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Evaluation of System Integration and Qualification Strategies using the Technical Debt metaphor; a case study in Subsea System Development

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Abstract. In software engineering, technical debt is often used to measure and describe the cost of accumulated work tasks resulting from design decisions deviating from the intended architecture of systems. This paper investigates how to apply the *technical debt* metaphor to support the selection of integration strategy for complex subsea systems.

The investigation presented in the paper is based on a case study that compares several aspects of technical debt in two alternative integration strategies used in an ongoing subsea development project at Aker Solutions (AKSO). Especially, aspects related to using technical debt to describe consequences of unexpected systems emergence during integration, and performing integration activities earlier in the development lifecycle, or in parallel with other engineering activities, have been investigated. The paper furthermore compare and support the case study results with literature.

Results from the case study indicate that there is a higher level of inadvertent technical debt related to integration strategies that conduct Integration and Qualification activities late in the development lifecycle, or incorporate a temporal gap between activities for design, and integration.

Introduction

The rationale for this paper is the observation by the authors that system failures and requirements non-conformance in subsea development projects often are identified late; when the design is frozen and where the cost for remedies is high. Moreover, late design changes have been identified as one of the main reasons for cost overruns in subsea development projects (Tranøy och Müller 2014). The case study analysis in this paper is based on the assumption supported by systems engineering and integration theory (INCOSE 2015) (Forsberg 2005) (Langford 2012) that emphasizes the need for early integration activities to avoid late design changes.

This paper focuses on potential improvements of the processes for Integration and Qualification (I&Q) related to thermal requirements of subsea systems, by identifying and investigating the level of technical debt present in the current integration strategies used in projects at Aker Solutions (AKSO), and compare it with alternative integration strategies.

Technical Debt is a metaphor used within the software industry to communicate the consequences of pragmatic design decisions deviating from the intended design of a system (Cunningham u.d.).

Problem statement. The thermal performance of some of the subsea systems developed by AKSO varies highly between the various sub-projects. The deviations differ from over-performing to non-conforming with customers' requirements. Integration strategies chosen by the different sub-projects vary and reveal a lack of a generic workflow for thermal I&Q-requirements, and a gap between some sub-projects and the Computational Fluid Dynamics (CFD) engineers. The CFD engineers are responsible for conducting computerized analysis of the developed systems and fulfil the role of System Integrator (SI) for the systems pertaining thermal requirements.

System design and system I&Q for thermal design are in some cases conducted independently. There is a large variation between the different sub-projects in the approach selected to the thermal management process. In some cases, early thermal management is addressed early in the development lifecycle, whilst in other cases these activities are postponed to a time closer to detailed design due to the maturity of system design. Postponing I&Q of the systems thermal performance until the end of system testing substantially increases the relative cost of extracting potential system defects.

In this paper we have conducted a case study to identify the reasoning behind the varying integration strategies, and the potential consequences this might bring to some sub-projects.

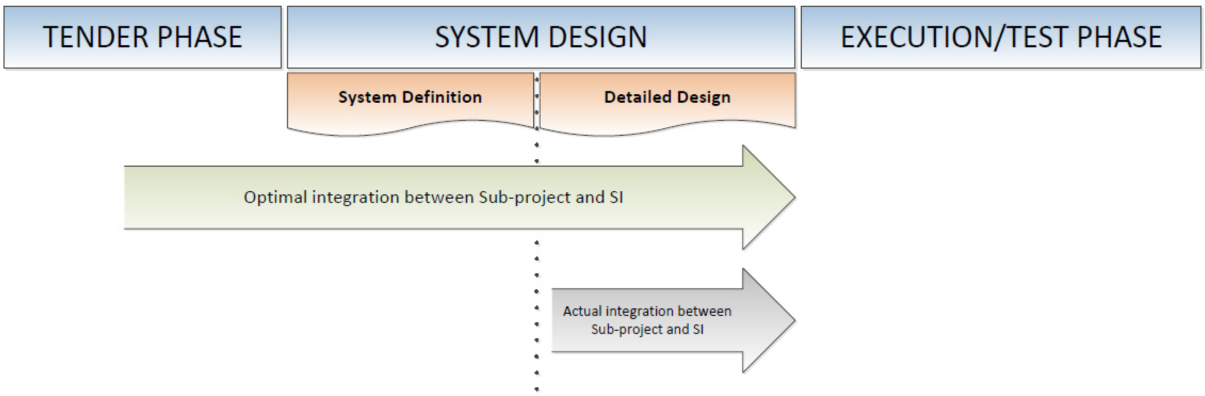

Figure 1. Figure showing the varying approaches to thermal integration present in AKSO.

Background Due to the geophysical environment surrounding the subsea systems on the seabed, there is a significant possibility of hydrate plug formation in various locations of the production pipework, during system cool-down. The temperature difference between the oil producing systems and the surrounding environment, and hydrostatic pressure increase the probability of hydrate formation during a production shutdown. This could potentially plug the piping and in worst case limit further production. Subsea systems are therefore insulated to reduce heat loss in the event of a production stoppage. Other mitigating actions are the injection of mono ethylene glycol (MEG), methanol or other chemicals.

At AKSO, the subsea systems thermal profile is developed and verified through the thermal management process, led by the Systems Engineers. Relevant requirements are identified and communicated to applicable sub-projects, and the CFD group conducts necessary analysis activities. Their scope of work includes Integration and Qualification (I&Q) of the functional requirements related to thermal performance of the developed system through complex computational analysis. Systems Engineers assist by supporting on architectural issues and system I&Q activities.

Most I&Q activities are usually conducted through analysis and simulations, but for some vital systems, the customer requires a full scale Cool Down Test to be conducted. In these tests the systems operational scenario is replicated, usually, in a test pit filled with chilled water. The system is heated up to reach the steady state temperatures that would occur during production subsea, before a production shut down is initiated. The system is naturally cooled down and it has a required minimum amount of time before attaining the temperatures within the hydrate formation zone. This test is usually conducted on the fully assembled system before handover to customer.

The main activities relating to thermal insulation design are performed during the tender phase and the design phases of the systems development lifecycle. The systems engineers, are responsible for identifying and interpreting the requirements that relate to thermal performance and insulation. The subsequent task is the definition of insulation thickness and location on the system. This is achieved by means of input from previous projects, the CFD engineers and material specialists. The information is thereafter handed over to the sub-projects responsible for developing the specific design, which then establish design concepts and initiate detailed design. All relevant documents are established and the insulation contract is signed with third party vendor.

Outline of paper. In the case study conducted, we have measured the effect of the tailored development lifecycle according to the "Collapsed Vee" approach, which encourages parallel execution of the system decomposition and composition phases of the traditional Vee development lifecycle. Initially we will present some research literature in order to establish a basic understanding of the Technical Debt metaphor and how this relates to our research. Results are presented from our research into of the varying integration strategies, using the Technical Debt metaphor as a measure of consequence.

Research approach

In order to prove that the Collapsed Vee adaptation of system development can improve the system integration process, we identified and classified the amount of Technical Debt present in thermal integration strategies used in AKSO today. We have investigated two sub-projects from the same subsea development project where non-conformance of thermal requirements have been identified.

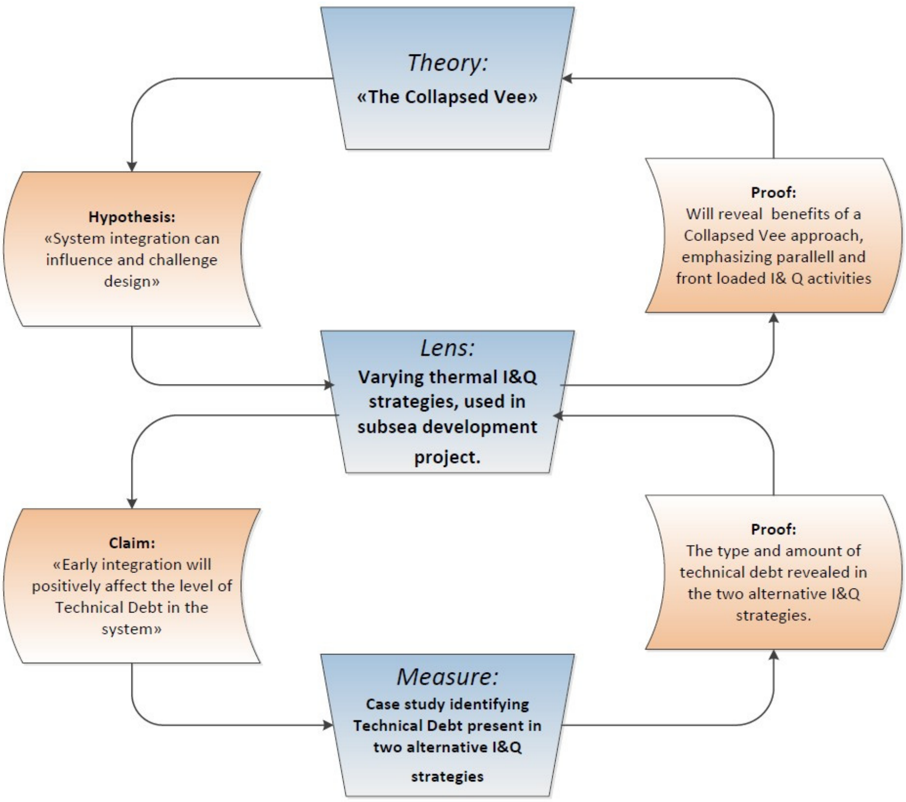

Figure 2. Figure showing flow of research and analysis.

An empirical case study was conducted, revealing Technical Debt present in the integration activities of two of the sub-projects; *XMT (X-Mas Tree) systems*, and *Structures and Manifolds*. The case study was carried out by in-depth interviews with key personnel from the various sub-projects, the CFD lead engineer and the project systems engineers. Several interview iterations were conducted, in order to gain a basic oversight of the various viewpoints of the process. Data from Lessons Learned workshops were also used to establish how the Technical Debt is captured in the organization today. Reference literature was used to classify the debt and further analysis conducted to establish why the debt might have occurred and its consequences. As the project is still ongoing, the actual consequence of the Technical Debt accrued is based on available data and assumptions supported by subject matter experts.

The results were compared to a third sub-project from the same subsea development project: *Tie-in and structures*, which has a history of adhering to system thermal requirements. By comparing theI&Q strategies chosen by the different sub-projects, we were able to establish the possible benefits gained by increased "frontloading" of integration activities. We benchmarked our results against research findings in the literature in order to identify similar benefits.

The Collapsed Vee

In AKSO the project development model is closely related to the traditional document driven application of Vee development life cycle model (INCOSE 2015)Although the model encourages early planning of activities traditionally performed later in the development lifecycle, it indicates a mainly sequential system development process, from early concept of operations and system requirements definition, into the system design and build (implementation) phases. After build phase, systems verification, integration and validation activities are conducted in the "right" leg of the Vee using input and planning produced during the system architecture, design and requirements phases.

Some claims that the model, as visualized in its original form and as implemented at AKSO, is outdated (Jackson 2014) (Montgomery 2013). The model, as presented in the INCOSE handbook (INCOSE 2015) is often interpreted as a sequential process of system development with forward feeding activities, somewhat similar to the waterfall model, e.g. resulting in a separation between design and integrations activities. The authors have observed that the common simplified visual presentation of the original Vee-model provide little support to emphasize that activities normally outlined in the right leg of the Vee, in fact can be initiated early in the development lifecycle.

To better convey the potential of parallelism and "front loading" in the Vee development lifecycle, we have in this case study used a visualization of the Vee that overlays relevant lifecycle processes, according to (INCOSE 2015) (ISO/IEC/IEEE 2015), on the dual-Vee development lifecycle as described by (Forsberg 2005). We have named the visualization, "the collapsed Vee" (Andersson 2014) as visualized in Figure 3.

The intention behind the collapsed Vee is to encourage tailoring of both the development lifecycle and its supporting lifecycle processes to the unique project and product-of-interest.

In this paper, the strategy behind the tailoring is to explicitly paring I&Q activities from the integration, verification, and transition processes with the system decomposition activities traditionally that traditionally have their gravitas in the left leg of the Vee. A particular advantage of using collapsed Vee model in this case study is that validation, that often tends to be performed late in the project lifecycle, if addressed at all within a development project, now naturally can be performed throughout the development lifecycle by including activities that perform validations on the representation of the system-of-interest at hand at the time. Examples of system representations that can be validated early includes stakeholder needs and requirements, system requirements, concepts, models, and other document/artifacts. The collapsed Vee can also be used to emphasize early verification activities using methodology such as simulation based test, modelling, and system analysis. In this particular tailoring, we consider systems integration as the natural coordinating process for activities related to the verification, transition and validation processes according to (ISO/IEC/IEEE 2015), as well as a balancing "sparring partner" to the lifecycle processes focusing on system decomposition, such as stakeholder and system requirements analysis, system architecture and design, as well as implementation.

Model Based Systems Integration. Model Based System Engineering (MBSE) emphasizes the value of of modeling and simulation based systems engineering. If employed early in the development lifecycle the outcome of MBSE activities can also be used to support integration as suggested by (Montgomery 2013). The model representations of a particular system can then be analyzed and tested until the real product is available, with the intent of reducing the risk related to late testing (Bjorkman, Sarkani och Mazzuchi Autumn (Fall) 2013).

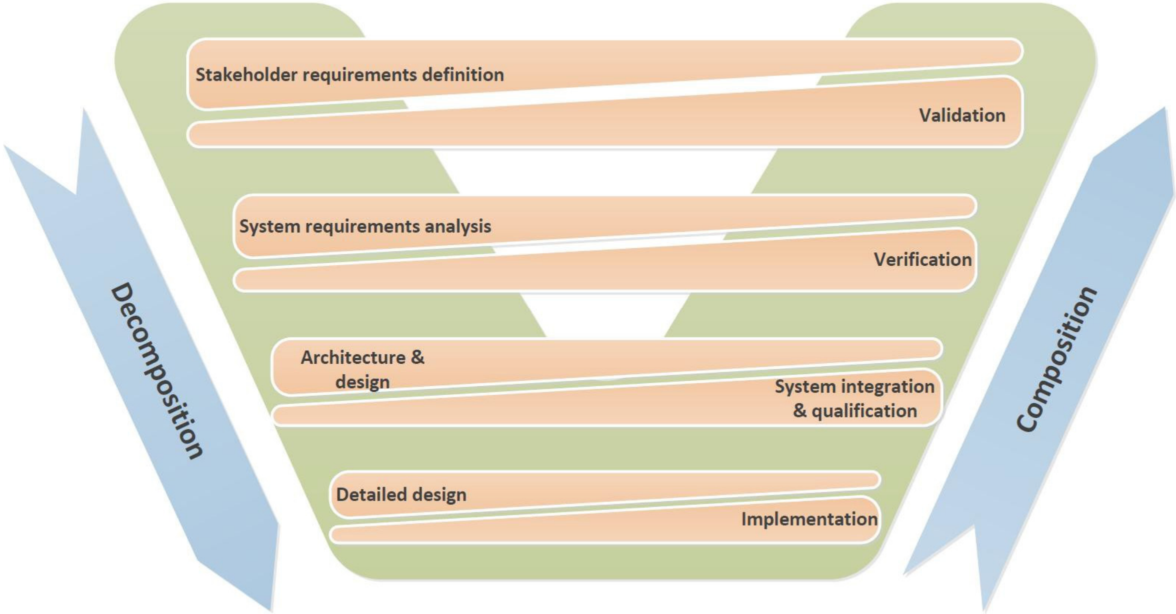

Figure 3. An illustration of the Collapsed Vee (Andersson 2014).

Graphical general-purpose model representations, such as SysML (Object Managagement Group 2014), can then be combined with more detailed models that include the rigor needed for detailed analysis and simulations, e.g. evaluating systems performance (Friedenthal and al. 2008). Montgomery (Montgomery 2013) introduces the term Model Based System Integration (MBSI) by applying the essential tools of MBSE to influence and improve the early integration of system design and architecture. This includes involving the Systems Integrator at the beginning of system design. In the case studies investigated, Montgomery observed a high probability of [project] failure if the projects had not implemented MBSE/MBSI methods (Montgomery 2013).

The Collapsed Vee model suggests necessary process tailoring improvements, by combining the strengths behind the core ideas behind the original dual Vee model as presented by (Forsberg 2005) with the flexibility of process oriented development provided by the system lifecycle processes in ISI/IEC/IEEE 15288 (ISO/IEC/IEEE 2015). The resulting framework is intended to be more easily combined with recent development approaches such as Lean product development, the ideas sprung from the Agile manifesto and the reality of development processes the authors have observed in the Oil and Gas industry.

Technical Debt

The Technical Debt metaphor was established by Ward Cunningham and is today used mainly within software system development (Cunningham u.d.). In this paper, we aim to show that it is equally applicable to subsea systems development. The metaphor describes the cost and time for accumulated work due to design decisions deviated from an intended design. The accumulated work, or debt, will have to be repaid to ensure system completion according to the system requirements, or intentions. As there is ongoing discussion on what the Technical Debt metaphor communicates and how it should be used (Norton 2014), in this paper we have decided to use the classification by Tom et al. (Tom, Auruma och Vidgena 2013).

Technical debt can be divided into two main categories; *Intentional* and *Unintentional* Technical Debt (Tom, Auruma och Vidgena 2013). The *Intentional* Technical Debt is a form of debt which is identified and deliberately accumulated. The reason might be a tight schedule, or the need to prioritize some tasks and so taking on this kind of debt will serve some benefits. An example from the software industry would be the strategic benefit of ignoring long term system failures if the intent is to reach the market prior to competitors. *Unintentional* technical debt on the other hand, is the type of debt which is unknown to the system designer. This debt and following interest will accumulate in size without the system designer being aware. This could eventually lead to complete project failure. The unintentional technical debt is not only hard to identify, but is generally also difficult to quantify and manage.

In principle, accepting accumulation of technical debt, as the financial counterpart, yields positive benefits until the debt is no longer controlled (Epps 2012). Maioli describes to what extent accumulation of technical debt is beneficial through the *Threshold for Technical Debt* (Maioli 2013). Maioli identifies the threshold at which the further accumulation of debt will only give negative consequences. By acquiring additional debt and crossing the threshold, the cumulated effects of system violations will be increased to such an extent that it will negatively affect the value of the system developed.

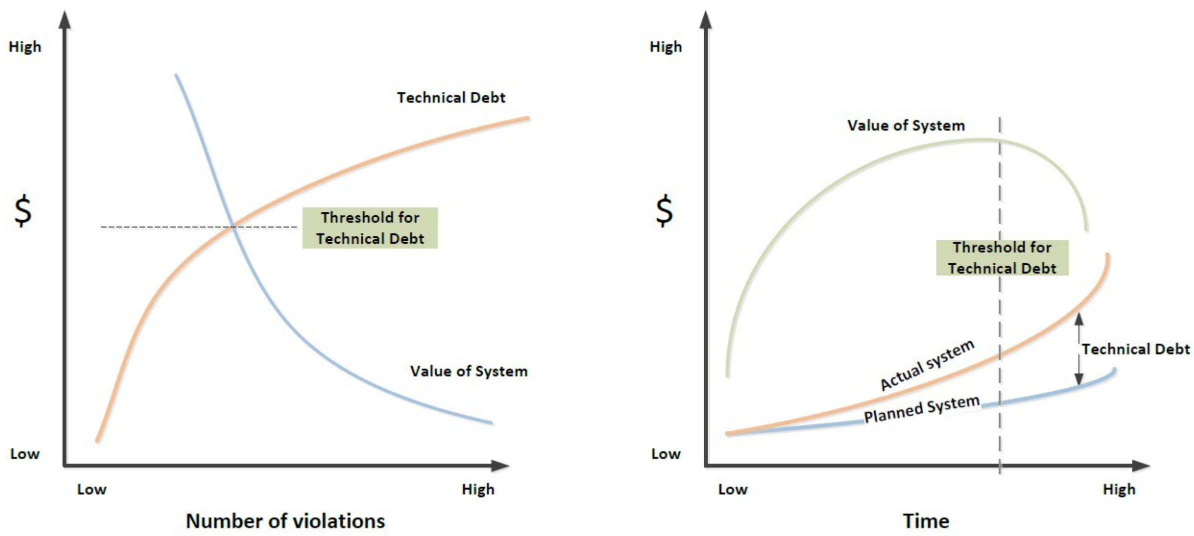

Figure 4. The authors' adaptation of graphs indicating impact of Technical Debt on the value of the system (Maioli 2012) (Highsmith 2010).

Technical Debt and Systems Integration. By exploring the opportunities of integration provided by computerized tools, the Collapsed Vee promotes increased coherence between system architecture and integration. Technical Debt can be used as a tool for measuring and controlling the efficiency of early integration.

Epps (Epps 2012) conducted a workshop with the intention of identifying Technical Debt within the systems engineering domain. The objectives were to identify and discuss the management of Technical Debt in systems development, and how decisions during the development lifecycle influence the level of Technical Debt within the system.

During the workshop it was identified that top level architectural issues will have the greatest impact on the development of Technical Debt. This is also highlighted by Ozkaya (Ozkaya 2011), whose research focuses on the Technical Debt accumulated in the planning or execution phases by taking architectural "short cuts" in order to achieve high-priority functionalities. Brown et al. also researched the possibilities of increasing system agility through architectural anticipation (Brown, Nord och Ozkaya 2010). By developing an agile architecture, and anticipating emerging system needs, one is better able to manage Technical Debt. Inflexible architecture is common where technical debt occurs (Lane, Koolmanojwong och Boehm 2013).

There is evidently a relationship between architectural design and technical debt, and a clear and well understood architecture is a prerequisite for solid integration. We observe a gap between system architecture and design and system I&Q in AKSO, which limits most of the integration activities to system completion testing only. Unintentional Technical Debt accrued in the design and architectural phase is therefore not likely to be identified until the final stages of systems development. By implementing the Collapsed Vee approach, emphasizing system I&Q activities during system architecture and design, test related Technical Debt and interest can be reduced.

Case Study: Alternative integration strategies in an AKSO Subsea development project

This case study was conducted in an ongoing subsea development project in AKSO. Through interviews with stakeholders with concerns or interests related to system thermal I&Q, we have estimated an accrual of Technical Debt in the development lifecycle. Our findings are classified in a Technical Debt trade space and linked to the Project Execution Model (PEM) used by AKSO.

The PEM Process

In AKSO, all major system development projects must follow the Project Execution Model. This model describes the main activities and milestones which should be covered and controlled by the Systems Engineers, throughout the development project.

The PEM plan serves, among several functions, as a guideline for establishing the steps necessary for verifying thermal requirements and analysis. The intended process is not consistently followed by every sub-project. Evidence shows that some of the sub-projects align their work with the Computational Fluid Dynamics engineers during the early conceptual stages, whilst other sub-projects wait until detailed design has been concluded. *Tie in and strctures*, consistently delivers systems exceeding the thermal performance specified by the system requirements. A comparison revealed that *Tie in and structures* emphasizes a different approach to thermal integration of the systems they develop, as opposed to *Structures and Manifolds* and *XMT systems*. They work closely with the CFD engineers from early phase system definition, including the SI in architecture and initial design of the system. By taking into account all internal stakeholders and treating the CFD engineers as an internal interface, *Tie in and structures* is able to deliver systems performing well above the thermal requirements. Interviews indicate that this is often a biased decision based on previous experience of implementing analysis work in the design process. The *Tie in and structures* team see the benefit of early input and integration of their designs, whilst the other sub-projects delay this as the CFD engineers input might require the modification of the adopted designs. There is evidently a mentality present in some of the sub-projects that the system should be designed first before insulation is applied. The CFD engineers are therefore not included until detailed designing. In this way the sub-projects is taking on uncontrollable Technical Debt with subsequent interest.

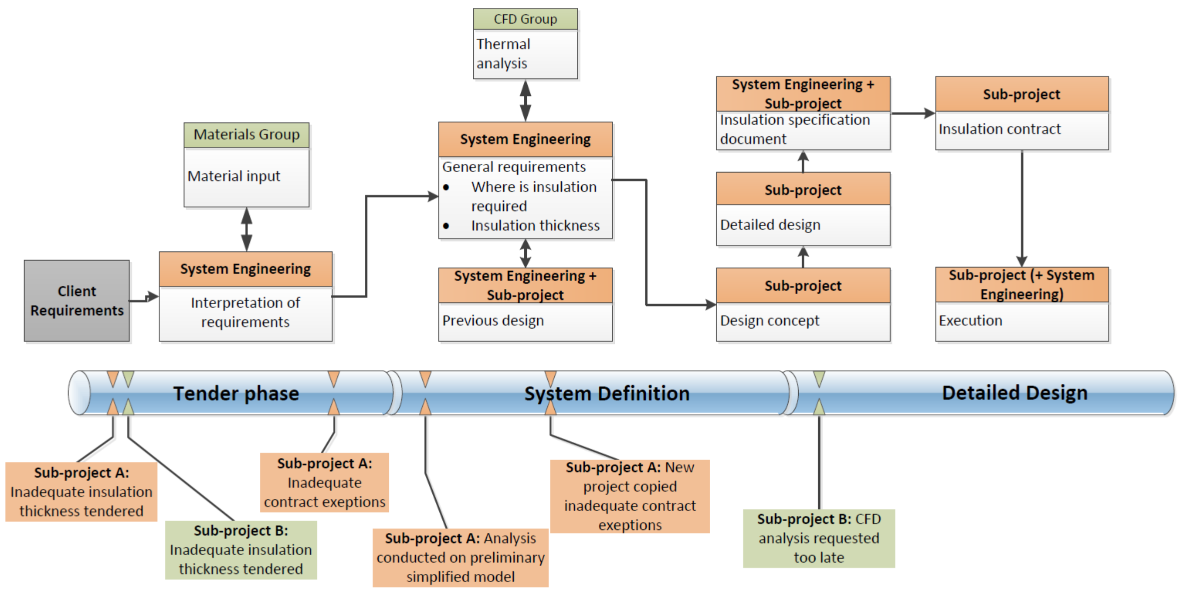

Figure 5. Occurrence of Technical Debt in *Sub-project A*and Sub-project B identified in the PEM process.

In interviews with personnel from the CFD engineers we identified that their involvement in systems development of systems varies. Optimally they should be involved from the interpretation of requirements all the way through to detailed design and support work during execution. The CFD engineers addressed the lack of technical experience in some of the sub-projects, indicating that the sub-projects do not have sufficient knowledge of how to take thermal requirements into account during system design. There is a lack of understanding as to how the geometrical design of the systems will affect thermal performance and not only the thickness of the insulation applied. The need for “correct analysis, early on” was a clear prerequisite in order to develop a thermally proficient system design.

The timeline above, from tender through to definition and the detailed design phases of system development, indicates where Technical Debt is accrued by the sub-projects in question.

Included in the timeline above is a flowchart showing the actions required by the PEM Insulation Global Procedure.

Technical Debt in Thermal Integration and Qualification

The case study has focused on the thermal verification process of two sub-projects in the same project, in order to identify an accumulation of Technical Debt. The research revealed several occurrences of Technical Debt related to the Integration & Qualification of the subsea systems in question.

The tender phase. Tender phases are usually subject to tight schedules. It is during these phases that the thickness of the insulation applied to the subsea systems is defined and priced for the customer. In order to exactly identify the required insulation thickness, substantial analysis would have to be conducted. Therefore the insulation thickness tendered is usually based on a combination of benchmarking against previous projects and calculated guessing. Tactical Debt is the debt incurred deliberately as a result of time constraints, in order to prioritize other tasks (Tom, Auruma och Vidgena 2013). In the analyzed project, two tactical benefits of not detailing the insulation thickness during the tender phase were identified:

1. Analysis on the insulation thickness was not prioritized during the tender phase due to time constraints. Detailed analysis would take too much time
2. In order to stay competitive during the tender process the tendered insulation price cannot be too high.

In the analyzed project we identified two cases of underestimation of the insulation thickness, which is identified in the timeline above. For the *XMT systems*, detailed analysis showed that the insulation thickness had to be increased from the original tendered thickness in order to adhere to the thermal requirements. This was not identified until the manufacture of the first system had started. The price of insulation in the contract did include a buffer to cover a possible increase, but it did not take into account the work related to applying the extra insulation. By introducing a buffer on the tendered insulation price *XMT systems* is somewhat able to control its Technical Debt. The interest of the Technical Debt will, in this case, be represented by the difference in cost of the insulation sold to the customer and the cost of the actual insulation applied. By introducing the buffer they are somewhat able to control the Technical Debt and interest, but as the tendered price is based on assumptions there are some related uncertainties.

Similar issues were identified in *Structures and Manifolds* where insulation had to be increased on most of the designed system. Evidence shows that this debt or interest was not controlled as there was no buffer included in the insulation pricing.

During the tender phase requirements are clarified and identified from the client specification documentation. In this phase any necessary exceptions or clarifications to contract requirements should be identified. For the case study, project exceptions were made during the tender phase for *XMT systems* which were not applicable for the designed system. These contractual exceptions were drawn up based on previous experiences, but were not relevant due to geophysical differences. This under-defined exception was also used by a later project.

In the event that the contract is won, and the project is put into execution there is no actual system or process to backtrack which shortcuts, assumptions or trade-offs have been made during the tender phase. After handover from the tendering team, a new project team will be handling the execution phase and the knowledge of shortcuts will have disappeared with the re-allocated personnel. The intentional debt therefore becomes unmanageable due to a lack of traceability. Other evidence shows that a similar case might result if the contract is not won. At some later stage the work performed for one tender might be picked up by another similar project in order to save time. The debt is therefore unknowingly adopted and duplicated.

Due to tight schedules, the tender phase is evidently a source of Technical Debt especially when related to the insulation thickness. Observations reveal that this Technical Debt is not always controlled and is usually taken on to serve a tactical benefit.

The System Definition phase. During the System Definition phase of the PEM process, where basic system architecture and design are established, we were able to identify several cases of design debt accumulated by both of the sub-systems investigated. Design and architectural debt (Tom, Auruma och Vidgena 2013) is the Technical Debt accrued by developing a sub-optimal design or architectural solution which does not take adaptability into account.

The Cross-over loop (X-Over loop) is tubing on the XMT system used for chemical injection in the production flow-line, or for equalizing pressure between the lines internally in the system. The X-Over line is uninsulated and will therefore affect the temperature of the horizontal part of the XMT. Analysis work initiated on a preliminary model of the XMT system during architecture phase, was intended to identify cold spots and detail the insulation design. This work was initially carried out by a resource not belonging to the CFD group. The analysis engineer worked independently without any support from the baseline organization. Due to resource availability the CFD engineers later had to overtake the analysis scope of work for the XMT. The CFD engineers revealed several issues on the analysis model used:

- Simplifications were made to the X-Over loop, leading to the analysis not capturing its effect on system cool-down. New analysis revealed a 63.64% increase in the temperature drop of the horizontal part of XMT due to the un-insulated X-Over loop.

- The analysis model did not employ the most conservative temperatures as mandated by contract, and was therefore not representative. The model had to be rebuilt

- The analysis was conducted on a preliminary model of the XMT and therefore the thermal profile identified was not representative for the system as built

- Due to the use of varying software for initial analysis a delay was caused before the faults were discovered. The simplifications and faulty model were not identified until the assembly phase of the project. Already machined parts had to be discarded and the X-over loop had to undergo design changes

This type of Unintentional Technical Debt is often a consequence of taking several smaller shortcuts. As with the financial debt accrued when using a credit card - it is often hard to identify and control. By conducting analysis work internally in *XMT systems* sub-project, with no interaction with the CFD engineers, the analysis work was seemingly more proficient.

Unintentional Technical debt was also identified in the Detailed Design phase of *Structures and Manifolds* system development lifecycle. Analysis work was requested after a design freeze of the system, based on the assumption that manifold piping is easy to insulate due to simple geometry. Additional cold spots were revealed at this stage. This led to substantial design changes and increased insulation thickness, subsequently impacting cost and schedule. Due to these new insulation requirements the assembly sequence also had to be altered, which further impacted the supply chain execution strategy.

Observations revealed several incidents of unintentional Technical Deb as a consequence of taking many small shortcuts during the architecture and design phases. The incidents identified are mostly uncontrolled and in some cases are not revealed until late in the development lifecycle.

Discussion

By comparing the findings from *Structures and Manifolds* and *XMT* with *Tie in and structures*, there is a clear difference in integration methodology. *Tie in and structures* shares its designs with the System Integrators during early conceptual design and weighs its input and knowledge for further design work. By utilizing the approach of front-loading I&Q through early analysis as visualized using the Collapsed Vee (Andersson 2014), the sub-project is able to develop systems satisfying thermal requirements. As expressed in multiple literature references (Epps 2012) (Brown, Nord och Ozkaya 2010) (Lane, Koolmanojwong och Boehm 2013) development activities related to systems architecture and design is usually where Technical Debt often occurs and can be managed. Comparisons from our research show that there are several examples from AKSO where work packages have decided to conduct important I&Q activities related to thermal design late in the development lifecycle. The case study shows that this is done with the intention to speed up the system development process, with the consequence of accruing

Technical Debt. We have also found evidence of unintentional Technical Debt, which is accrued without the knowledge of the systems developers.

The increased accrual of Technical Debt that we see evidence of in our research from the tender phase of the development lifecycle, can be explained by the fact that the conceptual architecture and design is established during this phase. Through our research we have found that the Technical Debt metaphor is a useful tool for communicating the consequences of conducting integration activities in the later stages of the development lifecycle. The classification of Technical Debt as intentional or unintentional has also been found useful in communicating how the Technical Debt it is accrued, as well as how it can be controlled.

Montgomery's research on the implementation of MBSE tools to facilitate integration work yielded lessons learned emphasizing the benefits of MBSI (Montgomery 2013). By involving System Integrators in design, there is a clear risk reduction related to system I&Q. In the systems developed by *Structures and Manifolds* and *XMT* clear functional gaps were observed between the required thermal performance and what is actually delivered to customer. The CFD engineers identified the lack of understanding of thermal effect in the sub-projects as one of the root causes for system failure; a belief that the systems geometry and insulation can be designed independently. With an absence of early integration the sub-projects run the risk of developing sub- optimal systems. *Structures and Manifolds* initially developed an underperforming system, which had to be modified after design freeze.

Montgomery adds that it is essential that the System Integrator does not inherit the developed system, but is included throughout the development process (Montgomery 2013). The knowledge and experience of the SI will help reduce the risk of coming testing activities. Evidence from *Tie in and structures* developed systems, where the system integrators are included early in the system design and evidence, confirms this. Our research indicates that in *Structures and Manifolds*, where the system geometry is defined prior to being thermally qualified, the system has a high likeliness of failure. Analysis of the manifold system identified several cold spots on the designed systems, relating to the sub-projects belief that it is solely insulation application which affects the thermal performance, and not geometry of the system.

Evidence indicates that the issues some of the sub-projects are having in relation to thermal I&Q may be caused by the lack of a structured work process. It was stated that the current procedure describing the work related to definition, design and execution of insulation is not compatible with the current process of thermal requirement and is therefore outdated. For several of the interviewees the procedure was unfamiliar. . This could be an explanation of the arbitrary level of contact of the various sub-projects towards the CFD engineers.

Conclusion

Throughout the conducted case study, we have revealed the benefits of implementing integration and qualification activities in parallel with system architecture and design. Our findings from the thermal verification process show that the presence of Technical Debt is substantially higher in the sub-projects that postpone integration activities. This is compared to the sub-project enforcing early Integration & Qualification, who consistently deliver systems satisfying thermal requirements. Technical Debt has also proven to be a useful tool for communication the consequences of postponing integration activities.

The case study further revealed that the strategy of front-loading the development process, e.g. by conducting critical system analysis as early in the development lifecycle as possible, including the Computational Fluid Dynamics group in early system design, varies greatly across the different sub-projects. The sub-projects that include the Systems Integrator early on have a greater likelihood of developing systems with little to no Technical Debt that adhere to thermal requirements. By utilizing computerized tools available for System Integration and Qualification, such as thermal analysis software, the possibility of developing a flexible and agile system increases.

The benefits identified in our research, on the effect of implementing system integrators in design and architectural phases through a Model Based System Engineering approach, is supported by the research references in the literature.

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Biography

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