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Offshore application of High Strength Steel: a problem and a challenge

Report of MIF seed money study

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Summary

Various Dutch Offshore companies experience problems in applying and validating welded High Strength Steel ("HSS") structure. This limits the sector in maintaining and expanding their strong position in specialities. A consortium of companies (Allseas, Gusto-MSC, IHC-Merwede) and knowledge institutes (TUD-3ME, TNO) collaborated to summarise problems and directions for solving them. The study, subsidized by the Martiem Innovatie Forum, is performed by TNO. This document reports the results of the study.

An inventory of the issues has been made through interviews, meetings and a short literature review. The issues identified are complex and can be decomposed into sub-issues related to various knowledge domains, technologies and companies involved in the production and use of safe, reliable structures. To make the report succinct, it will focus on main items and tendencies, and it will make black and white statements. The reader should keep in mind that the reality is much more interconnected and contains many shades of gray.

The problems and serious limitations in the application of HSS can be charaterised as: steel with a yield <690 MPa can be applied without problem, HSS 690 with thickness up to 70 mm can be used when taking care of welding, beyond this problems and limitations start to occur and even more when operating temperature drops to arctic conditions. When some of the technical draw backs have been removed and the price of the manufactured structure (improved weldability) is reduced, HSS becomes a better proposition. Now it is only used when one do not have an alternative solution available. The issues are related to the availability of material, material performance, testing, the ability to analyse the structural performance required, the validation process and the safety framework.

For solving the issues, it is advised to evenly distribute effort on metallurgy, material modelling (including testing), structural modelling and safety modelling. Focussing on one aspect only leads to sub optimization. Also, the complete value chain from material manufacturer till end-user should be involved in this. A multidisciplinairy approach is required to solve the issues. It is believed that a balanced approach by setting up both short term application projects and (long term) scientific research projects, valuable steps to tackle the problems can be made. The submitted IOP-Offshore project proposals are examples of that.

From interviews and conversations it became clear that the issues are recognised by stakeholders in the value chain and that they are willing to cooperate. The ability and willingness to spend financial resources has not been discussed since no concrete project proposals were available at that time. Joint industry project is likely to be the format for setting up projects.

Building upon the experience in this Seed Money project, it is advised to set up a Thematic Network or a similar body that coordinates and stimulates a multi domain and multi stakeholder approach.

Content

1 Introduction

Various Dutch Offshore companies experience problems in applying and validating welded High Strength Steel ("HSS") structure. This limits the sector in maintaining and expanding their strong position in specialities. A consortium of companies (Allseas, Gusto-MSC, IHC-Merwede) and knowledge institutes (TUD-3ME, TNO) collaborated to summarise problems and directions for solving them. The study, subsidized by the Martiem Innovatie Forum, is performed by TNO. This document reports the results of the study. The issues identified are complex and can be decomposed into sub-issues related to various knowledge domains, technologies and companies involved in the production and use of safe, reliable structures. To make the report succinct, it will focus on main items and tendencies, and it will make black and white statements. The reader should keep in mind that the reality is much more interconnected and contains many shades of gray.

2 Aims of the study

The study aims to, see project plan (appendix 1):

1. summarise industry problems in certifying HSS structure for offshore use;
2. research background of current regulations of class society;
3. chart current acceptable relaxations and their justifications;
4. identify which regulations are open for (additional) justification;
5. define a thorough problem definition and discuss it with all actors in the Dutch Offshore sector;
6. plan for solving problem(s) identified.

3 Tasks performed

Meetings

Three meetings with industry have been held to discuss and share issues and define directions for solving issues. A fourth project closing meeting is to be held in the next coming weeks.

Interviews and contacts

Interviews have been held with:

- companies in the sector: Allseas, Damen, Gusto, Heerema, Huisman, IHC, Kenz-Figee;
- Class society: Lloyds Register (Aberdeen);
- Material suppliers: NSC;
- Knowledge institutes: TUD-3ME, TNO (various business units).

Telephone conference/contacts with:

- Class society: Lloyds Register (London), DNV (Oslo);
- Knowledge institutes: TUE;
- Materials suppliers: Tata steel (UK, NL).

Literature study

A brief literature study into the background of current rules and state of the art w.r.t. fracture and fatigue has been done.

Project plans for solving issues
Though not formally part of the study, 3 project proposals for IOP Offshore and a proposal for setting up a Thematic Network have been submitted to MIP.

4 Visual guideline

The issues appeared to be complex, scattered over various knowledge domains and companies in the value chain. The issues can be de-composed into sub-issues that are frequently connected to multiple companies in the value chain and multiple domains. This complexity makes it somewhat hard to understand and report what the issues are and what directions for solutions may exist and who should be involved.

In the course of the project the pictures below, presented here without further explanation, have been used as visual guideline for the discussion. Figure 1 shows the relation between the various companies/domains in the value chain related to validation of the safety and performance of structures.

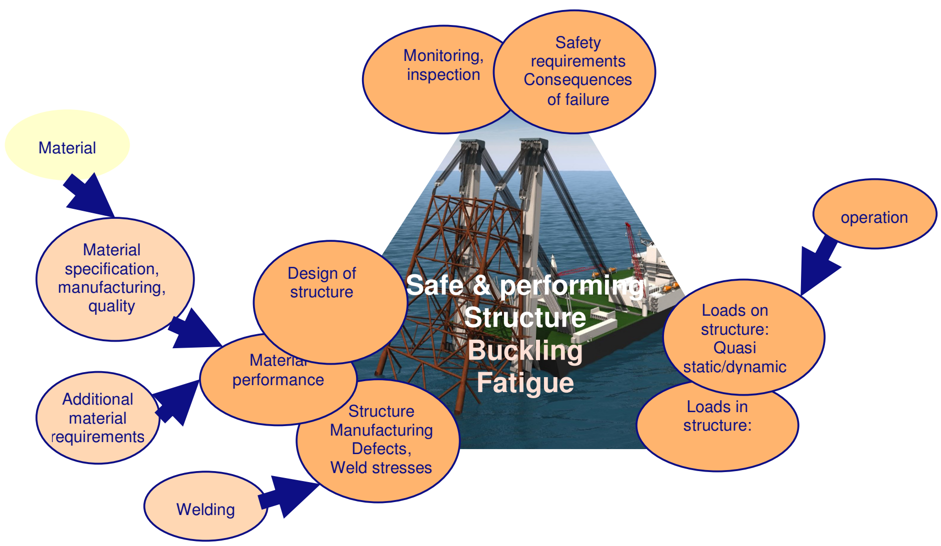

Figure 1. Domains involved in validating structure.

Figure 2 shows the key elements in the models used to validate structure and some of the important supporting technologies.

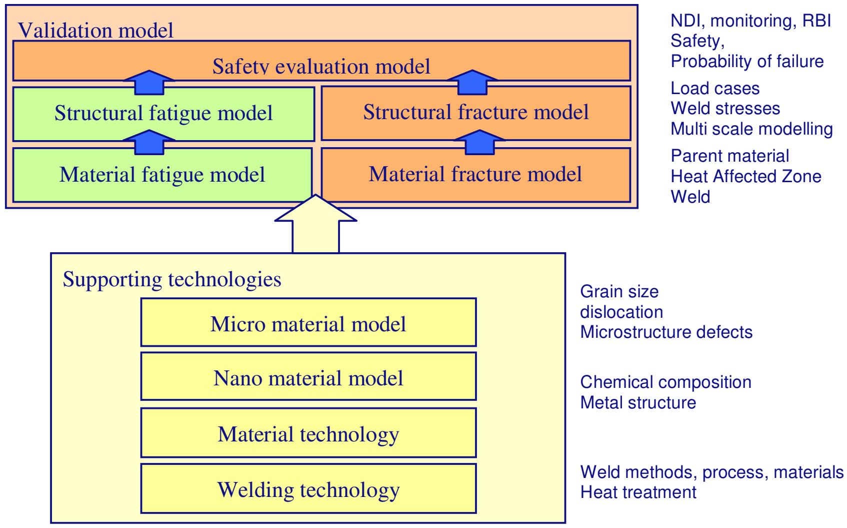

Figure 2. Models supporting technologies for validating structures.

5 Summary of industry problems

5.1 End-user perspective

HSS is generally associated with risk, problems and high(er) costs ("don't use it unless you have to") though some view it as a challenge to reduce manufacturing costs in the future when some obstacles has been solved. The higher the yield strength and the higher the plate thickness, the higher the perceived costs and risks. The tendency to explore arctic regions adds a dimension: the lower the temperature, the higher the risk.

Application

- grades lower than 690 are considered as non-exotic and are not a major point of concern
- 690 grade HSS is increasingly applied in welded structures typically untill a maximum thickness of 70 mm;
- higher grades are less frequently used, if so the majority is forgings or castings;
- thinner HSS plates (typical t=40 mm) are used for structures with load regimes that make the structure fatigue dominated rather than fracture dominated;
- thick HSS plate are used for structure with load regimes that make the structure fracture dominated rather than fatigue dominated. However, low cycle fatigue may still be an issue.

Availability and costs of material

HSS is more expensive, and fewer sources are available. This is more so when particular grades and high thickness is required. Lack of availability of HSS half-finished products also further adds to production costs for some applications.

Manufacturing HSS structure

- Structure of steel with a yield strength lower than 690 MPa can be a manufactured without problems, even in non-specialised yards, without adding much cost compared to mild steel.

- Passing the border of “500 steels”, the structure manufacturing costs for HSS 690 and higher suddenly increases amongst others due to preheating and heat treatment. The much more strict welding conditions required, also limits the number of yards that can handle these materials.
- Obviously, weldability and the narrow process boundary conditions is a major point of concern.

Validation

- Though procured according to a very similar specification, various sources may result in material with quite different structural performance.
- Passing Charpy-V and/or CTOD requirements is a major issue. In particular considering the limited availability of sources. The higher the yield strength, the thicker the plate, the lower the operation temperature, the bigger the issue is. Ultimately the fracture toughness may need to be substantiated with a wide plate test that comes at high costs and long lead times. For very thick HSS the availability of test facilities with sufficient high load capacity is an issue as well.
- On a case by case basis relaxations to the standard class requirements are negotiated. This results in costs and long lead time. Some companies have agreed to a “standard” relaxation scheme.
- Not all companies are sure how conservative the current class rules are.

5.2 Base material and weldability

Chemical composition, heat treatment, rolling processes and proprietary process steps amongst others determine the average material properties and weldability of the base material. While the average properties fulfill the specification requirements, the material properties may vary considerably over the plate thickness. Again, the higher the yield, the higher the thickness, the bigger the difference seems to be.
High nickel alloy HSS tends to have preferred and more homogeneous properties, but it comes at high costs, and not many sources are available.

For HSS, the critical/determining properties from a structural point of view are in and near the weld. The welding process causes formation of brittle zones in the heat affected zone (HAZ) that appear to be the weak link for structural performance.
A crucial issue is that a particular source of base material, in combination with a particular weld consumable and welding process, results in particular structural performance where the material specification concerns the base material only. Again, the thicker the plate, the higher the yield strength, the bigger the weldability issues is. HSS 960 is considered to be “non/hardly weldable”.

For mild steel, the fracture behavior changes from ductile abruptly to brittle when lowering the temperature. This transition temperature, determined by Charpy-V testing, is an important parameter for determining the minimum allowable operating temperature of the structure. For HSS this transition from ductile to brittle develop gradually over temperature. As such, the minimum operating temperature of HSS is less easy to establish, and better, more precise material performance requirements are required to do so.

6 Safety framework

6.1 Structuring the validation issue

A brief explanation is given below on the 3 items that governs validation to understand some of the proposed directions for solutions. In the validation of a structure, the following “models” play a role (see figure 2):

- Material model: this describes the material performance for fracture and fatigue as measured in tests. Usually it is considered to be a homogeneous and isotropic model. One may distinguish between models for the base material, the weld material and the HAZ. These material models can be supported by micro mechanical models.
- Structural model: usually a “global” finite element model (FEA) of the structure that predicts stresses/strain in structural components due to internal and external loads. Fatigue and fracture processes are governed however by defects that are one to four orders of magnitude smaller than the elements used in the “global” model. An additional model, either mathematical or FEA, is used as a “local” model to translate the stresses from the global model to local stresses and compare these with the material model. Note that local details (e.g. geometrical mismatches, stress raisers), stress state and internal loads (e.g. weld stresses) may significantly affect analysis results.
- Safety model: commonly a global safety factor is used to cover uncertainties in e.g. loads, materials, manufacturing process, inspection, etc. It also covers uncertainties/inaccuracies in material and structural models. In some sectors the global safety factor is replaced by so called “partial factors” for the various uncertainties to be considered. This has the advantage that, when a particular part of technology (e.g. mild steel) is replaced by another (e.g. HSS), the effect can be assessed more easily with respect to safety.

6.2 Background of current rules

Current class rules have been carefully developed over years and validated by long lasting experience. Remains of old techniques and approaches are still present but alternative ways of justification are usually acceptable. When new technology is introduced, the current rules are extrapolated conservatively and gradually fine tuned over time. DNV, BV, LR have similar rules that are applied in common for vessels and lifting appliances.

A search was done in the open literature on the history of Charpy-V testing and requirements to find a basis for the fracture toughness requirement that is linked to 10% of the material yield strength. No evidence of a sound supporting theory was found. One of the class organizations admitted that the Charpy-V requirement may be too conservative and not based on well-established scientific research. Much research is done on assessing/comparing various fracture mechanics tests, including the relation between Charpy-V requirements and the CTOD requirements. The CTOD tests serves in class rules as a second line of defense for material requirements. Though some relations have been established, these are not unquestioned. Although CTOD has a much better foundation in fracture mechanics theory than Charpy-V, the relation between the CTOD test, the requirement and the assumed defect in the structure to be validated is often not very strong. When common CTOD tests (SENB) fail to pass requirements, wide plate testing is used as an escape.

Open literature did not reveal the background on the 0.41 factor used to determine the allowable stress. It was suggested that it is more or less an engineering approach to bridge mild steel and HSS.

The literature review revealed that HSS is a very active field of research. Contacts with class societies revealed that they actively participate in research and consider the rules related to HSS open for improvement.

6.3 Acceptable relaxations

Relaxations on the standard rules are granted on a case by case basis. No generally accepted schemes for relaxations are spotted except from company specific relaxation schemes. Class organizations are reluctant to relax requirements because they can not judge the effect on safety without having well-understood partial factors. Potential threats such as H_2 brittleness, stochastic sea loads and sensitivity to the weld process are used for not relaxing requirements.

In other sectors (nuclear power plants, civil infrastructure, oil and gas) a similar situation and issues exists. These sectors have developed standards and requirements as well. These inputs were translated over time into national and international standards. British Standard 7910 is an example of that. In recent years, several joint industry projects and harmonization and standard improvement projects relevant to welded HSS have been executed within Europe. The FITNET project (2002-2006) aimed to develop a single European standard on fracture and fatigue of steel. Though this aim was not reached, it is considered to be the state of the art approach that is acceptable to class organizations. BS7910 will have a major update based on the FITNET work shortly.
FITNET covered material modeling, and material characterization. It does not cover the structural and the safety model. FITNET (as well as BS) considers several levels of validation. The first level is quite simple and conservative and is similar to the current class rules. Each higher level requires more testing and more complex analyses and is intended to be less conservative. This tiered approach allows the user to zoom in as needed for a particular structure or detail. Little research is found on the effect of the FITNET approach on the safety of HSS structure in the maritime and offshore sector. Class organisations may have researched it internally.

6.4 Material model and material tests

The link between material structure, grain size and shape, precipitates, (repeated) heating during welding and migration of alloy elements on the resulting mechanical properties to be used as input in the material model (see figure 2) is a research topic in academia. In view of the many material sources, weld consumables and weld processes, understanding this link is a very valuable enabler to reduce validation costs and steer material development.
Various material models exist dependent on the structural model used (refer amongst others the tiered approach of FITNET). Within each material model multiple model variations and views on how to establish material properties usually exist. This makes selecting the (most) correct options and designing the adequate test specimen and test procedures an expert task. Standards like BS7910, try to accommodate this process. In academia, and recently at TNO, uncracked body approaches are researched that may overcome some of the deficiencies of the commonly applied cracked body approaches.

As already stated above, Charpy-V is not considered to be the perfect test to characterise the fracture performance of material due to the high strain rate and absence of sharp pre-crack. The test is however inexpensive and easy to perform. Tests such as SENB and SENT are considered to be more representative for fracture characterization.
The inhomogeneity of thick plates may require using multiple material models over plate thickness. However, this is commonly not done.
In this project, the situation with respect to weld stresses has not been assessed. Based on a very quick screening only, it is believed to be a subject that is relevant for the structural performance and has already been researched to some extent.
Wide plate testing (full thickness welded plate with fatigue crack) is considered to be a "material test" with a better defined level of constrained than SENT, SENB, etc. Due to costs involved, the wide plate test is used if all other material tests did not pass the requirements. The wide plate test is not considered to be a structural validation tests since it may not take into account the actual joint geometry, the complex stress state of the structure and so on. In particular for thick HSS plates, wide plate test requires equipment with high load capacity that is scarcely available.

6.5 Structural model

Some of the higher-precision levels of FITNET describe analysis procedures that require "local structural models" (see 6.1). Where many commercial software packages exist to make global structural models, commercial FEA tools/procedures for "local models" do exist but are expensive and time consuming to use. As a result, these higher level procedures of FITNET are not commonly used in engineering practice. It is not known how well these FEA procedures and tools have been validated theoretically and by testing.
Note that the stress state in thick structure (not to be confused with the level of constraint in the material test) may be quite different from thin structure. In addition, a surface defect in a brittle zone may, for example, grow into material with different (lower?) properties than on the plate surface. This adds to the complexity of the analyses and material testing required.

6.6 Safety model

As mentioned above, a global safety factor is the common approach in the offshore and maritime sector. For particular off-spec conditions or applications, reliability approaches are available. Introducing partial factors for structures may be a key enabler to apply HSS since this reveals the relative importance of each contribution to safety and allows discussion on options to "exchange" safety from one contributing item to another. It also answers the sector question on how safe the HSS is when current class rules are applied.

7 Directions for solving issues

This chapter suggests a few directions for solving some issues identified above, focusing on validation. Advancement in other areas (see fig 1) can certainly contribute to making HSS structure a better proposition. This chapter is by far not comprehensive; it highlights directions that can alleviate some of the major concerns of industry. On every sub-topic mentioned in previous chapters, good and valuable research can be done. The items listed below are partly a result of a discussion with the consortium partners.

7.1 Safety framework

Having no quantitative insight into the contribution of specific uncertainties to safety is a major obstacle for changing rules, and it blocks innovation. In other sectors (civil infrastructure for example) partial factors have been introduced. The path for developing such safety framework is known. The big advantage of partial factors is that, when one wants to introduce a new technology e.g. HSS 960, the effect on the safety can be assessed by concentrating specifically on the uncertainties associated with HSS 960. It also directs developments in reducing such uncertainties, for example on the weldability of HSS 960. The same holds for using advanced analysis techniques. If traditional safety factors are applied, then the benefit of using advanced analysis techniques may deliver no benefit other than confirmation of the safety level or even worse, result in rejection of the structure. In the framework of IOP Offshore, project proposal “Safety assessment framework for use of new materials and other innovation in offshore structures under extreme conditions” has been submitted that received support of some of the consortium partners.

7.2 Improved material and structural model

Existing materials models have limitations that can be improved. Issues such as material inhomogeneity, multiaxial stress state in structures (in particular thick plates), level of constraint is testing are some of those. However this should be addressed in combination with the material test methods and the structural model to be selected. It is advised to make a more specific plan with industrial partners and class organization(s) before starting with one subject. Obviously, the fit with the safety framework has to be considered. Some more specific development directions are mentioned in the sub-chapters.

7.2.1 Material model and material testing

Charpy-V is pictured as an easy, inexpensive test that can qualitative judge the fracture mechanic performance of HSS. In conjunction with the requirements, it frequently leads to rejection of a material source resulting in additional/other testing to be performed or selecting other sources. Selecting another easy and inexpensive test that is better characterizing the fracture mechanical properties will a) better safeguard safety when it passes the screening test, b) therefore allow less conservative requirements compared to Charpy-V) and c) considerably speed up the material source screening process at lower cost and lower risk of rejection when further testing is performed. Therefore, in the frame of IOP Offshore a project proposal “Economically attractive and accurate fracture substantiation method for welded HSS in offshore and maritime industries” has been submitted that received support of some of the consortium partners.

To address the issue of testing thick plates and the apparent inhomogeneity of these, it is advised to review options for using sub-sized material specimen in combination with an adapted structural and material model.

7.2.2 Structural model

Advanced “local structural models” are not suitable to be applied as engineering tool. Making this available will enable companies to use less conservative approaches.

It is advised to review the state of the art w.r.t. weld stresses, how that affect safety and service life and what can be gained by improving knowledge in this field.

7.3 Extended material specification

Current base material specifications do not adequately cover the structural performance parameters. In part this is caused by the requested test and requirements to fit the current safety framework. In addition to the base material specification, class organizations request to material manufacturers to perform weldability tests before a source is accepted. Nevertheless industry experience that specimens from welded plate do not pass the class requirements. This can result in lengthy and costly screening tests. The main cause is that a base material source is combined with a particular weld consumable source and a specific weld process. For welded HSS, the combination of sources and processes significantly influence the material performance. Similar situations exist in the composite industry where several sources merge.
A solution might be an extended material specification that includes a consumable and process selected by the material manufacturer and testing of the weld zone. In the material purchase process the industry can review expected properties of the extended material data. Should the yard decide to use other consumable and processes, of course additional tests may be required. Benefits are: the material manufacture can position them selves better, reduce one of the barriers and may ask for a higher price reflecting the added value; the yard shortens material screening and reduce validation costs.

7.4 Blueprint for relaxation

Clearly, class rules with respect to HSS need to be improved. In the current situation, companies negotiate relaxations on a case by case basis. The ultimate goal would be that the rules of all class societies change. However, changing rules and deriving new standards is a time-consuming process due to its required accuracy, general applicability, large number of stakeholders, large interests, etc. An intermediate step can be that the Dutch Offshore sector agrees with a class organization(s) on a blueprint for relaxations. Such a blueprint would contain alternative validation procedures that are state of the art and have a certain level acceptance. When possible, it would contain alternative requirements. The blueprint may reference existing standards/documents (e.g. FITNET) and be updated when “detailed research results” become available. On a case by case basis, the blueprint can be used as a template for negotiating alternative means of validation. The benefit to the industry is that the blueprint can be used as a starting point and that the class organizations cannot ignore it. Class organization in turn benefit for having a frame agreed as starting point. It also sets a course to changing rules.

7.5 Material related issues

This chapter highlights some ideas for further development that is more connected to the metallurgy domain and material manufacturers.

Improved weldability and homogeneity of HSS is required for expanding its application. The thicker the plate, the higher the yield, the lower the operating temperature, the bigger the issue. From HSS 690 and t=70 mm onwards, it is primarily considered to be a “material issue” which need to be solved by material manufacturers.

Research on the relation between micro structure and the material model (grain size, precipitates, effect of heat input etc.) is very valuable in speeding up the material and process innovations. Both the domain of metallurgy and micro mechanics should be involved (see figure 2). In the framework of IOP Offshore, project proposal "Understanding microstructural influences on fracture toughness in welded, thick-section HSS" has been submitted that received support of some of the consortium partners.

8 Conclusions

The Offshore sector encounters several problems and serious limitations in the application of HSS. To characterise it: steel with a yield <690 MPa can be applied without problems, HSS 690 with thickness up to 70 mm can be used when taking care of welding, beyond this problems and limitations start to occur and even more when operating temperature drops to arctic conditions. When some of the technical draw backs have been removed and the price of the manufactured structure (improved weldability) is reduced, HSS becomes a better proposition. Now it is only used when one do not have an alternative solution available.

For solving the issues, it is advised to evenly distribute effort on metallurgy, material modelling (including testing), structural modelling and safety modelling. Focussing on one aspect only leads to sub optimization. Also, the complete value chain from material manufacturer till end-user should be involved in this. A multidisciplinairy approach is required to solve the issues. It is believed that a balanced approach by setting up both short term application projects and (long term) scientific research projects, valuable steps to tackle the problems can be made. The submitted IOP-Offshore project proposals are examples of that.

In academia and knowledge institutes research is ongoing. However, the integrated approach as advocated above, seems to be missing. The good Dutch knowledge position from the past faded away and is today somewhat scattered. However, sufficient knowledge is still available (partly focused on other sectors) that can be utilised for HSS. Moreover international cooperation is feasible.

From interviews and conversations it became clear that the issues are recognised by stakeholders in the value chain and that they are willing to cooperate. The ability and willingness to spend financial resources has not been discussed since no concrete project proposals were available at that time. Joint industry project is likely to be the format for setting up projects.

Building upon the experience in this Seed Money project, it is advised to set up a Thematic Network or a similar body that coordinates and stimulates a multi domain and multi stakeholder approach.

Appendix 1: Project plan Seed Money Project