technologies can.
**: IMU is used for SLAM and within processing of the Radar Absolute Positioning. As shown in Table 3 of D6, using a similar tactical grade IMU as for this CBA, tight coupled IMU does not offer sufficient holdover to allow its use as a standalone part of the System-of-Systems.

The adequacy assessment uses the information present in Table 3 and 4 of **WP4** – D5 *Conceptual PNT Architecture* and inputs from experts.

The technologies in the scope of the analysis were selected due to their ability to fulfil the maritime PNT requirements in the case of a signal disruption. It is assumed that the selection of a SoS will enable the completion of all activities without efficiency loss (or with negligible loss). The rationale is summarised below with longer justification provided in deliverables D4 and D5.

In ocean phase, the PNT requirements are lower than at any other point of the voyage and eLoran signals are sufficiently accurate for navigators to be able to complete the activity 1.

For activity 2 and 3, for most of the coastline and nearly all port approaches, eLoran + DLoran is a suitable solution. However, due to signal geometry in particular locations, notably around Dover and the approaches to the Channel, eLoran + DLoran is not sufficient by itself. For such areas, it is necessary to supplement the wide area capability of eLoran with a local area system to ensure the completion of the activity. In this case experts support a combination of Radar technology with VDES-R mode as a resilient addition.

In port approach and manoeuvre, (activities 4 to 6), eLoran with DLoran and VDES R-mode are recommended. The navigational performance of those technologies in combination is sufficient.

Finally, the Locata system has been selected for cargo handling. The installation of Locata transceivers around ports with automated rovers would provide sufficient accuracy for all automated systems to carry on their job of container stacking.

The remaining activity 10, is the only activity for which no system has been identified as adequate. The reason is that the MarRINav SoS focusses on maritime technologies, the capacity to cover road transportation (even within the port) has not been assessed in detail. We assume no effect of MarRINav technologies on the tenth activity and full loss of efficiency as defined previously. The loss is 30%. However, it is conceivable that UK-wide, terrestrial eLoran coverage could induce innovation in road navigation receivers to incorporate the signal and improve efficiency of road navigation in the absence of GNSS.

# 3 Estimation of the benefits

## 3.1 Container value estimation

The overall economic value that transits through UK ports is not fully attributed to containers. The MDS Transmodal report analyses and estimates the value of goods passing through UK ports. In this analysis, they show that containers carry **69%** of import and export value. Although containers account for the greatest value, the MarRINav SoS will improve the resilience of all ship types. This implies that the benefits estimated for MarRINav will represent a conservative estimate of the value the SoS can save for the whole population of users.

| Cargo type | Total value (£m) | Share |
|---|---|---|
| Dry bulk | 10,000 | 2% |
| Liquid bulk | 71,000 | 14% |
| Other general cargo | 8,000 | 2% |
| Vehicles | 68,000 | 13% |
| Other unitised | 354,000 | 69% |
| **Grand Total (seaports)** | **511,000** | **100%** |

***Table 8 - Estimation of the value of imports/exports. MDS Transmodal.***

In table 8, we estimate the loss attributable to containers. Given the findings above, 69% of the economic value transits through containers in the UK. However, the reliance on container transportation differs by manufacturing sectors. As shown in Table 9, The automotive industry relies **exclusively** on containers for imports. Other sectors rely on bulk shipping instead, these sectors are aggregated in the Table 9 as *Other import, bulk*. Based on these considerations, the overall value attributable to containers amounts to **£601m**.

| Area | Loss (£m) | Share attributable to containers through 10 largest ports | Value attributable to containers |
|---|---|---|---|
| Ports | 44.6 | 62.4% | 27.9 |
| Warehousing, etc. | 38.9 | 62.4% | 24.3 |
| Total manufacturing | 670.2 | | |
| *Automotive industry* | *117* | *90.5%* | *105.9* |
| *Other import, bulk* | *163.3* | *0%* | *0* |
| *Lower import* | *294.6* | *62.4%* | *184.0* |
| *Low import* | *95* | *62.4%* | *59.3* |
| Foregone export | 315.6 | 62.4% | 197.1 |
| Beacons | 0.1 | 0% | 0.0 |
| Shipping | 4.8 | 62.4% | 3.0 |
| Fishing vessels (returning to port) | 2.1 | 0% | 0.0 |
| Fishing vessels (reduced efficiency) | 0.8 | 0% | 0.0 |
| Fish processing | 1.3 | 0% | 0.0 |
| Fish hospitality | 2.9 | 0% | 0.0 |
| **Total** | **1,081** | **56%** | **601.4** |

***Table 9 - Value loss attributable to containers***

By combining the value loss attributable to container transport and the criticality assessment we can estimate the indicative value loss at each stage of the voyage, bearing in mind that the combined effect of all activities is of interest.

## 3.2 Value loss

We define the value loss as the economic value at stake due to a GNSS outage. We compute it by superimposing the efficiency loss to the economic value attributable to containers.

### 3.2.1 Without MarRINav

Table 10 illustrates the efficiency loss and the economic value at stake.

| | Activity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Efficiency loss | 15% | 60% | 40% | 70% | 70% | 70% | 100% | 100% | 100% | 30% |
| Values loss (£m) | 90.2 | 360.8 | 240.6 | 421.0 | 421.0 | 421.0 | 601.4 | 601.4 | 601.4 | 180.4 |

***Table 10 - Estimation of the value loss given the efficiency loss without MarRINav***

In the case of a GNSS disruption and without an alternative system-of-systems (SoS), maritime transportation would be hit by the maximum loss of efficiency. If the cranes stop working, unloading does not occur and therefore the cascading effect will induce delays and even freeze operations in major ports.

The below figure illustrates the value loss due to GNSS loss. The blue area shows the proportion of economic value remaining in each activity (independently from the others) and the red lines show the combined efficiency, considering prior activity.

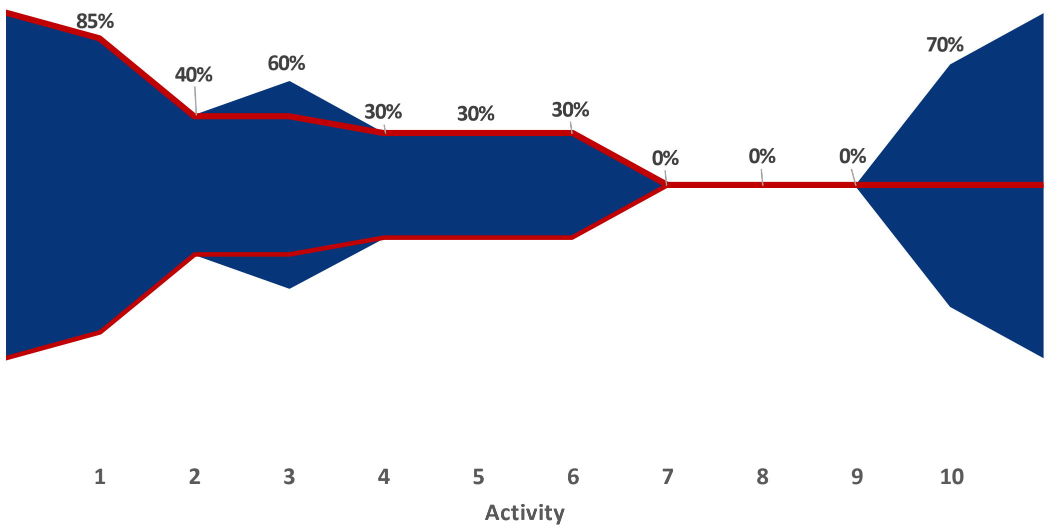



***Figure 1 - Bottleneck effect induced by a GNSS loss, without MarRINav***

### 3.2.2 With MarRINav

Using the assessment in section 2.2 and applying the same methodology as before, we can estimate the value loss with MarRINav technologies available.

| | Activity | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Efficiency loss | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 30% |
| Values loss (£m) | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 180.4 |

***Table 11 - Estimation of the value loss given the efficiency loss with MarRINav***

With a resilient SoS, better efficiency is achieved in all but one activity. The MarRINav SoS enables the ships to be fully operable and the bottleneck effect is pushed back to the truck operations in activity 10.

The degree to which road haulage can be supported by the MarRINav SoS has not been assessed and the implementation of any suitable solutions not considered. The maximum efficiency loss remains at 30%, inducing a value loss of approximately **£180m**. However, it should be noted that eLoran could bring resilience to road transport applications as part of a future resilient SoS designed to mitigate against that sector's vulnerability to loss of GNSS.

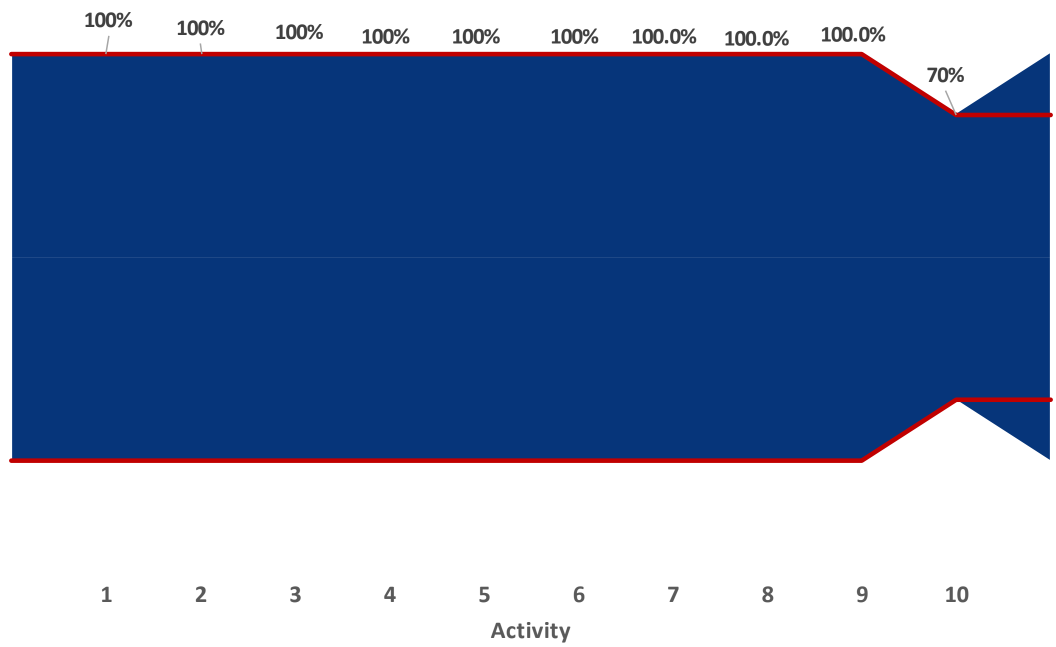



***Figure 2 - Bottleneck effect induced by a GNSS loss, with MarRINav***

## 3.3 Assessment of the benefits

The benefits from MarRINav are the consequence of the development of a SoS capable of maintaining maritime operations. The previous subsections have shown that without this system, the total economic loss is **£601m** whereas, with MarRINav, the total loss is reduced to **£180m**.

Under our assumptions, the total economic value saved is **£421m.**

# 4 Estimation of the costs

The introduction of alternative technologies will require installation (or upgrade) of additional equipment on the shore and on ships.

With the inputs provided by **WP3** and **WP4** we can define the baseline systems requirements for MarRINav. We focus on the 10 largest ports in the UK (in value) and we propose a SoS that provides a resilient solution to all of them. As presented in table 4, these ports support more than 90% of the shipping value in the UK.

The global number of vessels at the end of 2018 was approaching 60,000[7]. The number of container vessels represents slightly less than 9% of the total number of ships, i.e. approximately 5,200[8]. The ships' equipment is required on any vessel that intends to approach UK ports. We assume that all ships are likely to trade in (or transit by) the UK at least once a year and therefore, all container ships will be equipped with the necessary equipment.

Some technologies have been selected for further study in previous packages. This set defines a potential SoS for maritime resilience this chapter defines the costs. These technologies are: eLoran, Radar absolute positioning, VDES-R mode, Locata and ePelorus.

The combination of onshore and on-board equipment is considered to provide the necessary PNT data to meet safety requirements and maintain maritime navigation at its most efficient level (see section 3.2.2).

We split the costs into two categories namely ashore infrastructure costs and shipowner costs.

## 4.1 Costs of ashore infrastructures

Table 12 details the infrastructure required on land. eLoran infrastructure has the highest unit cost, but only few are required for national coverage. Each transmitter costs **£4m** with a recurring cost of **£0.25m** per year and each control centre costs **£1m** with a **£0.1m** annual cost. Up to six antennas and two control centres are required to cover all 10 ports.

Some specific geographic zones like Dover suffer from poor coverage. Therefore, differential stations would be needed to consolidate the signals. Differential eLoran stations and eRacons are used for this purpose.

The maritime navigation and port approach phases are handled by eLoran, radar technology and VDES-R module. But there is still a need for PNT data within ports, to handle containers.

[7] Department for transport (2019). *Shipping fleet statistics: 2018*. Available at: https://bit.ly/2NtmSYX
[8] Equasis.org (2018), *World Fleet Database*

Locata is the best option. Automated cranes and rovers in ports can easily be upgraded to be compatible with its signal and the accuracy is reliable.

Here we draw the assumption of the number of modules required by the ports with respect to a case study on the port of Auckland, New Zealand. The Locata technology is currently used in this port and includes 67 rovers and 55 Locata transceivers. The port of Auckland covers approximately 1.2 km² and therefore, **45 transceivers per km²** are needed. We use this factor as reference for the UK ports.

For the rovers, ideally the assumption would be based on the number of cranes and stackers, but that data is not available. Instead we proxy the number of roving receivers by the volume of containers processed at each port. As the port of Auckland handled 952,000 TEU in 2018, we estimate that **1 rover is required per 14,200 TEU per year**.

We used GIS software to compute the size of each of the ten major ports[9] and the UK freight statistics[10] to estimate the number of containers per port. We use the previous factors to estimate the number of rovers and transceivers.

| System | CAPEX (£'000) | OPEX (£'000/y) | Units |
|---|---|---|---|
| **eLoran** | | | |
| eLoran Transmitters | 4,000 | 250 | 6 |
| eLoran control centres | 1,000 | 100 | 2 |
| Differential loran reference stations | 60 | 3 | 10 |
| Integrity monitor stations | 3 | 3 | 1 |
| ASF surveys | 31 | Negligible | 10 |
| **Radar absolute positioning** | | | |
| eRacon | 30 | Negligible | 12 |
| **VDES-R module** | | | |
| Conversion AIS station to VDES | 50 | Negligible | 10 |
| **LOCATA** | | | |
| LocataLite | 30 | Negligible | 1,050 |
| Rover | 10 | Negligible | 700 |
| Control centre | Update existing | Negligible | 10 |

***Table 12 – Costs of ashore infrastructures per unit***

[9] The estimation was carried out using QGIS.
[10] UK DfT. Port0203. Available at: https://www.gov.uk/government/statistical-data-sets/port-and-domestic-waterborne-freight-statistics-port#major-port-traffic-by-cargo-type. [Accessed on 07/11/2019]

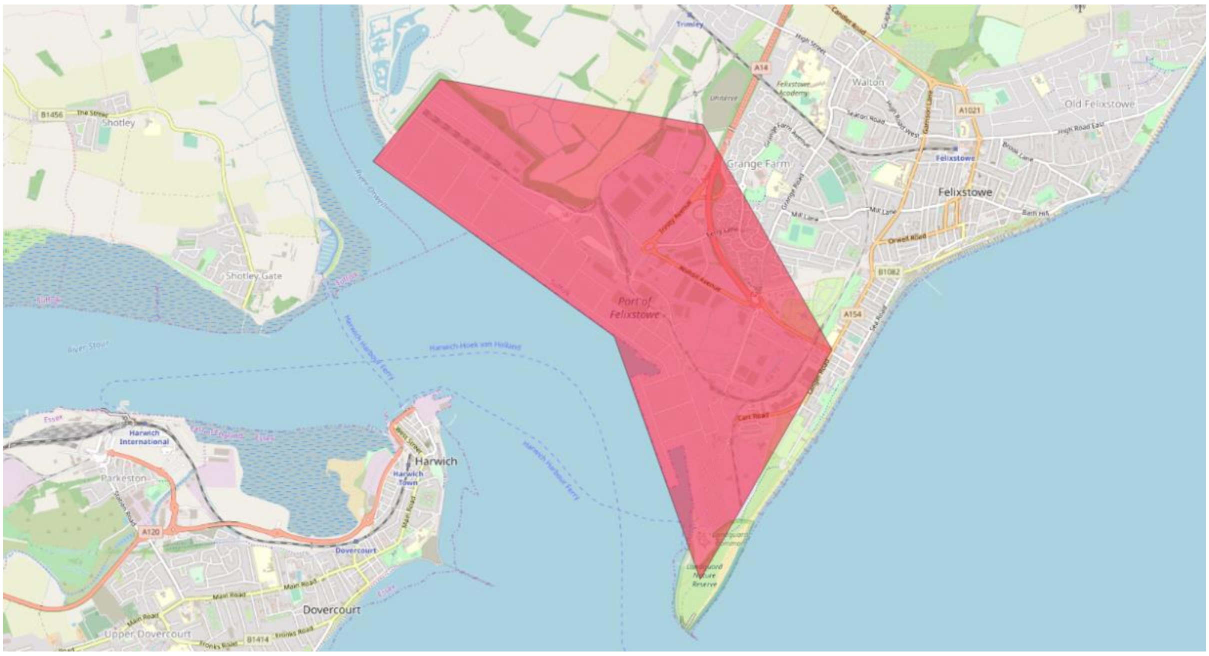



***Figure 3 – Surface area polygon of Felixstowe, using QGIS.***

The present value of costs for onshore technologies is **£80m** over 10 years.

## 4.2 Costs to shipowners

We estimate that 100% of the world's container ships transit at least once per year through UK waters. Therefore, all of them must be equipped with the selected resilient technologies.

Table 13 gives a summary of these technologies alongside the capital and operational expenditures. Overall, the investment cost per ship is equal to **£23,000**. The marginal operational expenditures are negligible. Therefore, the costs to shipowners is only an upfront investment.

| System | CAPEX (£'000) | OPEX (£'000/y) | Units |
|---|---|---|---|
| **eLoran** | | | |
| Marine eLoran receiver | 1 | Negligible | 5,200 |
| **Radar absolute positioning** | | | |
| IMU | 18 | Negligible | 5,200 |
| GNSS-compass (included in IMU) | Negligible | Negligible | 5,200 |
| **VDES-R module** | | | |
| VDES receiver | 1 | Negligible | 5,200 |
| **ePelorus** | | | |
| ePelorus | 3 | Negligible | 5,200 |

***Table 13 - Costs of on-board equipment per ship***

In total, the cost to shipowners is close to **£120m**, in one year.

It brings the total cost for MarRINav to **£200m over 10 years**. This investment ensures the maritime activities to be fully operational and brings the loss of efficiency to 0%. Only road transport is still limited by the disruption (efficiency loss is 30%) and further analysis would be required to determine what technologies would be required to alleviate this loss.

# 5 Results and conclusion

Given the results from above, the net present value of the MarRINav system-of-systems is positive and equal to **£221m**. This is equivalent to a benefit-cost-ratio of **2.2**.

Under our assumptions and for **5,200 container ships and 10 major ports**, these results indicate that the investment in a resilient solution is highly beneficial to the wider society.

| Benefits and costs | Value (£m) |
|---|---|
| **Benefits (avoided loss)** | **421** |
| Loss without MarRINav | 601 |
| Loss with MarRINav | 180 |
| **Costs** | **200** |
| Costs of ashore infrastructures | 80 |
| Costs to shipowners | 120 |
| **Net Present Value** | **+221** |
| **Benefit-cost ratio** | **2.2** |

***Table 14 – Summary of benefits and costs***

The results also show vast differences between the beneficiaries. We can distinguish four groups of stakeholders: The Government, port operators, ship owners and the wider society (industry, manufacturers, etc.). These differences are highlighted in table 15. Wider society captures most of the benefits from MarRINav (**95%**) while incurring no costs at all. The shipowners have limited benefits and carry **60%** of the costs. The remaining costs are split between the Government and port operators (**20%**) each.

| Benefits and costs | Benefit | Cost | NVP |
|---|---|---|---|
| Government | 0 | 41 | -41 |
| Port operators | 19 | 39 | -20 |
| Ship owners | 2 | 120 | -120 |
| Society | 399 | 0 | 421 |

***Table 15 – Summary of benefits and costs, by stakeholder group***

This asymmetry indicates a need for **financial redistribution** as rational shipowners and port operators would be unlikely to implement MarRINav on their own initiative. It is beyond the scope of this report to propose a suitable mechanism for redistribution.

This report presents estimates of the investments required to enable the MarRINav SoS and the economic value at stake. While we are confident in this approach, which gives a strong estimate of the returns on investment, additional costs and benefits have been omitted.

We have focussed on the scenario defined in **WP1**. This choice of container ships was motivated by the fact that they carry the largest economic value in the maritime transportation value chain. Consequently, all other ships have been omitted. Additional analysis is required to grasp the full picture of the UK maritime economy.

Wider benefits can be expected as well. The inland infrastructure deployment could be useful to other sectors than maritime transportation. Some of these technologies may be applicable in road transportation, which could improve that sector's robustness. Further analysis would be required to determine the technical viability and suitability of using the services designed for maritime on the road. Additionally, users outside the transport domain, including the financial and telecoms sectors, may benefit from access to the timing service required to operate MarRINav. Such benefits have not been assessed.

The analysis ignores environmental costs. A disruption of GNSS signal reduces the transportation efficiency and increases the fuel consumption. Unless all ships stop, resilient PNT technologies will have a beneficial impact on this externality.

Some of the candidate technologies have been discarded due to their low readiness level. The development of technology has wider benefit than its direct application. Aside from the employment they leverage, spin-offs and spillovers are expected in society. Spaceborne technologies have varying but strong spillover potential[11].

## 5.1 Sensitivity analysis

The estimates in this report show that a resilient System-of-Systems can mitigate the adverse impacts of a loss GNSS in the maritime domain. The MarRINav project has been defined to identify a unifying solution for the UK maritime sector, but it is reasonable to consider whether subsets of the solution can or should be implemented in isolation.

An obvious candidate is to implement a solution that mitigates against the loss in Activities 7-9, namely port container handling. These activities would grind to a complete halt in the absence of GNSS (and MarRINav), but the identified solution – Locata – could be implemented at comparatively modest costs.

Introduction of Locata would generate benefits of **£180.4m** (£601.4m less £421.0m, see table 10 for details). The associated costs would be **£38.5m** (see table 11), yielding a Net Present Value of **£141.9m** and a Benefit-Cost Ratio of **3.7**.

[11] London Economics. 2018. Available at: https://www.ukspace.org/wp-content/uploads/2019/04/Spillovers-in-the-space-sector_March2019.pdf

A Locata-based port container handling system therefore represents a sound investment and should be implemented among the earliest. The high Technology Readiness Level of 9 also indicates Locata is ready.

However, it is important to remember that even with Locata, a loss of GNSS would cause economic loss of £421m through container vessels alone owing to the substantial loss of efficiency of efficiency in the previous activities. MarRINav therefore does not recommend a partial solution involving only Locata.

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