29th Annual INCOSE international symposium
Orlando, FL, USA
July 20 - 25, 2019

A Practical Study on How Proactive Quality Approach Can Improve System Development Process to Ensure System-Effectiveness and -Performance

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Abstract. This paper investigates how a proactive quality approach can aid in improving the systems development process for a young company in the water cleaning industry. We apply a mix-method gap analysis between the existing system development process, and a future desired state. The paper conducts a case study on an existing water cleaning system. Additional data complements this gap analysis, including surveys in the company, analysis of time sheets, water samples from the system, customer- and employee-interviews, work sessions with employees, and observations. Our results show that the company lacks emphasis on activities related to systems engineering. For the case, forty-nine percent of hours spent in the operational life related to non-conformances of customer requirements. The paper also illustrates how to implement the two proactive quality tools that are familiar to the employees, namely risk assessments and Quality Function Deployment. In conclusion, a proactive quality approach, with focus on the familiar tools that are easy to implement, could reduce non-conformances in system operations and improve system performance.

Introduction

Proactive quality is an approach that uses methods and tools to prevent poor quality and errors before they occur, and to ensure that products conforms with customer requirements (Suleiman, 2017b). We investigate how a proactive quality approach can aid in improving the system development process for a young company in the water cleaning industry.

The water cleaning industry is experiencing a shift where decentralized wastewater-treatment systems (DEWATS) are gaining interest due to their capability to serve small communities. These systems may require less up-front investments and maintenance compared to large centralized systems. Furthermore, they are effective in scaling operation to stakeholder needs, and provide significant flexibility compared to centralized systems. (United Nations World Water Assessment Programme, 2017). The DEWATS are providing the customer with a “fit for purpose” treatment system. This is important as the required quality level of the water is different in industries, agriculture, power plant cooling, as emissions to the environment, etc. (Mis, 2017).

Several companies produce Module-DEWATS (MDEWATS) using containers. The container designs from each company differ based on which and how many wastewater-treatment stages or functions the companies design into each container. The containers also differ in interior layout, and how they are connected to each other (Lenntech 2018 , Eurowater A/S).

The case company (Company) is a relatively small company with less than twenty employees. At the time of this research, they had just delivered their first Module-DEWATS. Intended use includes construction sites, tunnel work, or long-term on harbors and offshore. Company has a 3-month time-to-market in constructing these wastewater-treatment systems from project start to the system is operational. Each container is responsible for a specific cleaning function or stage within the system. The containers are working in series with pipes connecting the containers. These pipes allow water to flow from one stage to the other. Figure 1 illustrates how the system pumps up wastewater from a well and discharges clean water into a river. This module-based concept provides similar functions as other DEWATS. It also allows for re-usage. This helps in reducing up-front investments in future projects.

As shown in Figure 1, the system consists of a modular set of containers that represent treatment stages. Supporting systems include monitoring system, power system and sampling system. There are two access points to take out physical water samples at inlet and outlet.

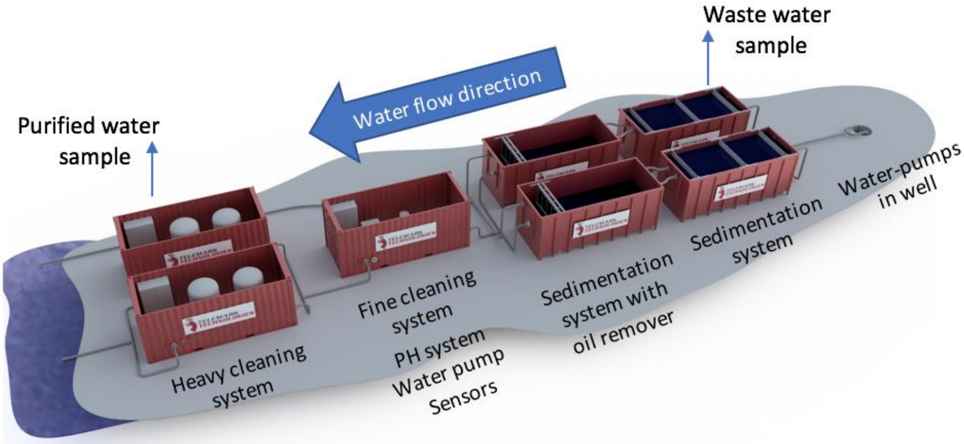

Figure 1. View of Module-DEWATS on Lierås (Telemark Technologies, 2018).

Company had improvement potential on certain systems engineering (SE) related activities. The Module-DEWATS was effective towards fulfilling the customer needs of purifying substances in the wastewater under the required measured levels. Yet, the performance of the Module-DEWATS was not at a satisfactory level. Some components and sub-systems failed as soon as the system became operational.

Proactive quality tools such as risk assessments and Quality Function Deployment (QFD) can be used to improve SE related activities (Boehm et al. 2017). A study by Ogawa and Piller (2006) showed that system failure is often not caused by component failure, but by not knowing customer needs. Rutledge and Mosleh (1995) described that the cause of component fails is often errors in design. Pollard (2016) explained that a component failure in one treatment stage will interrupt the follow-through of water for the rest of the system. This caused system failure and affected the systems performance. To our knowledge, there is lack of literature that describes how we can implement quality tools together, into a system development process, to serve the whole life cycle.

Research question. Based on the identified problems at Company we ask the following research question:

- How can a proactive quality approach aid Company in improving their system development process, and in ensuring that future wastewater-treatment systems are more effective and have a higher performance compared to the initial situation?

We establish the following sub research question to answer the main research question:

- How can the quality tools allow Company to improve their development process on systems engineering related activities?
- How can proactive quality tools aid in ensuring quality assurance for Company?
- How can quality assurance allow for more effective and higher performance of future wastewater-treatment systems created by Company?

This paper investigates how Company can use quality tools to pursue perfection from the very beginning of their system development process until the system is operational. The paper also looks at how Company can use quality tools throughout every phase of the system development process to ensure that they conduct small gains to improve quality at every phase.

The paper conducts a mixed method gap analysis to investigate the research question, supported by a solid literature review of quality tools. We identify the current situation in Company by analyzing the system development process, and an existing system that has gone through this process. Then, we utilize quality tools into the system development process. The paper illustrates how we applied a selection of the proposed tools. The purpose was to examine if the proactive quality tools help reducing the identified problems. Finally, the paper discusses and concludes.

Background

One definition of quality is to "achieve a satisfactory outcome for the customer". This definition entails that quality has three main characteristics: customer-focus, process-driven and metrics-oriented (Suleiman, 2017a). We can build quality assurance on this definition. We further include two principles that are "fit for purpose" and "right first time". This means that the product should be suitable for the intended purpose, and that mistakes should be eliminated through forward thinking and planning (NATO Communications and Information Systems School, 2015). Quality assurance therefore causes a proactive approach (Walden et al., 2015), and is an approach where the provider must conduct a process that has the customer objective in mind. This process must produce a product that is "fit for purpose" and "right first time".

Quality assurance is, as mentioned, a proactive approach. The benefit of a proactive approach versus a reactive approach is that the proactive approach reduces the true non-conformance costs to customer requirements. We often consider only the direct costs when dealing with either internal or external non-conformances to quality. Costs related to internal non-conformances occur before the customer receives the system. External non-conformance costs are those that occur when the system have become operational. With a reactive approach to quality, the focus and emphasis of the organization lie in dealing with internal and external non-conformances (Pyzdek and Keller, 2014). The iceberg principle as described by Campanella (1990) tells that the true non-conformance costs are often higher than the direct costs of non-conformances to quality. This is because the true non-conformance costs also include the indirect costs that we consider as hidden. This includes additional engineering time used on non-conformances, decreased system capacity, delivery problems, loss of reputation for the organization, etc. Studies conducted by Sailaja et al. (2015) and Pascual and Kumar (2016) discovered that the true non-conformance costs are 3 to 10 times higher than the direct costs. This is further emphasized by Walden et al. (2015) and Stecklein et al. (2004). They identified that costs to fix faults in a system increases in an exponential fashion throughout the system life cycle. This means that cost of errors identified through a reactive manner will be higher than prevention through a proactive manner. Ficalora and Cohen (2009) have stated that for companies, which have never focused on the use of proactive quality tools, the implementation effort of such tools appears as time-consuming. We describe the proactive quality tools later. The authors emphasized that the proactive quality tools actually saves time and cost by avoiding the true non-conformance costs to customer requirements.

Systems Engineering relates to quality assurance. According to the Systems Engineering Handbook, (Walden et al., 2015) quality assurance is there "to provide an independent assessment of whether development and SE processes are capable of outcomes that meet requirements". Sofer (2017) described how quality assurance is an activity that is a part of the scope of SE. However, the author described that the quality-assurance activity is also a part of systems management and system implementation. They created a Venn-diagram in to illustrate this.

The scope of SE does not involve all activities that are parts of the SE environment. SE itself can *enable* realization of a successful system. Nevertheless, to *ensure* a successful realization of systems, it is critical that we properly manage and execute activities outside the scope of SE. These activities are then normally parts of project management and systems implementation.

System-effectiveness and system-performance are important when measuring the level of quality. Where the viewpoint of the customer defines the measures of effectiveness (MOE), the viewpoint of the supplier defines the measures of performance (MOP). The MOE is the customer key indicator to evaluate if the delivered system satisfies their intended needs. We use the MOE on system validation against customer requirements. Because the MOE are used on system validation it reflects the a quality of "fitness for purpose" or for producing the intended results, and is in line with the definition of quality assurance (Roedler and Jones, 2005).

The supplier uses MOP to assess how well the system performs against the system level requirements. The MOP provides a system verification against system requirements. The supplier can further derive MOP down to technical performance parameters, where they use the technical performance parameters to measure critical technical parameters of system elements. These parameters are those that if not met, will reduce the system performance. We often state technical performance parameters in terms of size, range or operational requirements such as mean time to failure, fault tolerance, availability etc. (Roedler and Jones, 2005).

Quality tools and the system development process. A study conducted by Yeh et al. (2010), and literature by Pyzdek and Keller (2014) and Hodgetts (1998) have described tools of quality that improve the performance of the system development process. Measurement of performance here is amongst other things return on investment, customer satisfaction degree, product development time, product quality level, etc. By investigating these three literature, we identify tools of quality that improve the performance of the system development process. Pyzdek and Keller (2014) and Suleiman (2017b) has further described tools of quality that are proactive. We can thus, identify the following proactive quality tools that can improve performance of the system development process: Project evaluation sheet, Kano analysis, QFD (Quality Function Deployment), risk assessment through the usage of Failure Mode and Effect Analysis (FMEA) and supplier evaluation criteria. Table 1 describes these more in detail.

Systematic use of quality tools. Existing research shows how we can sequentially combine quality tools with different purpose to improve specific aspects of the system development process. This involves a combination in where the output from one quality tool becomes direct input to another. Lai et al. (2004) and Tontini (2007) have discussed the use of Kano analysis as an input to QFD. Juran and Gryna (1980), and Quality-One (2015a) have described the use of QFD as an input to FMEA. They further described how to conduct an FMEA analysis for each level at the QFD. This is to identify how top-level system, sub-system, part or production process can fail. Table 1 describes this more in detail.

Table 1 describes the identified proactive tools. These tools will improve performance of the system development process.

Table 1. Proactive quality tools with description and reference.

Quality tool	**Description**	**Reference**
Project evaluation sheet	Used as a standard of evaluation at top management to assess if they should initiate the project. Formed as a matrix-diagram that is a live document to reflect current organizational priorities. This allows for better judgment and justification for which project to pursue by evaluating each projects overall score. Should select the one that receives the highest score. Often used to evaluate projects feasibility towards expected quality level due to the triple constraint theorem.	Pyzdek and Keller (2014)
Kano analysis	A tool used to capture customer needs through "voice of the customer". It separates customer needs in three different types: must, wants and desirable. It aid in translating customer needs to customer requirements.	Akpolat (2004)
Quality function deployment (QFD)	A tool that allows us to translate customer requirements from Kano analysis with their corresponding importance ranking (where musts receive ranking 4 or 5, wants ranking 3 or 4 and desirables ranking 1 or 2), to top-level system requirements. By creating subsequent houses, we can break down the top-level system requirement down to sub-system requirements and eventually production requirements. We should write the system requirements in a *nonfunctional* manner. QFD is therefore a tool that allows the developer to select the winning concept by ensuring that every action made in system development process is towards creating a product that fulfill customers need. Requirements for each level, which receives the highest importance ranking, can be a direct input to a design- or a process-risk assessment. The reason to analyze the requirements with highest ranking is that risks regarding the system- or production-elements based on these requirements will have the most impact on the overall customer requirements. Goal is to identify risks before they materialize to reduce probability of dealing with non-conformances in end-product.	Burn (1990) Blanchard (2008) Verma et al. (2009) (Quality-One, 2015a) (Quality-One, 2015b)
Concept-, Design- and Process-risk assessment	Risk assessment is divided into three distinct process based on where in the system life cycle we conduct them: - Design risk assessment: Conducted to analyze system design before releasing it to production. Goal is to improve design of sub-systems and components to ensure that the operation of the system is safe and reliable during its operational life. - Process risk assessment: Conducted to analyze the production and assembly processes. Goal is to improve production process to ensure building of a system happens in in a safe manner, with minimal downtime, scrap and rework. - Concept risk assessment: Conducted to analyze the functions of a system at the early concept and design stage. Goal is to have a	Stamatis (2003) Carlson (2012) FMEA-FMECA.com

	high-level analysis of the entire system, made up various sub-systems. Focus is on functions and relationships that are unique to the system as a whole (i.e. do not exist at lower levels) We can use FMEA tools in all three types of assessment. First, we identify the failure mode, which is the manner in how the system or component fails. Then we analyze the following for the failure mode: consequence level (C) of the effects of failure mode, probability level (P) that causes for failure mode will occur and detection level (D) to identify cause of failure mode based on current design controls. Multiplication of C, P and D gives us a risk priority number (RPN). There can be described recommended actions in the analysis to reduce C, P or D, which in turn reduce the RPN. As low as reasonably practicable (ALARP) principle decides if we should implement the recommended actions.	(2006) (Standards Australia & New Zealand Committee, 2013).
Supplier evaluation criteria	Outsourcing production of parts to suppliers can reduce costs and improve quality of products. This is because suppliers often have the technology or knowledge to produce parts more efficiently. This reduces costs and improves the quality of the products. The criteria are a matrix-diagram in where companies can document and compare different suppliers' dedication, capability and stability in providing the required parts. We establish the criteria to ensure that the sub-systems or components provided from the supplier do not weaken the overall quality of the product.	Gryna (2001) Beil (2009) Fox (1993)

Research Method

This paper uses a mixed research method, illustrated in Figure 2. This method emphasizes on the usage of one primary research method, but is complemented by secondary research methods to support the findings in the primary method (Clark and Ivankova, 2016). For this project, the main research method is the qualitative research method of gap analysis. This analysis is about looking at the "as-is" state to evaluate how Company currently conducts their system development process and the output of this process, which is an existing Module-DEWATS. This is analyzed against a "to-be" state of the system development process where we evaluate how this state can produce Module-DEWATS that are more effective and have a higher performance than today situation (Business Dictionary). We therefore conducted a case study on an existing Module-DEWATS that has gone through the current system development process. Figure 2 shows this case study as a green circle.

Clark and Ivankova (2016) have described that using a mixed method research on case studies such as the one for Company, is a useful framework to understand a complex case. This is because the method incorporates multiple research approaches to validate researchers' interpretations about the case. By adding quantitative information to a qualitative study, this allows us to get a better understanding of the context of the case study and validate our qualitative findings.

We conducted additional qualitative methods such as two separate work sessions. One work session was with a systems engineer, project coordinator and sales manager in Company to map out the original conducted system development process. This was done since there did not exist any complete illustrations of this process. The systems engineer has two years of working experience and has an education in process engineering. The project coordinator has six months of experience in this job and four years of previous experience as a document controller in the same company. The sales manager has thirteen years of experience in this role with extended responsibilities as production manager on projects. The map of the system development process was the foundation for an interview with the same systems engineer where the aim was to identify the SE related activities that Company does not conduct or have improvement potential. We conducted the other work session with the systems engineer to validate that the revised system development process where we implemented the QFD (Quality Function Deployment) and design risk assessment were correct. This correctness regards if the system requirements we identified ourselves were appropriate for the system used on Lierås.

Other qualitative methods involved observations in the offices of Company and secondary research. We used these methods to verify the data gathered from interviews. Secondary research such as previous literature from the background section provided evidence on whether the quality tools can improve the system development process for Company.

We identified how the system conforms to requirements by both quantitative and qualitative methods. The qualitative method consisted of an interview with customers on the case study from Bane-Nor and Mesta. The stakeholders from Bane-Nor were two persons: the construction manager with five years of experience on this type of projects and the environmental advisor with seven years of experience in this role at construction sites. The stakeholder from Mesta was the construction manager with five years of experience in this position. The quantitative method consisted of analyzing time usage on the project to identify time spent on non-conformances to requirements and in what system elements the non-conformances occurred. The quantitative method further consisted of analyzing physical water samples to evaluate the system performance.

We gathered additional quantitative data through a survey on the internal stakeholders in Company involved in the system development process. Figure 2 shows all the quantitative data as a red circle. We conducted the survey to reach a larger sampling size to analyze how the focus on quality was in Company prior to our research to see if quality improvement is necessary. We also applied the survey to understand which quality tools that the employees were familiar with from previous work, they claimed.

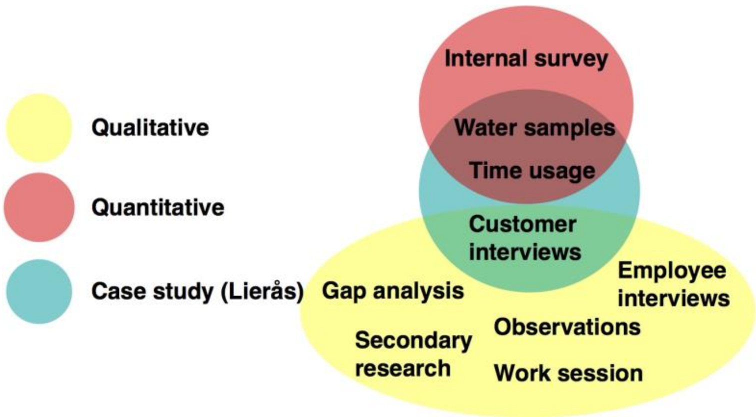

Figure 2. Overview of the mixed method research approach

Current system development process in Company

Organizational focus on quality. We wanted to get an understanding of how the focus on quality has been in Company prior to our research. This was to evaluate if an improvement on quality assurance is necessary in the company. To achieve this, we used a survey developed by Hodgetts (1998) to understand if employees in Company have the right focus on quality or if there were any misunderstood beliefs among the employees. We used the answers from the survey to evaluate if there truly were a need for quality assurance improvement in the system development process for Company. The survey consists of ten questions. Each question goes on a scale from 1 to 10. On each end of the scale, there is a statement. The people answering the question should give a number that reflects how much they agree with each statement. The maximum score of the survey is 100 points. Figure 3 shows the average score for each department.

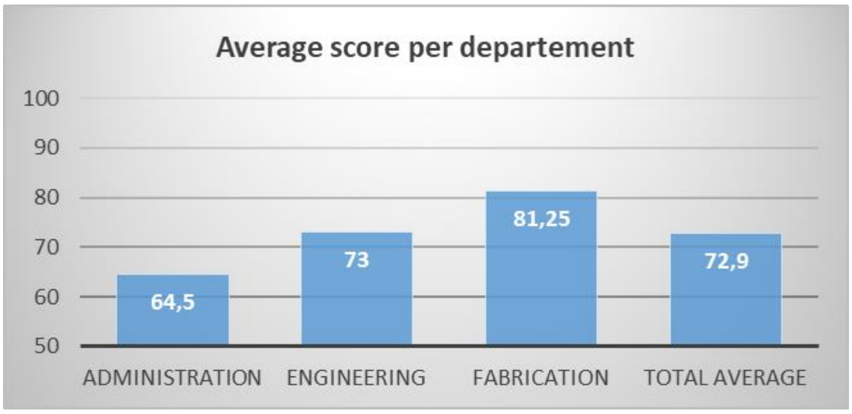

Figure 3. Departments in Company average score on right focus on quality

We applied the interpretation key described by Hodgetts (1998) to understand where each department stands on their quality performance. Hodgetts described the following for each score range:

- 90-100 points: Your organization is on the cutting edge of quality understanding.
- 70-90 points: Your organization has not fully accepted some of the truths about quality and has some mistaken beliefs that need examination.
- <70 points: Your organization needs to review its philosophy and operating data and work to dispel the myths that currently cloud its thinking regarding quality.

We applied Hodgetts survey on Company and 71, 4% of the employees answered the survey. We therefore believe the data to be valid and reflect the view of the whole organization. Hodgetts survey received an average score of 72, 9%. This score shows us that there is improvement potential in all departments in Company on their focus on quality assurance. Per the interpretation key, Company has overall not fully accepted some of the truths about quality. Statements that received the lowest score from the survey were “perfection should be actively pursued” and “large and small gains are necessary to improve quality”. These statements are the truths about quality that employees in Company mostly misunderstand, and that they would like to improve in the system development process.

System development process compared to SE related activities. We wanted to get an understanding of what kind of SE related activities from the Venn-diagram in Figure 4 that Company does not conduct or have an improvement potential in their current system development process. Sofer (2017) has already described in the background that these activities are important to both *enable* and *ensure* a successful system that satisfy customer needs.

We conducted a work session with three people in Company to map the system development process in the organization by using a process flowchart. Flowchart is a graphical tool that we used to develop an understanding of the current “as-is” state of system development process to analyze where Company can implement improvement steps to achieve a desired “to-be” state of their system development process (Pyzdek and Keller, 2014, American Society for Quality, 2018). Appendix 1, shows the current “as-is” state of the system development process. The “to-be” state is a state where Company does conduct SE related activities that can *enable* and *ensure* realization of a successful. These people in Company were a Systems engineer, Project coordinator and Sales manager as described from the research method.

Afterwards, we used the chart as a basis for an interview with the Systems engineer to understand what SE related activities that Company does not conduct or have an improvement potential in their system development process. The interview involved the Systems engineer and us comparing the process flowchart of the system development process against the Venn-diagram in Figure 4. We told the Systems engineer to highlight activities from this Venn-diagram that they either do not conduct or have improvement potential. We then processed these answers from the Systems engineer where highlighted the activities they do not conduct with the color red and the ones that have improvement potential with the color yellow. Observations of the working culture in Company and the flowchart of the "as-is" state verified the answers in this interview.

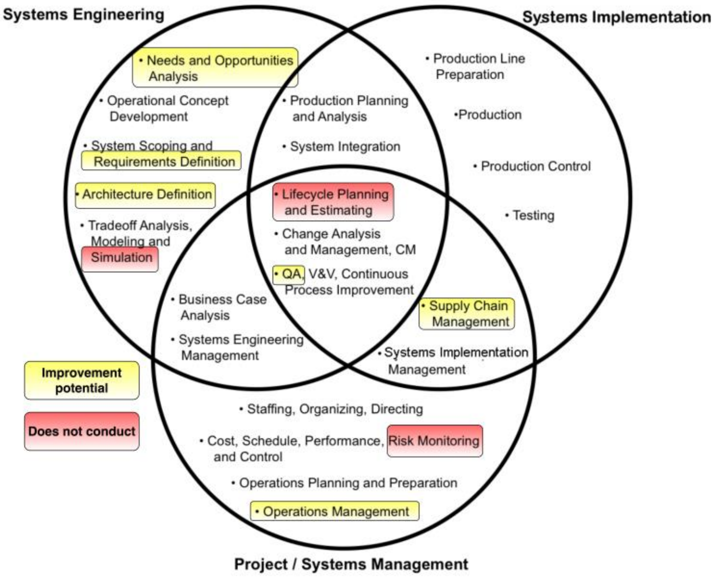

Figure 4. Venn-diagram of SE related activities. Adapted from Sofer (2017). Red indicates the activities that Company "does not conduct", and yellow the ones with "improvement potential".

We revealed in the interview that Company does not conduct the following red boxes from Figure 4:
- ***Risk Monitoring.*** They do not conduct risk assessments of their designs or the production process.
- ***Lifecycle Planning and Estimation.*** They do not have any strategy on what to do with retired sub-systems or components that they cannot use into the given or future systems.
- ***Simulation***. Company does not conduct simulations before building the systems. This is due to limitations in the software they use and the engineers lean on previous knowledge in designing the systems.

We revealed in the interview that Company has improvement potential on the yellow boxes from Figure 4:
- ***Architecture Definition.*** They do not conduct an architectural design process, because the higher-level functional architecture of the system is fixed. Almost each container stands for one cleaning function as shown in Figure 1. However, an architectural design process can link system requirements to design selection, regarding which cleaning functions to include in the system.
- ***Needs and Opportunities Analysis.*** Company does not document their need and opportunity analysis when justifying why they should consider one project in front of another. This makes it difficult for third parties in the organization to understand why the leadership select or disregard projects.
- ***Supply Chain Management.*** The company has a list of preferred suppliers. However, they do not document the comparison of suppliers directly against each other when figuring out which one fulfills the required criteria better, to produce the given part.

- ***Requirements Definition.*** Company does not have separate documents for customer- and system-requirements. They do neither have any documented importance weighting of these customer requirements.
- ***Quality assurance.*** Company does modify their system for different purposes. However, they do not live by the "right first time" principle as they have quality related issues, as shown later in the costs section.
- ***Operations Management.*** The company is the operator of the system. However, because of non-conformances in the system, the company invests a lot of work force into operating it, as shown later from the cost section.

Case Study: Lierås-tunnel project

As mentioned from the research method, we wanted to conduct a case study on a Module-DEWATS that has gone through the original system development process. This was to identify how the system conforms to customer- and system-requirements. The aim also was to identify what sub-systems of the Module-DEWATS Company can improve to enhance its effectiveness and performance in future projects. The Module-DEWATS that Company uses on the Lierås-tunnel is one that has gone through this system development process. We must first describe the customer requirements to understand the effectiveness and performance of the system.

The Lierås-tunnel is going through extensive rehabilitation during the period 2017-2021 under the direction of Bane-Nor and main contractor Mesta. The execution of the work will be in November 2017, Easter 2018 and in six weeks periods each year from 2018 to 2021. Mesta will carry out the work. The contractor will generate a lot of wastewater from work related to washing the tunnel in the given periods. (Norconsult, 2017a, Bane Nor, 2017).

Company has received a subcontract to build and operate a system that can continuously purify the wastewater leaving the construction site during the given working periods. The regional county has issued a discharge permit and Bane-Nor have developed an environmental monitoring plan. These are requirements that Company must follow. The discharge permit states the accepted levels of toxins and chemicals that Company can discharge into the nearby Lier-river through their system (Skålevåg and Engen, 2017, Engen, 2017). The permit requires that Company take physical water samples two times a week for heavy metals. A continuous measurement of turbidity and PH levels is required. Company must take samples from the wastewater entering the system to document the cleaning effect of the plant. They must send all gathered data to Bane Nor digitally (NorConsult, 2017b).

How Company originally conducted the system development process on Lierås project

Costs. We analyzed quantitative data on time sheets acquired from Company on the number of hours used on the project from its initiation on 22nd of January 2017 to its current date of 20th of April 2018. We analyzed this data for primarily two reasons. First was to understand where in the system development process the company spends time on non-conformances costs to requirements. This was to reveal in the company lives by the "fit for purpose" and "right first time" principle of quality assurance. It was also to identify if there were room for quality improvement in their existing system and working practices. Second reason was to identify in what system elements from Figure 1 that the non-conformances occurred. These non-conformances costs to requirements are what we further identify as costs of poor quality.

Figure 5 shows the hours Company used on different phases of the system development process and in the operational life of the Module-DEWATS on Lierås. We can see from Figure 5 that employees in Company used almost half the time on the system while it was operational to fix Costs of poor quality. These hours used on Costs of poor quality represent 16 percent of the total time used on the project. We need to emphasis that the data is not completely accurate and probably can be higher. This is because not all the registered work on the time sheets has a work description. The actual costs can even be higher when we factor in the iceberg principle described in the background section.

Through the time sheets, we identified that the Costs of poor quality consist of three major groups. This was Costs of poor quality related to rework on the system, power problems and other small issues causing downtime on the system. The rework on the system consists mostly changing frozen pipes between the working periods in November 2017 and Easter 2018. The power problems relate to empty fuel tank on the generator and power failure. The downtime relate to draining water out of the system due to inspections, to fixing surveillance camera and to changing out components as leaking valves and gauges. We identify where in the system these Costs of poor quality occur by looking at the system build-up shown in Figure 1. The Costs of poor quality likely relate to the following sub-systems: piping system, the external power system that was a mobile fuel-driven power generator, power distribution system and the monitoring system. The company therefore lack on quality assurance because they did not build the system "right first time" as shown by the Costs of poor quality.

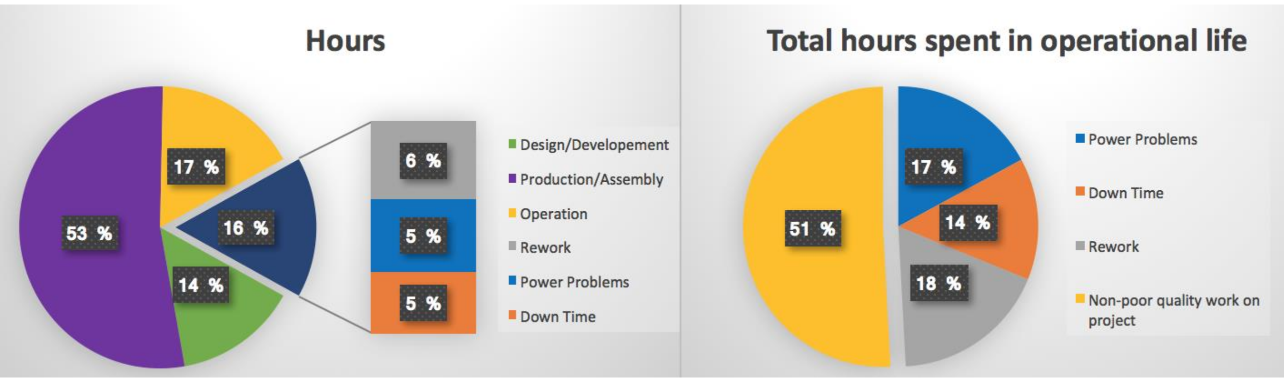

Figure 5. Percentage of hours spent on in each phase of system development process on Lierås project

System effectiveness. The customers from Bane-Nor and Mesta are overall satisfied with the Module-DEWATS. The values of purified water are well within the required levels stated from the discharge permit. Bane-Nor has expressed some improvement potential on the systems effectiveness. One issue is the possibility for continuous operation. This is required as the discharge permit states that turbidity and PH should be measure continuously. This has been difficult because of the mentioned Costs of poor quality such as power problems and downtime on the system, which as interfered with the operation.

System performance. We have identified two distinct issues with the system performance. The first is that physical water samples from the first cleaning period in November 2017 shows us that the performance of Module-DEWATS solution is not at a satisfactory level. The system is well within the required levels stated from the discharge permit. However, the physical water samples show us that some of the measured values of toxins exiting into the Lier-river have higher values than measured wastewater entering system. This gives us an indication that either the system does not purify some of the toxins or the measured data from the sampling system is biased. The performance of the system is therefore not at a satisfactory level because of this non-conformance. The second issue relates to the requirement from customer about continuous operation. There has been interruption in operation of the system due the mentioned Costs of poor quality on downtime and power problems.

Revised system development process in Company including quality tools

Proposed quality tools to implement. The tools described in the background section emphasize on implementation of quality tools to improve specific phases of the system development process. We wanted to take this one step further and see how we could collectively use the tools over multiple phases to evaluate the whole system development process. This was to ensure that Company improves their focus on quality by ensuring that they pursue perfection actively throughout the system development process, and that each tool aid in small gains to improve quality in every phase of the system development process. We therefore propose to implement the following quality tools into the existing system development process that Company already conducts: Kano analysis, project evaluation sheet, QFD (Quality Function Deployment), concept-, design- and process-risk assessment and supplier evaluation criteria. We propose to implement these tools because the background literature has identified them as proactive and can improve the performance of the system development process.

Where Company can implement proposed quality tools in system development process. We created a new process flowchart where we implemented the mentioned quality tools into Company existing system development process. Appendix 2 shows this new process flowchart. Yellow colored boxes show the tools we propose to implement. The activities with other colors are those that Company already conducts, which we uncovered through the work session mentioned earlier. Some of the tools have a direct connection to each other. Table 1 makes the basis for these connections. The chart shows how the tools collectively serve over more stages of the system development process in Company. We implement the tools in the following phases of the existing system development process in Company:

- ***Project procurement & tendering***. Company can implement the project evaluation sheet after they have acquired the competitive basis. The company receives this basis today from announced projects on DOFFIN or they ask potential customers about projects. DOFFIN is a national data base for notices of procurement in the utility sector (Agency for Public Management and eGovernment). In this manner, they can now document their need and opportunity analysis on which projects to pursue. Company can conduct the concept risk assessment after they have written the offer and conducted the initial SE of the system design. SE that Company conducts at this stage is often a high-level design of the system used as a basis of negotiation with the customer. The risk assessment can therefore as described in Table 1, highlight concerns about the system based on the high-level SE, SE domain, etc. that Company can discuss with customer before taking the project.
- ***System design & development.*** Company can conduct the Kano analysis after the kick-off meeting with the customer. This is to systematize the customer needs from this meeting into customer requirements with weighted importance. They can use these requirements as an input to the QFD tool. The QFD tool translates these customer requirements into system requirements at multiple system levels, and process- and production-requirements. They can now have separate documents showing customer- and system-requirements. Company can send the system requirements into a design risk assessment as Table 1 states and conduct an FMEA. This risk assessment can be a part of the iterative design process so that this process reflects more towards Boehm (1988) spiral model.
- ***Purchasing.*** Company can implement the supplier evaluation criteria after they have searched out potential suppliers for each outsourced part of the system. This allows for a documented comparison of suppliers when figuring out which supplier should produce the given system parts.
- ***Production & assembly.*** Company can retrieve the process requirements from the QFD and put these into a process risk assessment. They can use this assessment when they hand the project

over to production. The production team can apply this risk assessment on the required production processes, before carrying the production out to produce the Module-DEWATS.

Which quality tools Company should focus on first, is something we want to investigate further. Rosenberg and Mosca (2011) have described that employees in an organization can be resistant to changing the way of conducting activities, if the changes affect them. They highlight amongst other reasons that fear of the unknown, disruption of routine and increased workloads are some of those that cause this resistance amongst the employees. We therefore wanted to understand which of the described quality tools that were familiar for employees in Company. We asked the employees in the same survey used to map the organizational focus on quality, which of the quality tools that are familiar to them. We analyzed the results based on what department the employees were working in Company. This was to understand if employees involved in the given phases shown in Appendix 2 indeed were familiar with the tools intended for them to use in their stage of the system development process. Table 2 shows the intended department and level of familiarity within that department.

Table 2. Intended department to use the quality tools and their level of familiarity

Quality tool	**Intended department involved**	**Familiarity % respondents**	**Purpose**
Project evaluation sheet (matrix-diagram)	Administration & Engineering	4 of 6 = 66,7 %	Project feasibility
Kano analysis	Engineering	1 of 2 = 50 %	Fit for purpose
QFD (Quality Function Deployment)	All	6 of 11 = 54,5 %	Fit for purpose
Concept-, Design- and Process-risk assessment	All	7 of 11 = 63,6 %	Right first time
Supplier evaluation criteria (matrix-diagram)	Administration	4 of 4 = 100 %	Fit for purpose at lower cost

We used the familiarity percentage and compared this against the background section when figuring out which tools Company should implement first. We identified the following:

- The supplier evaluation criteria and process risk assessment receive less priority. Company consider the design of the system as complete after going through the project procurement & tendering phase, and system design and development phase. As mentioned by Walden et al. (2015) and Stecklein et al. (2004), costs to fix faults in a system increases in an exponential fashion throughout the system life cycle. Therefore the focus should lay in the project procurement & tendering phase, and system design and development phase where there is still possibilities to do design changes at lower costs.
- Company should therefore consider implementing project evaluation sheet, design risk assessment and QFD, which are tools that the employees in Company have the most familiarity with from previous work. These tools are rather early in the system development process when we consider the costs to make changes in the system design. These tools do further aid in each aspect of the definition of quality assurance: “fit for purpose” and “right first time”.

Implementing quality tools on Lierås project

We implemented the QFD and design risk assessment, on a theoretical basis, on the Lierås project. The aim was primarily to examine how Company can use the tools in the system development process to improve on the identified non-conformances to customer requirements. We disregarded the project evaluation sheet. This was because the sheet is only applicable when evaluating different projects against each other to figure out which one to take forward. We did not have any comparative basis to other projects, since the Lierås project was the first the company conducted for these type of water-treatment systems.

Quality function deployment

We have based on our interview with the customers from Bane Nor, weighted the customer requirements from the discharge permit and environmental monitoring plan. The Kano analysis is where we weighted the requirements. We then inserted these requirements into the QFD (Quality Function Deployment) with a representative importance as described from the background. Level 1 of the QFD in Appendix 3 shows the customer requirements on the left-hand side. It shows the top-level system requirements on the top-hand side. Different symbols show the strength of relation between the customer requirements and system requirements. Appendix 3 describes the strength of each of these symbols. We brought with us these system requirements over to level 2. We listed the same system requirements on the left-hand side and the sub-system requirements for each sub-system on the top-hand side. This level shows the existing sub-systems on the Module-DEWATS used on Lierås. These are the same sub-systems as described in Figure 1. Each sub-system has their own system requirements that we analyzed against the top-level system requirements. The sub-system that received the highest importance score on the bottom line on level 2 are those that affect the customer requirements most. We identified the following sub-systems that affect the customer requirements most on the Lierås project: piping system, monitoring system, power system, sampling system and water pumping system. Afterwards, we sat down with the same Systems engineer in Company and showed him the two levels of the QFD from Appendix 3. He went over the QFD to validate that the strength of relation we had identified between the customer requirements, system requirements and sub-system requirements indeed were correct for the system used on Lierås. This ensured that we had identified the correct system elements that affect the customer requirements most.

Design risk assessment

We conducted a design risk assessment on an individual basis. The aim with this assessment was to illustrate for Company how they could mitigate non-conformances from the original project by focusing on the system elements with highest importance from the QFD. We implemented the sub-systems from the QFD level 2, which achieved the highest score from the QFD. The background literature emphasizes that reason to analyze the system elements with highest ranking is that risks in these elements will have the most impact on the overall customer requirements if they do materialize. The following failure modes for the identified sub-systems from the QFD were analyzed in the design risk assessment shown in Appendix 4: disrupted surveillance for monitoring system, biased data for sampling system, disrupted water flow for water pumping system, leaking valve for piping system and loss of power for power system.

The identified system elements in the design risk assessment that we conducted in Appendix 4 is targeting some of the non-conformances we identified through the Costs of poor quality in the original Module-DEWATS used on Lierås. It targets the piping system due to leaking valve, the power problems due to empty fuel tank, and the monitoring system due to fixing surveillance and gauges. We gave each of the system elements an Risk priority number (RPN) score that reflect our observations on how Company have designed the current system regarding probability for failure to occur, consequences of failure and how easily Company can identify these failures. We looked on the RPN score for each system element and evaluated the score against the ALARP principle to decide which of the failure modes that Company should mitigate. We identified that all sub-systems except the monitoring system had failure modes that Company should mitigate to reduce the RPN. The reduction in the RPN could have reduced the chance for the risks to materialize in the correlating system element. This could then have reduced the probability of non-conformance materializing to the most important customer requirements shown on left-hand side of the QFD level 1 in Appendix 3. This is because we identified these system elements as those that have the most impact on customer requirements due to their high importance score as described earlier.

How the system development process, System-effectiveness and -performance is improved

We revealed from the original project that the company has some improvement potential in their existing system development process and the Module-DEWATS, which is the output of this process. The company lacks on quality assurance because creation of the system is not "right first time" as shown by the costs section. The customers have expressed that there are improvement potential regarding the system effectiveness. This relates to continuous operation, monitoring and sampling aspects of the system. The system performance is not at a satisfactory level as shown from physical water samples from November 2017 and because of the Costs of poor quality. There is improvement potential on the system development process regarding emphasis on SE related activities.

To understand how the system development process, system-effectiveness and –performance is improved we needed to answer our main research question. This was "How can a proactive quality approach aid Company in improving their system development process, and ensuring that future wastewater-treatment systems are more effective and have a higher performance compared to today situation?" We had to answer the three sub-research questions in order to answer the main question.

The first sub-research question is "How can the quality tools allow Company to improve their development process on SE related activities?" We identified that Company does not conduct or have improvement potential on certain SE related activities as shown in Figure 4. The quality tools that we identified should improve Company on some of the identified activities. This is due to the intended application of each of the tools as Table 1 describes more in detail. Company can now to conduct risk assessments of their concept in the tendering phase to highlight issues or concerns about the proposed system when negotiating with customer. They can conduct risk assessments of their design and production processes. Company can now conduct the need and opportunity analysis in a documented manner through the project evaluation sheet to justify the project selection for third parties in the organization. The Kano analysis allows Company to document the importance weighting of customer requirements in a separate document. By retrieving system requirements from every level of the QFD (Quality Function Deployment), they can now document these system requirements in an own document. The supplier selection criteria allow for a documented comparison of suppliers to decide which is suited to provide sub-systems or components. The tools ensure that Company pursue perfection actively throughout the system development process and each tool aid in small gains to improve quality in every phase of the system development process , which were their misunderstood beliefs about quality.

The second sub-research question is "How can proactive quality tools aid in ensuring quality assurance for Company?" The background section has already stated that the tools are proactive quality tools. Table 1 describes this and the right-hand column in Table 2 emphasizes the tools purpose. As shown in the case study, the QFD and FMEA together could have aided in quality assurance for Company. The study showed a link between the non-conformances that exists in the current Module-DEWATS identified by the Costs of poor quality, and how the use of these tools could have prevented the non-conformances to occur in the operational life. The tools therefore could aid Company by eliminating the non-conformances before the system became operational through forward thinking and planning of possible failures. This was one of the issues identified from the Venn-diagram in Figure 4, where the company lacks on the "right first time" aspect of quality assurance.

The third sub-research question is "How can quality assurance allow for more effective and higher performance of future wastewater-treatment systems created by Company?" To answer this question we need to base our answer on the previous two questions. The improvement in the SE related activities as emphasized in a previous question should aid in improving the effectiveness of the system. Sofer (2017) states that SE related activities enables and ensures a successful realization of systems, and a successful system is one that satisfy customer needs. Roedler and Jones (2005) further states that MOE (measures of effectiveness) is a measure on how well the system satisfy customer needs. The more SE related activities Company conducts successfully, should therefore aid the company to satisfy customer needs better, which in turn should improve the system effectiveness. In Figure 6, we have tried to illustrate this connection between the quality tools to system effectiveness.

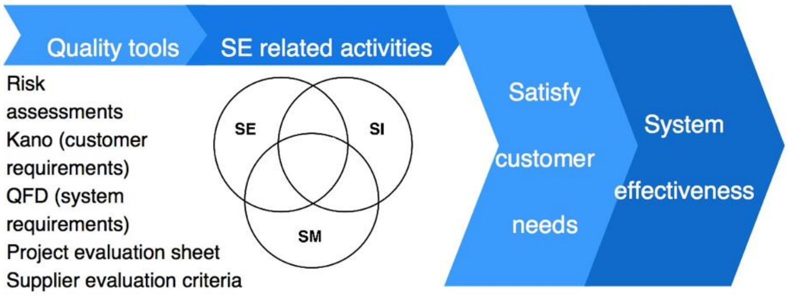

Figure 6. Improved SE related activities satisfy customer needs better, which improve effectiveness

Firstly, the new system development process aid Company in having own defined system requirements, through the use of QFD that they now can compare the system performance against. Secondly is that the QFD and FMEA, as illustrated earlier could have aided in quality assurance for Company where the non-conformances could have been eliminated before the existing Module-DEWATS became operational. By ensuring that Company deals with non-conformances internally, the end product will have less defects in its operational life. This in turn should yield a more stable and reliable system, where technical performance parameters such as mean-time-between-failure and system availability should increase compared to the existing system. An increase in technical performance parameters should in turn aid in a higher system performance as Roedler and Jones (2005) states. Figure 7 illustrates this connection.

Figure 7. How quality tools can increase system performance through defect reduction.

To answer the main research question a proactive quality approach improves the system development process for Company. This is because the quality tools improve on SE related activities that Company did not conduct before. The tools further correct the misunderstood focus about quality that employees had in the organization prior to our research. The proactive quality approach improves the system effectiveness by improving on SE related activities, which in turn should yield a higher system effectiveness. The approach improves the system performance by ensuring quality assurance in the system development process where the company deals with non-conformances internally in their organization. This should in turn reduce defects in the system when it is operational, which should yield a more reliable system that can aid in a higher system performance.

Discussion of findings

How can a proactive quality approach aid Company in improving their system development process, and in ensuring that future wastewater-treatment systems are more effective and have a higher performance compared to the initial situation?

We establish the following sub research question to answer the main research question:
- How can the quality tools allow Company to improve their development process on systems engineering related activities?
- How can proactive quality tools aid in ensuring quality assurance for Company?
- How can quality assurance allow for more effective and higher performance of future wastewater-treatment systems created by Company?

There are plausible reasons for why Company lacks focus on a proactive quality approach, and why they do not conduct all these SE-related activities. Some of the identified non-conformances can be justified, especially since this is the first Module-DEWATS to be delivered. Company will eliminate many of the non-conformances when they develop the next similar system through this process because they learn from their mistakes. A proactive quality approach will force Company to conduct more activities in their system development process.

We believe the long-term benefit for Company lies in improving their system development process on the SE related activities through a proactive quality approach. The improved system development process will probably require investments and extra costs to implement the proposed quality tools. However, based on the background literature and the identified costs used on fixing non-conformances, which stands for 49% of the time used on the system in its operations, we believe that Company should improve their current system development process. This is supported by Ficalora and Cohen (2009), who describes that costs invested in a proactive quality approach will reduce the costs used on non-conformances. It is further supported by the “iceberg principle” described by Campanella (1990), and by the exponential increase in cost of quality (Walden et al., 2015) and (Stecklein et al., 2004).

A focus on a proactive quality approach in the system development process can have a wide impact on SE related activities, and not only quality assurance. Literature has described that risk assessments and QFD has a wider impact. However, we identify additional quality tools that can affect other SE related activities. This is because the nature of the described quality tools forces a company to focus on other SE related activities to ensure a proactive quality approach in their company. Our research further shows how system developers can use quality tools with different applications throughout the whole system development process to ensure that they pursue perfection to quality at every phase of the system development process. This involves a proactive approach from the moment a company considers creating a new system, until it is operational.

This research on a proactive quality approach can be applicable for other young SE companies. Such companies will most likely have improvement potential on certain activities related to SE during the first run-through of their system development process. This research-paper can be applicable as a template for other companies on how they can improve their own system development process to yield higher system effectiveness and performance. The companies should first identify their improvement potential, and relate to SE activities. We have identified different proactive quality tools that target different activities, and in turn yield higher effectiveness and performance of their own systems. In turn, the companies can use our research to identify where in their own system development process they can implement the suggested quality tools.

Similar studies. Alsyouf et al. (2015) showed in their case study that the use of QFD and FMEA amongst other tools, yield a higher product performance. This study identified the same findings as us. The usage of the tools yielded a product that was more reliable and stable, which the author further explained lead to less service and maintenance. However, their study only focused on the product, while we also investigate how and where the tools can improve the system development process on SE related activities to improve the system effectiveness. We have not been able to identify other studies that discuss this aspect. We need to emphasis that some of the quality tools date from the late 1950s to the 1980s, are therefore relatively old. There is a reason to believe that there are relevant publications that are more recent. If so, we have not been able to identify these.

This study has several limitations. We asked the employees in Company which quality tools they were familiar with, but the survey did not really explain in details the different tools. This could therefore give a wrong impression regarding the respondents' familiarity with each of the quality tools. We should also have regarded other factors such as cost versus impact for the company when deciding on which of the given tools to implement first. This was difficult since costs for implementation most likely differentiates from company to company.

Our research looks into one company only. In addition, the company does not really have an existing quality system. Given the state of systems engineering at the company, almost any added structure and discipline could improve outcomes. Our results shows that QFD, risk assessments, and project evaluation sheets could improve outcomes (less defects, higher customer sat, etc.), but so could other tools and methods as well.

Another limitation of this study is that the illustrated use of the QFD and design risk assessment in the new system development process is a theoretical study. We cannot be completely sure that proactive quality approach will improve the system development process for Company before we carry it out in real life and measure the effectiveness and performance of the new Module-DEWATS created from this process.

We found literature to be inconsistent regarding how to use quality tools. Different sources had different opinions whether to state the system requirements in a functional or nonfunctional manner in QFD.

Conclusion

This research illustrates how a proactive quality approach can aid Company in improving their system development process, and how to ensure that future wastewater-treatment systems are both effective and have a high performance. A proactive quality approach ensures that the company deals with non-conformances, and thus improves operational reliability. We have classified and analyzed more than twenty quality tools, and compared for the wastewater-treatment system. Recommend for first implementation are project evaluation sheet, design risk assessment and Quality Function Deployment (QFD). The reasons for this recommendation are that the employees are familiar with these tools, and the tools are early in the system development process when it is less expensive to make changes in the system design. Furthermore, the tools aid in each aspect of the definition of quality assurance: "fit for purpose" and "right first time". In general, the company should pursue quality at every life-cycle phase, and use a proactive approach from the moment the company considers creating a new system until it is operational.

This work can serve as a reference point to companies that want to understand synergies between different quality tools, and to ensure a proactive quality approach throughout the life cycle. As further work, we recommend that Company implements our recommendations, and measures if the new Module-DEWATS indeed yields a higher effectiveness and performance.

Acknowledgments

Many people have aided us in conducting this research. We want to thank Company for opening their doors, and allowing us to conduct the research on their organization. We want to thank all the employees throughout the organization for taking their time answering surveys and interviews, productive working sessions and providing us with relevant data. We also want to thank customers on the given case study for taking their time to answer our questions.

Appendix

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Appendix 1: System development process “as is”. The process flowchart shows how Company conducts their existing system development process. The rationale behind this chart is that there did not exist any charts of the whole system development process in the company. We therefore needed to create the chart to understand what SE related activities that lacks emphasis in Company. We also used the chart to understand where in the system development process in Company there is a potential for quality improvement. Green boxes represent handover from one development phase to another. Blue boxes represent decision points. Red boxes represent documents.

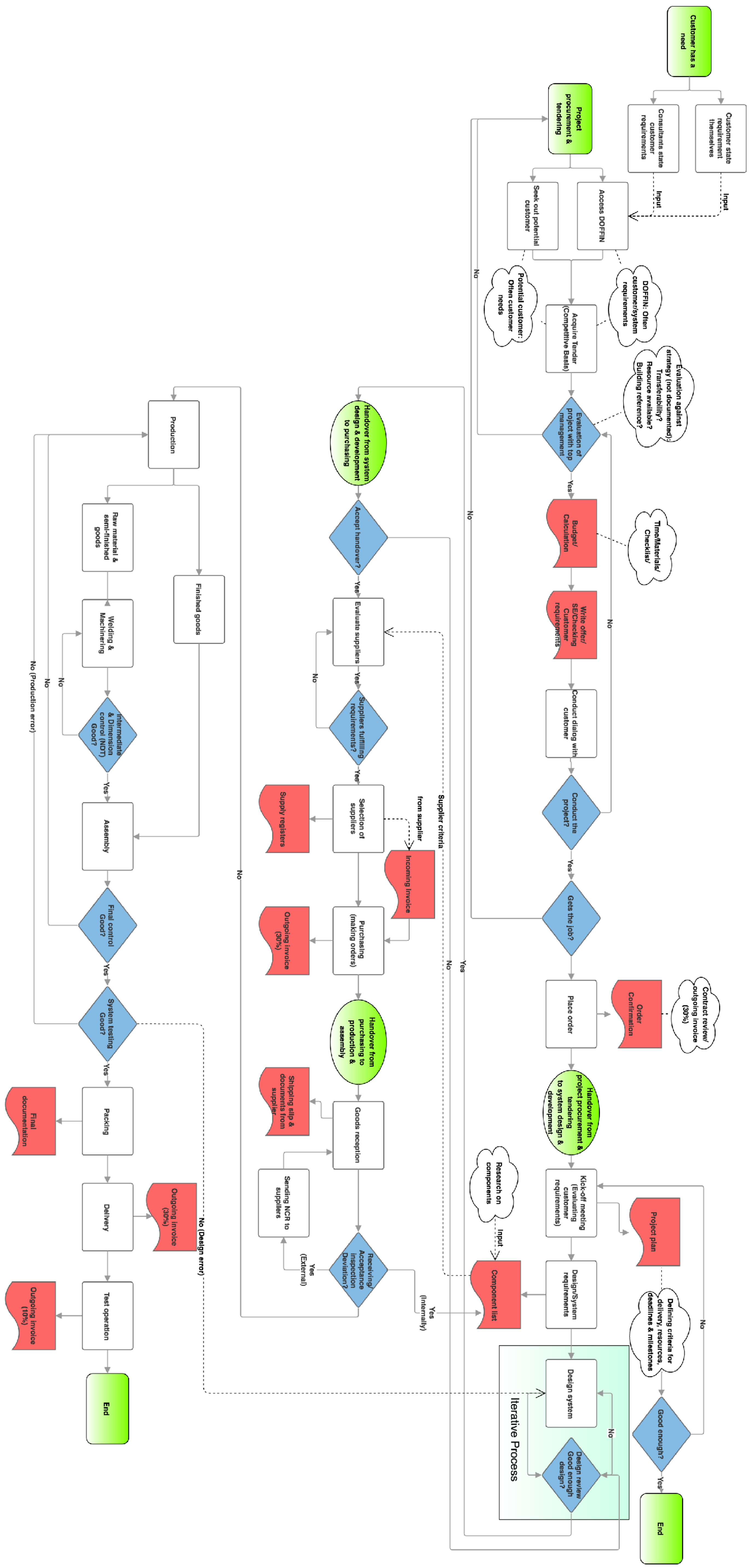
Appendix 2: System development process “to be”. The process flowchart shows where Company can implement the proposed quality tools into their existing system development process. The rationale behind this is to show, based on the background literature, where Company can implement the quality tools into the system development process. The rationale is also that it shows how the tools collectively can serve over more phases of the process. The green circular boxes represent the handover from one phase to another in the system development process. It also shows how each tool interacts with the other tools and other activities that Company already conducts. The changes made from the “as is” of the system development process is shown by yellow colored boxes.

Appendix 3: Quality function deployment. We used the QFD to translate the customer requirements with their weighted importance to first level system requirements. We then translated these system requirements to second level system requirements. The second level requirements are sub-system requirements. The rationale behind this was that the QFD now ensures that every sub-system we create are based on the customer requirements and in this manner providing a system that is fit for the intended purpose of the customer. The output of the second level system requirements also worked as an input into the design FMEA shown in the next appendix.

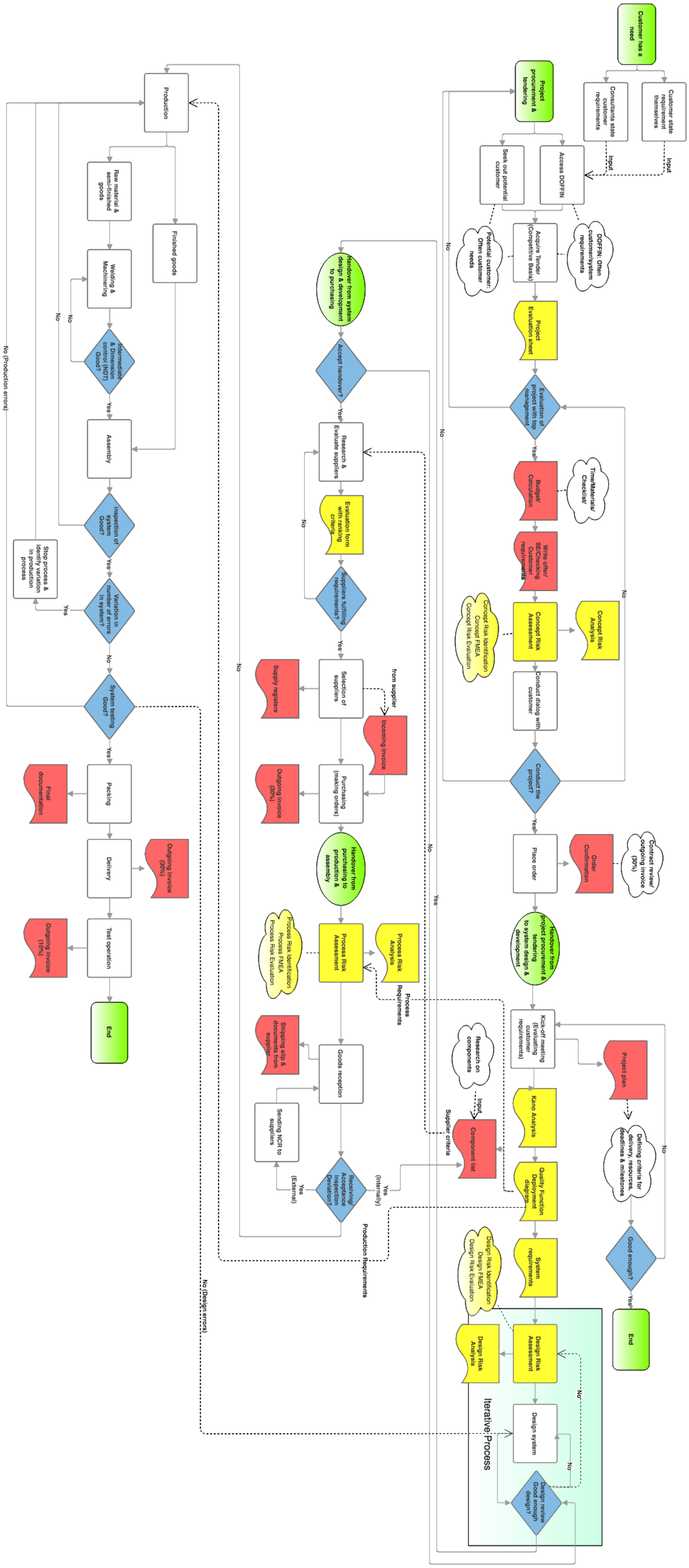
Appendix 4: Design FMEA. This FMEA works in the same manner as the concept FMEA. However, the difference is that we here implemented the sub-systems, based on the second level system requirements from the QFD in the previous appendix. In this FMEA, we have selected the system elements, which achieved the highest score from the QFD. The rationale behind this selection is that these elements, because of their score, are those that affect the customer requirements most. If these elements fail, then there can be non-conformances to customer requirements. The FMEA is therefore there to prevent that these element do not fail to ensure conformance with customer requirements. The other reason for doing this FMEA is that it also could have mitigate possible Costs of poor quality before they materialized. The FMEA targets the power problems related to empty fuel tank and piping system due to leaking valve. It therefore shows that the tool could have aided Company in mitigating the Costs of poor quality before they materialized and in this manner ensured conformance with the customer requirements.

The design FMEA also shows the Risk priority number (RPN) by coloring, which is represented by the as low as reasonably practicable (ALARP) principle. The color region decides what mitigations we should take. Red color is a region where risks are intolerable, no matter what benefits the activity may provide and treatment is necessary. Yellow color is a region where risks are tolerable, if the benefit outweighs the cost. Green color is a region where risks are acceptable and no treatment is necessary.

Appendix 1: System development process "as is"



Appendix 2: System development process "to be"



Appendix 3: Quality function deployment

Level 1: Customer requirements to system requirements

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Waste water plant layout (Infrastructure)	Waste water plant capacity	Energy consumption	Portability (Modularity)	Reliability (Mean time between failure)	Time to change filters (Response time)	Piping dimensions	Component costs	Purification effectivity	Software suitability	Plant flexibility (adjusting load)	Operability	Flowthrough time of waste water	Plant deployment (Time required to set up on site)	Documentation handling	Security	Supportability	Data integrity/quality
1	9	6,1	5,0	Water cleaning	O	O					O		Θ				O				▲	
2	9	4,9	4,0	User friendliness	▲			▲		O					Θ	Θ			▲		O	
3	9	6,1	5,0	Safety	▲				O						▲					Θ	▲	O
4	9	6,1	5,0	Documentaion of sampling															Θ			Θ
5	9	4,9	4,0	HMS	O														▲	Θ		
6	9	4,9	4,0	Customer service					▲	O	O				O			Θ	▲		Θ	
7	3	6,1	5,0	Connection to Lier river	O	▲		▲														
8	9	6,1	5,0	Bellow permit level									Θ									▲
9	3	6,1	5,0	Pollution Containment	▲								O		▲					▲		
10	9	4,9	4,0	Independent operation										Θ		O					O	
11	9	3,7	3,0	Mobility	▲			Θ			▲							Θ				
12	9	3,7	3,0	Conitnuous operation		Θ	▲		Θ					Θ	▲	O						
13	9	4,9	4,0	Periodic measuring	Θ														▲			O
14	9	4,9	4,0	Water capacity	▲	Θ					Θ				O		Θ					
15	9	3,7	3,0	Online measuring	O									Θ								Θ
16	9	4,9	4,0	Price			O					Θ	▲	▲				▲			▲	
17	9	3,7	3,0	Continuous measuring	O				Θ							▲						O
18	9	3,7	3,0	Time saving		▲		Θ	O	▲		▲	▲		▲		Θ	▲				
19	9	4,9	4,0	"Siltent" operation	O	O	▲									Θ		▲			▲	
20	9	2,4	2,0	Sandardized reporting/feedback process															O		Θ	
21	9	1,2	1,0	Areal effectivity	Θ			▲			▲		▲	O								
22	9	2,4	2,0	Results interpreted from suppliers side										Θ					O		Θ	Θ
23																						
24																						
25																						
				Target or Limit Value	Bellow 900 sqr meters	Up to 46 L/sec		30% up/down scaling	99% up time	Less than 5 hours from notified	Accuracy of +- 3 mm	At market average	Bellow levels from permit (2020 requirements)	Processing time < 0.001 seconds	Improve/reduce L/Sec of cleaning to +-50%	Operate up to 800 hours without physical interaction	Bellow 200 seconds	2 days	0% deviation from customer/governmental requirements	0 damage of human or animal lives	Available 18/5	No unbiased data
				Difficulty (0=Easy to Accomplish, 10=Extremely	0	5		8	8	3	2	6	4	0	1	7	3	8	6	2	5	9
				Max Relationship Value in Column	9	9	3	9	9	3	9	9	9	9	9	9	9	9	9	9	9	9
				Weight / Importance	168,3	119,5	23,2	78,0	100,0	32,9	81,7	47,6	137,8	140,2	92,7	117,1	95,1	90,2	89,0	104,9	139,0	159,8
				Relative Weight	9,3	6,6	1,3	4,3	5,5	1,8	4,5	2,6	7,6	7,7	5,1	6,4	5,2	5,0	4,9	5,8	7,7	8,8

Level 2: System requirements to sub-system requirements

Row #	Max Relationship Value in Row	Relative Weight	Weight / Importance	Quality Characteristics (a.k.a. "Functional Requirements" or "Hows") / Demanded Quality (a.k.a. "Customer Requirements" or "Whats")	Power system: Reliability (Mean time between failure)	Power system: Capacity	Water pumping system: Capacity	Water pumping system: Stability	Power distribution system: Adjustability	Power distribution system: Capacity	Sedimentation system: Effectivity	Sedimentation system: Capacity	Heavy cleaning ssytem: Effectivity	Heavy cleaning system: Capacity	Post polishing/fine cleaning system: Effectivity	Post polishing/fine cleaning system: Capacity	PH system: Effectivity	PH system: Capacity	Piping system: Capacity	User interface system: User friendly	Monitoring system: Security	Montioring system: Data controllability	Monitoring system: Documentation	Sampling system: User friendly	Sampling system: Data controllability	Sampling system: Documentation	Waste removal system: Environmental protection
1	3	9,3	168,3	Waste water plant layout (Infrastructure)			▲				O	▲	O	▲	O	▲	O	▲	O	O				▲			
2	9	6,6	119,5	Waste water plant capacity	▲	Θ	Θ		▲	Θ		O		O		O		O	Θ								
3	9	1,3	23,2	Energy consumption	Θ	Θ	Θ		▲	O	▲	O	▲	O	▲	O	▲	O			▲						
4	9	4,3	78,0	Portability (Modularity)															Θ	▲							
5	9	5,5	100,0	Reliability (Mean time between failure)	Θ		O	O	▲	▲	O	▲	O	▲	O	▲	O	▲	▲		Θ						
6	9	1,8	32,9	Time to change filters (Response time)			▲	O			O				O					Θ		O					
7	9	4,5	81,7	Piping dimensions			▲					Θ		Θ		Θ			Θ								
8	9	2,6	47,6	Component costs		▲	▲		▲	▲	▲	▲	Θ	Θ	▲	▲	O	O	▲	▲	▲			▲			
9	9	7,6	137,8	Purification effectivity					Θ	Θ	Θ	▲	Θ	▲	Θ	▲	Θ	▲	▲			O		▲	Θ		
10	9	7,7	140,2	Software suitability				▲	O				▲		▲		▲			▲	▲	Θ	O	O			
11	9	5,1	92,7	Plant flexibility (adjusting load)		▲	Θ	O	Θ	▲			O	▲	O	▲	O	▲	O								▲
12	9	6,4	117,1	Operability	Θ			▲	O				▲		▲		▲			Θ	▲	O		▲	O		▲
13	9	5,2	95,1	Flowthrough time of waste water		Θ	Θ		▲	▲				Θ		Θ		Θ									
14	9	5,0	90,2	Plant deployment (Time required to set up on site)		▲		▲	▲	▲	▲		▲		▲		▲		Θ		▲			▲			
15	9	4,9	89,0	Documentation handling																O		▲	Θ		O	Θ	
16	9	5,8	104,9	Security	O			▲													Θ			O	O		Θ
17	9	7,7	139,0	Supportability	Θ	▲					▲		▲		▲					O	▲	O		▲			O
18	9	8,8	159,8	Data integrity/quality							▲		▲		▲					O		Θ	Θ		Θ	Θ	
19																											
20																											
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25																											
				Target or Limit Value	Provide power 24/7	Provide power 24/7'	Up to 46 L/sec	800 hours run before maintenance	Contionous power to 3 treatment stages & adjustable	Provide power to safety critical systems 24/7	Bellow permit level	Up to 46 L/sec	Bellow permit level	Up to 46 L/sec	Bellow permit level	Up to 46 L/sec	Bellow permit level	Up to 46 L/sec	Dimensioned in a manner that flow is up to 46 L/sec	Max 1 hour of educating system user	24/7 Surveillance	Accuracy = +-1 µm	All data stored electronically for min 5 year	Physical sample retrival max 1 time per week	Accuracy = +-1 µm Continuity	Date registered electronically & 3rd parties interpretable	Removal min 1 time per week
				Difficulty (0=Easy to Accomplish, 10=Extremely	8	7	2	4	3	4	1	2	1	2	1	2	1	2	3	5	3	6	2	7	9	6	1
				Max Relationship Value in Column	9	9	9	3	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9	3	9	9	9
				Weight / Importance	211,7	138,1	198,4	62,1	182,8	154,7	143,3	89,0	188,3	162,1	172,8	141,2	156,1	106,0	241,8	180,7	132,1	224,0	146,4	79,0	198,7	123,2	86,4
				Relative Weight	6,0	3,9	5,6	1,8	5,2	4,4	4,1	2,5	5,3	4,6	4,9	4,0	4,4	3,0	6,9	5,1	3,8	6,4	4,2	2,2	5,6	3,5	2,5

Description of relationship between what (left-hand side) and how (right-hand side) from diagram:

Legend		
Θ	Strong Relationship	9
O	Moderate Relationship	3
▲	Weak Relationship	1

Appendix 4: Design FMEA of system elements from QFD level 2

Item/ Function	Potential Failure Mode(s)	Potential Consequence(s) of Failure	C[1]	Potential Cause(s)/ of Failure	P[2]	Current Design Controls	D[3]	RPN	Recommended Action(s)	Action Results			
										New C	New P	New D	New RPN
Monitoring system	Disrupted surveillance	Loss of data integrity/quality	6	Software malfunction, unreliable gauges	3	Warning system, Online surveillance	1	18	None	6	3	1	18
Sampling system	Biased data	Loss of data integrity/quality	8	Manual handling	6	Sampling procedures	6	288	Automation in procedure or training of personnel	5	4	3	60
Water pumping system	Disrupted water flow	Loss of continuous operation, reduced plant capacity, operability	7	Blocked inlet (by large particles), to little pull from pumps	4	Inspections	6	168	Sensor or camera for surveillance of water flow and building fence before inlet	4	3	2	24
Piping system	Leaking valve	Contamination, Poor cleaning, reduced capacity	7	In-correct dimensions	6	Inspections	3	126	Simulations, Factory sub-system testing, 2 stage valve system	3	3	2	18
Power system	Loss of power	System down-time	8	Empty fuel	5	Cameras monitoring power distribution, inspections	5	200	Online surveillance of fuel level	8	4	2	64

[1]Consequence
[2]Probability
[3]Detectability

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Biography

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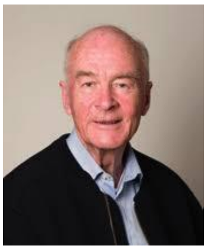

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