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# BENEFICIAL USE OF DREDGED CONTAMINATED SEDIMENTS

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**Abstract.** Sea transport is increasing due to its environmental and economic benefits. The related expansion of ports and the development towards longer, wider and more deep-draught ships cause a huge need for dredging of sediments in fairways and ports. A large volume of these sediments are contaminated with heavy metals and organic contaminants. Millions of $m^3$ of these sediments have to be dredged and handled in the coming years according to studies performed by the SMOCS/PortInfra network. The SMOCS project (Sustainable Management of Contaminated Sediments) within the Baltic Sea Region Programme 2007-2013 has developed a guideline on management of contaminated sediments based on a sustainability approach. Among all the studies as input for the guidance, a field test on the application of the stabilisation/solidification method for treatment of dredged contaminated sediments was implemented in the Port of Gävle, Sweden. The treated sediments were beneficially used as fill material in the new port area replacing ending natural resources. The outcome of the monitored field test shows that beneficial use of stabilized/solidified contaminated sediments can be applied in this type of geotechnical application in port constructions.

**Keywords:** Sediments, contamination, beneficial use, stabilization/solidification, field test, port, construction, environment, geotechnics, sustainability.

## 1. Introduction

There is a considerable increase in sea transport due to economic and environmental benefits. The required expansion of ports in addition to the increase of larger and more deep-draught ships imply a need to dredge sediments in fairways and ports. Several millions of $m^3$ of these sediments, out of which a considerable part contains contaminants, have to be dredged and handled in the coming years in the Baltic Sea according to studies performed by the SMOCS / PortInfra network.

The SMOCS (Sustainable Management of Contaminated Sediments in the Baltic Sea) project within the Baltic Sea Region Programme 2007-2013 with 10 partners from Sweden, Finland, Poland, Lithuania and Germany representing ports, universities and institutes has been part-financed by the European Union (European Regional Development Fund and European Neighbourhood and partnership Instrument) and part-financed by partners (SMOCS, 2012). The project has three main outcomes, a guideline, field tests and a durable network. All outcomes are available at the website www.smocs.eu and are free to be downloaded. In this paper the guideline, the field test in Port of Gävle, Sweden and performed assessments using environmental system analyses but also key issues regarding future plans and challenges for Baltic Sea Ports are presented.

## 2. SMOCS Guideline

The guideline provides, based on a sustainability approach, comprehensive but simultaneously easy to use guidance starting from a description of “what to do” in the different phases during the whole process of a project and adds on with descriptions on “how to do” in the different phases and decision situations. This “how to do” is a tool-box comprising tools for assessment of sustainability and decision support tools. They are Appendixes linked to the chapters. In addition the guideline comprises a number of reports produced in the SMOCS project.

The sustainability approach includes three pillars: environment, economy and social aspects. This is also stated in the “EU Sustainable Development Strategy - EU SDS”. The sustainability criteria reflected by the guideline comprises a scientifically sound environmental assessment of contaminated sediments and proposed measures, which need to be economically viable, social tolerable and environmentally protective.

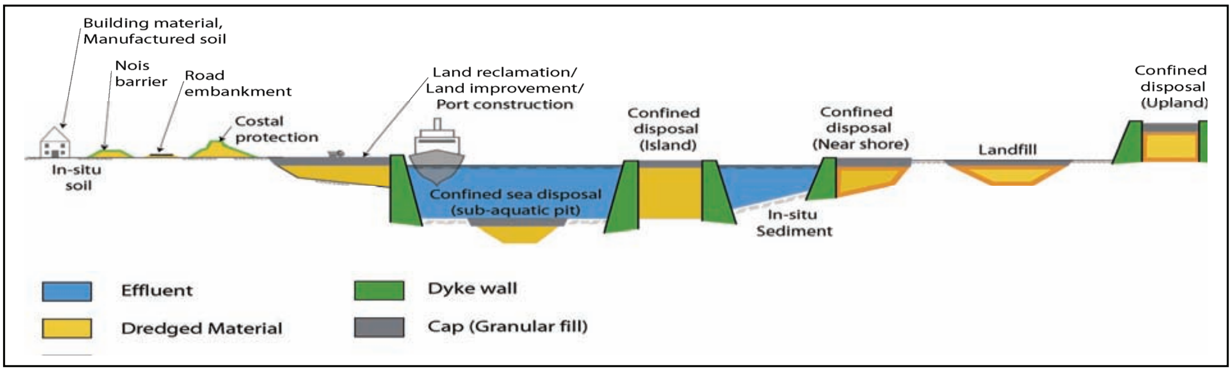


**Fig 1.** Examples of beneficial use of dredged sediments (based upon figure by Oakajee Port and Rail Pty Ltd)

The whole process from identifying the need to dredge, over the phases Characterisation and basic risk assessment, Feasibility study, Selection of handling options, Planning and permitting, Execution and Serviceability stage is complemented by a tool-box of assessment and decision support tools to be used at different times throughout the process.

The guideline guides the reader through the whole sediment management process, starting from the Basic Risk Assessment to give information about the sediment to be dredged, following with the handling options as an inventory of possibilities and finally it leads the reader to the point where the most sustainable, economically viable and technically feasible option is pre-selected.

The special attention is dedicated to the beneficial use of dredged sediments in e.g. constructions for new port areas with a focus on a sediment stabilization/solidification method (s/s-method) as a one technology with risk reduction possibilities. The s/s-method has over the recent years been applied in many Nordic port extension projects and also on remediation of contaminated land (Naturvårdsverket, 2007; STABCON, 2011; SGI Info 20, 2011).

There are a large number of possibilities for beneficial use of treated sediments, e.g. land reclamation, port facilities, embankments and dikes, sub-base for road constructions, see Fig 1 based on the type of sediments, in geotechnical terms: sand, silt, clay and mud and the matrix of contaminants. This kind of sediments can in some cases be utilized without further treatment and in other cases the material has to be modified. This can be done through different methods such as dewatering, stabilization/solidification treatment, thermal treatment and others.

## 2.1 Tool-box in guideline

There are 11 different tools presented in the guideline covering all the phases in a project e.g. “Sampling and Testing”, “Basic Risk Assessment”, Multi Criteria Decision Analysis”, “Sustainability Assessment”, “Environmental Impact Assessment”, “Design”, “Quality Assurance/Quality Control”, “Beneficial use by Stabilization/Solidification Method” and “Short and Long Term Monitoring”. There is guidance how to use each of these tools.

## 3. Field test in Port of Gävle, Sweden

The objectives with the field test were to demonstrate and verify the applicability of the s/s-method with respect to geotechnical and environmental properties of the treated contaminated dredged sediments, the behaviour of the construction with the s/s-treated material, the influence on the surroundings and the process stabilization/solidification technology

Construction alternatives considered when using s/s-treated sediments for beneficial use as a fill material are i) the s/s-treated sediments are placed behind a sheet pile wall and ii) the s/s-treated sediments are placed behind an embankment, e.g. consisting of crushed rock. In both alternatives a superstructure is applied upon the s/s-treated sediments. For the field test the first alternative was chosen. For the full-scale project the second alternative was chosen, see Fig 2.

## 3.1 The structure in the field test

The construction was a sheet pile wall anchored with steel rods to dead man anchors, see Fig 3 and Fig 4. The sheet piles hand rock bolts. In Fig 4 the basins for the s/s-treated dredged contaminated sediments are shown.

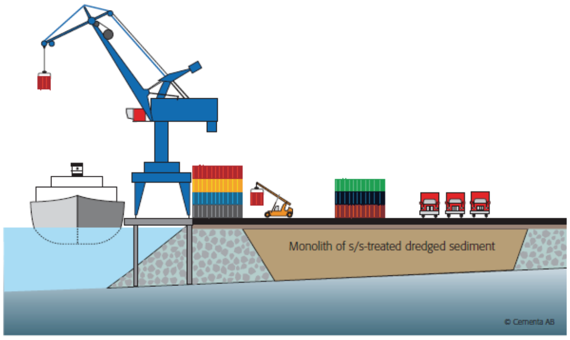


**Fig 2**. Principle sketch showing beneficial use of stabilized/solidified dredged contaminated sediments in the geotechnical structure containing the monolith of stabilized/solidified dredged sediment

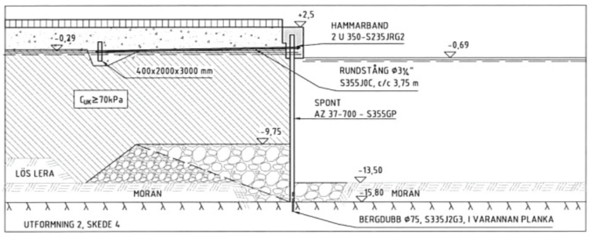


**Fig 3.** The structure with the monolith of s/s-treated sediments behind a sheet pile will incl. the superstructure on top of the s/s-monolith

**Fig 4.** The basins to be filled with s/s-treated sediments

**Fig 5.** The dredged sediments are pumped into the process stabilization equipment

## 3.2 The stabilization/solidification

The s/s-treatment of the dredged sediments was made by the process stabilization technology, see Fig 5. The sediments were mixed with the binder according to the decided binder recipe. The equipment used was ProSol which is a process stabilization equipment. It contains a chassis which carries the containers for mixing and four silos for binder components. Consequently it is possible to have up to four binder components. At the field test the binder consisted of cement, GGBS (Ground Granulated Blast Furnace Slag) and bio-ash with the proportions 40/20/40 and with a total amount of 150 kg/m$^3$of sediment. The s/s-treated sediments were pumped to the basins where they were placed by “under water casting”.

## 3.3 Monitoring

The monitoring programme comprised i) the behaviour of the whole construction, ii) possible influence on the surroundings and iii) the geotechnical and environmental properties of the monolith of s/s-treated sediments. All over time.

### *3.3.1 Behaviour of the construction*

The performance of the construction was studied with respect to vertical and horizontal displacements. The horizontal displacement of the top of the sheet pile wall is shown in Fig 6. The displacement was 50 -100 mm when the sheet pile wall was acting as a bracket. After the anchors had been installed the displacement was reduced to 50 mm. The measuring point SP1 was affected by another factor.

The vertical displacement of the top of the monolith of s/s-treated sediment is shown in Fig 7. The settlements were 25-70 cm after 1.4 months and after that no further settlements occurred. The measuring point 2 was affected by another factor.

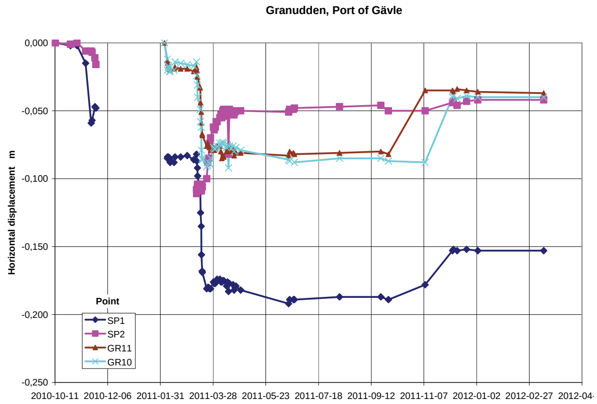


**Fig 6.** Horizontal displacement versus time. Measurement points at top of sheet pile wall. Negative displacement is against water. The measuring point SP1 was affected by another factor

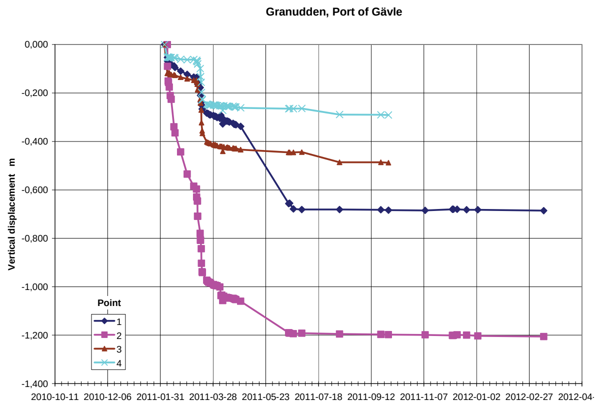


**Fig 7.** Vertical displacement versus time. The measuring point SP1 was affected by another factor

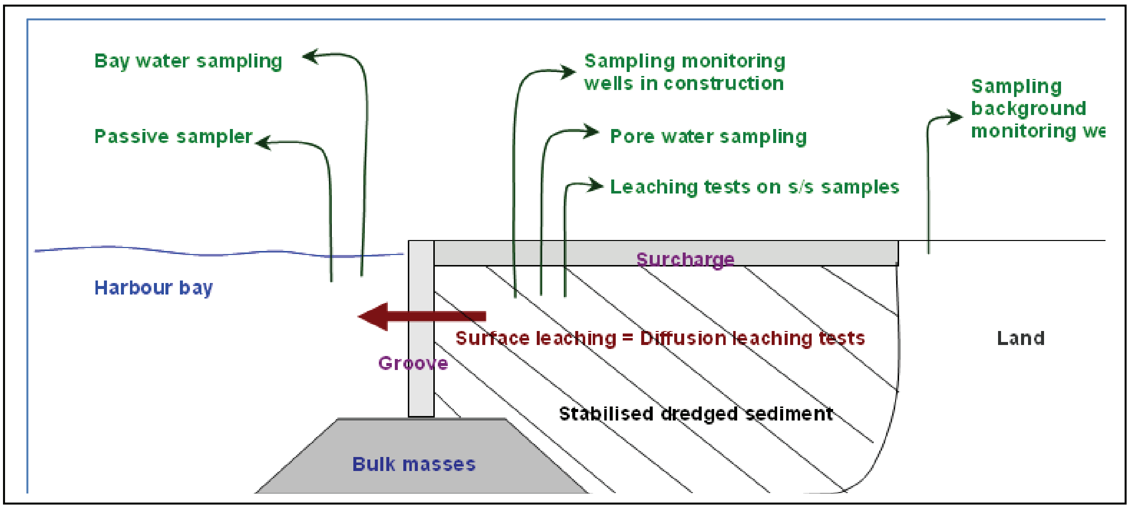


**Fig 9.** Principal sketch over environmental monitoring inside and outside the construction

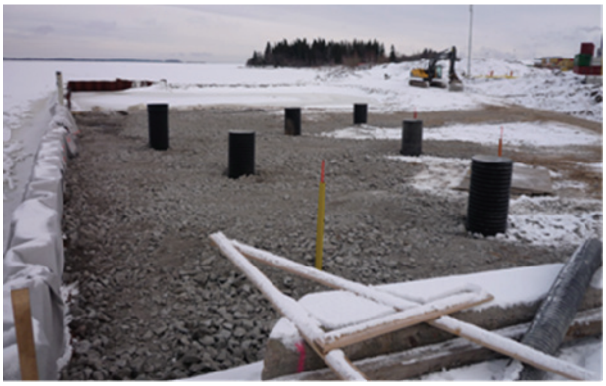


**Fig 8**. Photo from the pilot test area with large shield wells (placed in the surcharge but not down in stabilized material).

### *3.3.2 Geotechnical properties*

The geotechnical properties were measured by CPT-testing, core sampling (Swedish piston sampler) and pore pressure gauges (BAT).

The measured strength (compressive strength) was in the order of 40-60 kPa after 3 months and 60-100 kPa after 6 months. The hydraulic conductivity determined by permeameter tests on samples taken in-situ was in the order of $10^{-7}$-$10^{-8}$ m/s.

### *3.3.3 Environmental properties*

Photo from part of the stabilized test area is given in Fig. 8. The principle sketch over the environmental monitoring is shown in Fig 9.

The environmental characteristics within and outside the construction were monitored according to following: Solid samples/monoliths were drilled from small areas within large shield wells (P10, P20, P14, P24) at 28, 91 and 365 days after completed construction, see Fig 10. Monoliths from the two latter events were crushed (< 4 mm) and investigated according to either two stage batch test (modified SS-EN12457-3) or one-step batch test (modified SS-EN 12457-2), as wells as on samples from the dredged sediment. The tests simulate leaching behaviour of a fully crushed monolithic material to fine particles. However, diffusion tests are more representative for the leaching from the monolith. Other studies have shown less leaching by diffusion test than batch test.

In the voids generated from the drilling within P10, P20 wells (Fig 10) with 3 m filter level were installed and water was sampled with bailer in connection to next drilling event.

During each geotechnical investigation of the pore pressure in the construction, the waters generated, at three levels between 4– 9 m depth in each point, were analyzed.

Water samples were taken before, during, and three times after completion of the construction with bailers in two monitoring wells placed on land just outside the construction (M1, M2, Fig. 10). Water samples were also taken outside the construction in the bay water (Gf1, Gf2, Fig. 10). Additionally, passive samplers (DGT and SPMD) were placed at the depth of 2 m below water surface in Gf1, Gf2 (Fig. 10). Unfortunately, due to the extremely early winter the passive samplers were lost by the ice.

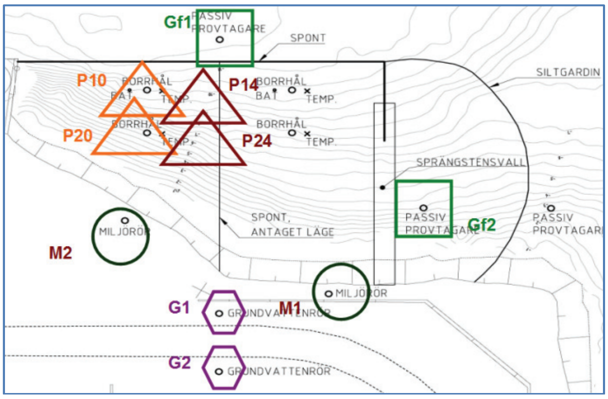


**Fig 10**. Principle sketch of sampling spots/areas within and outside the construction.

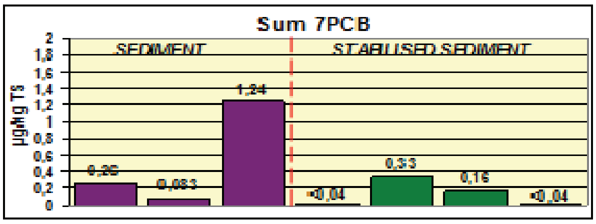


**Fig 11.** Leachable 7PCB from sediment and construction samples.

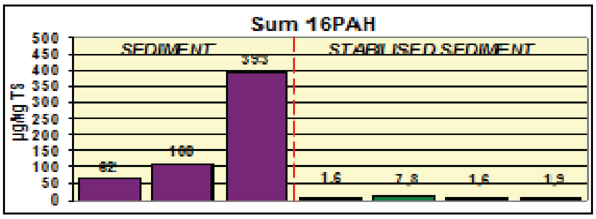


**Fig 12.** Leachable 16PAH from sediment and from construction samples.

Results from tests of the sediment gave elevated leachability of Arsenic and Sulphate, relative maximum levels for non-restricting reuse of waste in civil works (NV Handbok 2010:1).

Most heavy metals leached with similar or lower amount from the 91 and 365 days of hardening construction samples, relative the sediment. However, Nickel and Sulphate showed elevated leachability, relative sediment and maximum levels for non-restricting reuse of waste in civil works, but with decreasing leachability over time. Average levels of leachable 7PCB and 16PAH were lower from four construction samples relative three sediment samples (Fig 11 – Fig 12).

Filtrated (0,45 µm) water samples from both BAT and the 3 m filter wells were similar in content of heavy metals and showed elevated levels of Ni and As with no significant changes over time. All other heavy metals were below Swedish drinking water standard (SLVFS 2001:30). Analysis of non-filtrated water showed in general higher concentrations for several heavy metals, especially Pb, Cr, Cu, Zn and Fe, but Ni and Hg showed significant limited association to particles. However, calculation on possible transport of these particles within the construction indicated very low potential for impact on the surrounding bay water.

Inorganic content in groundwater samples from M1, M2, as well as from Gf1, Gf2, showed no significant changes over time and the levels was always below Swedish drinking water standard (SLVFS 2001:30).

## 4. Environmental assessment

### 4.1 Overview of tools

There are several tools that could be used for assessment of the environmental impacts when handling contaminated sediments. The starting point for how to choose which tool to use in decision making has to be based on an understanding of the nature of the decision that should be taken as well as the function and focus of the tool (de Ridder, et al., 2007). Therefore, the use of assessment tools depends on the decision level as well as the decision phase, see Fig 13.

Within the SMOCS project several case studies on assessment tools have been performed. Here results from case studies using life cycle assessment (LCA) and multi criteria analysis (MCDA) are presented.

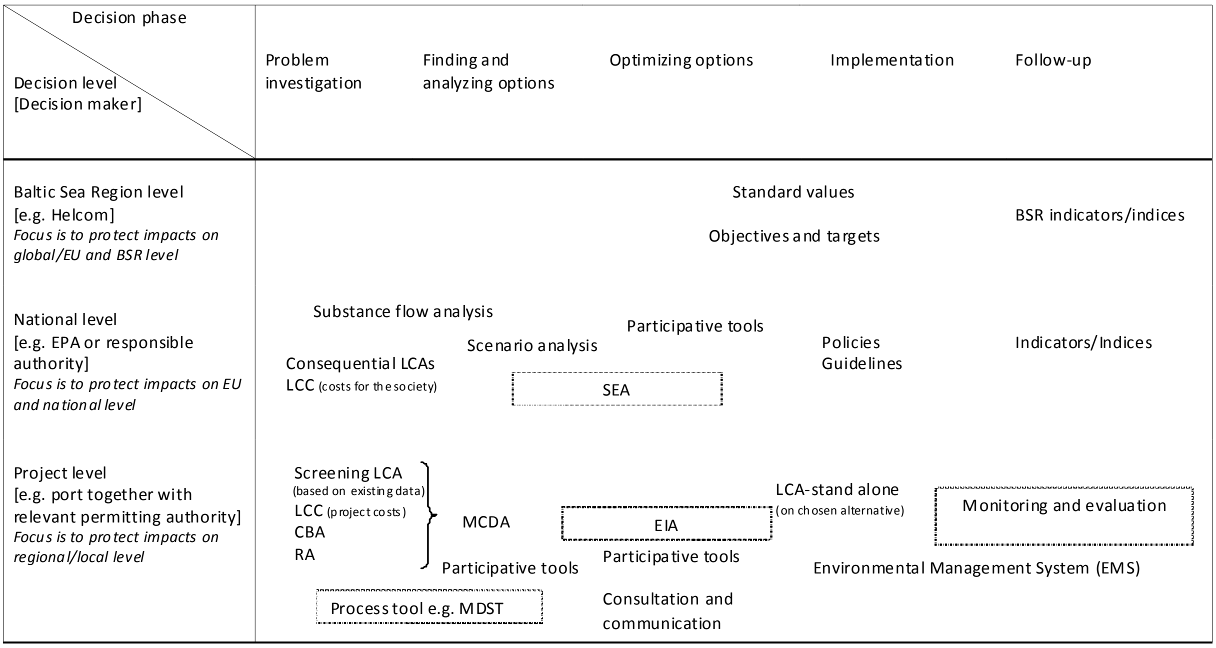


**Fig 13.** Examples of different types of assessment tools which may be implemented in a decision process (Lundberg, et al, 2011).

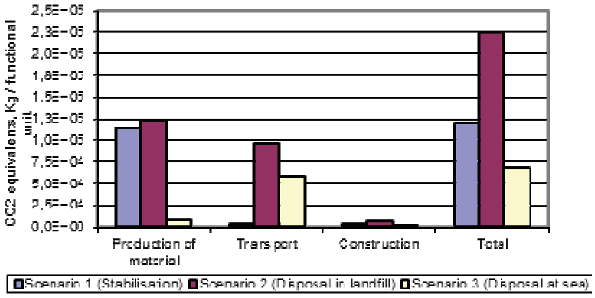


**Fig 14.** The energy use for the handling alternatives in the case study in Port of Gävle

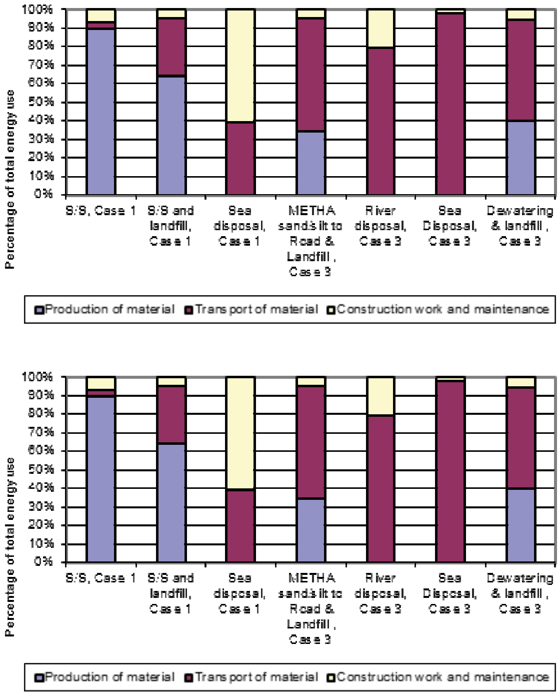


**Fig 15.** Percentage of total energy use (top) and climate impact (bottom) from the handling of sediments from in three categories of activities. Case 1 is Port of Oxelösund and Case 3 is Port of Hamburg

## 4.2 Life cycle analysis (LCA)

The purpose of a life cycle analysis (LCA) is to assess the environmental impacts associated with all the stages of a product or a service/action life from-cradle-to-grave. Thereby it is possible to find out which processes that generate environmental impacts and for which stages the environmental load is the greatest (ILCDA, 2011). Such information is important for a decision maker when comparing different activities. The LCA could thus be used in an early decision phase for comparing relative differences in e.g. energy use and climate impact between different handling options such as presented in Fig 14.

In the SMOCS project different management options of dredged contaminated sediments have been assessed by LCA. The case studies have been based on sediment management in three ports; Port of Oxelösund, Sweden, Port of Gävle, Sweden and Port of Hamburg, Germany.

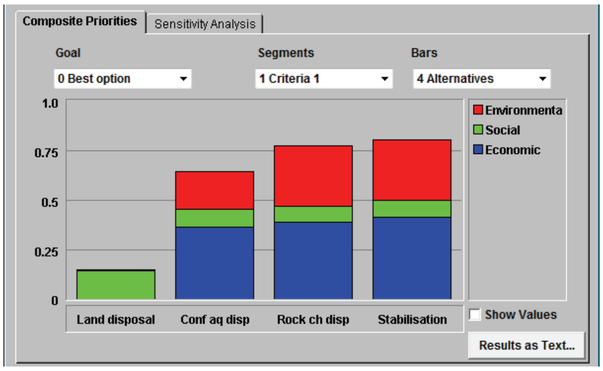
In the case studies from Port of Gävle, three possible management scenarios were compared (Fig 14). The management scenarios were 1) beneficial use of sediment in quay construction by stabilization/solidification method, 2) disposal in landfill and 3) disposal at sea.

In addition, an LCA could be used for displaying the relation between the energy use and climate impact from e.g. production of material, transport of material, construction work and maintenance respectively. This could be made with a stand-alone LCA approach making it possible to describe significant activities in each sediment management alternative. Such approach demands a more extensive data inventory but could provide information on which measures should be taken in each management alternative to reduce the energy use and climate impact. The stand-alone approach performed in SMOCS is presented in Fig 15. The data was collected from the cases of Port of Oxelösund, Sweden and Port of Hamburg, Germany and completed with data on previously excluded activities such as dredging and transfers of dredged material.

## 4.3 Multi Criteria Decision Analysis (MCDA)

With Multi criteria decision analysis (MCDA) it is possible to make a broader assessment, a sustainability assessment through integrating economic, environmental and social criteria. A decision maker can thus through the use of MCDA identify the most sustainable handling alternative (Belton, 2001). Thus, the MCDA approach could be used at the project level for establishing the overall favourable handling alternative for management of contaminated sediments from a sustainability perspective. The results from analytical tools such as LCA, LCC, RA and CBA are, however, needed in the MDCA in order to objectively score the performance of the different handling alternatives.

Within SMOCS, MCDA case studies have been performed for the Port of Gothenburg and the Port of Lübeck integrating economic, social and environmental


Goal: 0 Best option
Segments: 1 Criteria 1
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☐ Show Values

**Fig 16.** The MCDA results show the performance of each handling alternative in the Port of Gothenburg. A higher score should be interpreted as a better overall result, meaning that Rock chamber disposal and solidification/stabilization are the most favourable options.

criteria for decision. Results from a case study in the Port of Gothenburg are shown in Fig 16. The bar colors show the contributions of environmental, social and economic criteria to the overall performance of each handling option.

### 4.4 Risk assessment and durability

In a site specific perspective it is important to know that conditions vary a lot from site to site. Thus the main concerns in a risk assessment may differ between sites on issues such as compound, sediment type and organic content as well as surrounding conditions. Further it is a key concern that different countries and projects make use of different threshold or other type of criteria while assessing leaching potential and content of compounds. This is also the situation while introducing assessment by toxicological methods. All in all this is an unhappy situation causing difficulties to compare and validate different actions to be taken.

Durability is the ability of a structure to maintain its key properties and function over a long time perspective. Both inner and outer aspects, single or in combination will have impact on the durability of a structure containing s/s-treated sediments. In the several risk assessments performed and corresponding permitting processes the issue of durability has been a key concern. In the guideline proposed by STABCON (STABCON, 2011) and in the SMOCS Guideline (SMOCS, 2012) freeze and thaw cycles are especially addressed and recommendation given to always locate the s/s-treated sediments below ground water or sea level unless specific investigations indicate that it is possible otherwise.

## 5. Future challenges for ports

43 ports out of 125 in 8 countries around the Baltic Sea were contacted and 21 of them participated in the interview study covering 45 % of the total cargo handling volume.

Results show a majority of the ports plan to do dredging in next 1-5 or 6-10 years with the aim of maintaining or increasing the water depth, construction works or expansion of the port area. The fulfillment of all these plans depends on the financial situation. The respondents have presented different handling options of dredged sediments, which sea disposal of clean dredged sediments are frequently used. Some ports dispose dredged sediments in landfills. Contaminated dredged sediments are occasionally used for construction purposes by the stabilization/solidification technology. The study indicates that by making conservative assumptions, about 5-8 million m$^3$ of contaminated sediments could be expected to be dredged the upcoming years in 125 ports in the Baltic Sea. This is in accordance with the expected amount of contaminated sediments to be dredged in Swedish ports as reported by SMOCS 2012. The following possibilities and challenges are proposed to be elaborated in the further:

i) Permitting procedures; some ports have problem with getting permission according to the environmental legislations. In some cases this has caused delay in realization of their plans.

ii) Investigation of sediments and contaminated sediments; according to the previous experience ports will obtain more amounts of contaminated sediments after they starts investigating more precisely.

iii) Technologies for management; the existing practices and technologies in some cases are needed to be assessed and improved sustainably

iiii) Networking; although there is a high knowledge on many specific issues in the ports, there seems to be a lack of an established forum for exchanging knowledge and experience, thus respondents expressed an interest to participate in knowledge exchange activities.

## 6. Conclusions

1. The SMOCS project has established a guideline for the management of contaminated sediment based on a sustainability approach. Many tools to be used in the different decision situations in the whole process of a project are described.
2. The field test showed that the s/s method can be applied for the reuse of the dredged contaminated sediment. The dredging should be done using technologies limiting inclusion of sea water to enable improved the properties of the s/s- treated sediment (increased strength and lower hydraulic conductivity). No impact on the surrounding aquifer/bay could be found. Most heavy metal leached with similar or lower amount from construction samples, relative both the sediment and Swedish maximum levels for non-restricting reuse of waste in civil works. Nickel and Sulphate showed elevated leachability, relative these references, but with decreasing leachability over time. Filtered pore water content showed similarity to the outcome of the leaching tests. Average levels of leachable 7PCB and 16PAH were lower from the construction samples than from the sediment.
3. Performed risk assessments highlight the fact that each project is unique. Key parameters such as compound, sediments type, surrounding conditions etc. vary thus making it important to assess each site based on the actual conditions.
4. The conclusion from the case studies using LCA is that the selection of handling alternative for sediment management has major significance on the overall energy use and climate impact. Furthermore, it was shown that sediments utilized as construction material instead of disposed in landfill reduce energy use and climate impact significantly.
5. Further it was found that MCDA provides a structured way of decision making through a whole project. MCDA can provide the transparency and documentation necessary for creating consensus

between port owners and governmental organizations. This requires that a common opinion on decision criteria and weights can be established. It also requires that permit authorities embrace the concept of evaluating social, economic and environmental decision criteria together.

6. Durability is a key issue addressed while making risk assessments and in the permitting process. The main concern is on degradation due to freeze and thaw cycles. Addressed in Sweden by adjusting the lever of the structure to sub-zero levels.
7. A performed inventory shows that the expected amounts of dredged sediments in the Baltic Sea are significant both to volume and cost. The cost for handling of the expected amount of contaminated sediments in confined disposal (upland) is more than 1000 million Euros which is a significant amount.
8. There is a demand from ports that the construction industry utilizes and develops technologies which can support management of sediments both on land and in the sea. Thus a platform for exchanging experiences and knowledge is proposed. Such a cluster was initiated by SMOCS and is currently running under the name of PortInfra with participants from Sweden, Finland, Norway, Estonia, Lithuania, Poland, Germany and France. More information on www.portinfra.eu

## Additional Information

*Stabilization/Solidification method (s/s-method):* Treatment technology that encapsulates a contaminated material to a monolithic solid of high structural integrity. The s/s-treatment technology also enables a chemical interaction between the material and the reagents (usually binders such as cement, GGBS etc.) through a mechanical binding and/or immobilizing of the contaminants. Thereby contaminant migration is restricted by the decreased surface area exposed to leaching and the corresponding lower hydraulic conductivity.

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