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Development of Indicators for Maintenance Management within Integrated Planning

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Trondheim, October 2017

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Preface and Acknowledgement

This thesis is submitted for the degree of Doctor of Philosophy at the Department of Mechanical and Industrial Engineering under the Faculty of Engineering at the Norwegian University of Science and Technology.

My interest and curiosity for the maintenance management field started growing while I was working on my master thesis. During this time, I had the opportunity to collaborate closely with industry. This inspired me to scrutinize and consider improvements of existing theory in the field of maintenance.

During my time as a PhD researcher, I have experienced both successful and challenging periods. As in life in general, we must face whatever we meet, find good solutions and move on, often with the help of resourceful people around us. I first and foremost thank professor Per Schjølberg for invaluable guidance and support during the project period. With his experience and deep knowledge, he both supported my ideas and concepts and challenged me at the same time with new perspectives. He also provided me the possibility to meet and work with many knowledgeable and inspiring people in the maintenance society.

I also thank my co-supervisor Jørn Vatn for his support during this PhD report. In particular, his course and guidance in maintenance optimisation has been of particular value in contributing with new knowledge. I also wish to thank Peter Falster, Cecilia Haskins, and Marvin Rausand for advising me in scientific writing.

This PhD project is also a result of several industrial research initiatives and the compulsory work at the university. First and foremost the research programme IO Center (Center for Integrated Operations in the Petroleum Industry), provided me with a better understanding of the research topic of Integrated Planning in the oil and gas industry. The innovation project Green Monitor and the EU-project Maritime Unmanned Navigation through Intelligence in Networks (MUNIN) also provided me with valuable new knowledge.

It has been a great privilege to be involved in two research groups with workshops and seminars; both the RAMS group and the Production Management group at the department. Although these groups have different research topics, it has been valuable for me to receive varied feedback and inspiration in my research. And after all, maintenance is not an isolated field from the production field, neither in theory nor in practice.

In addition to my main supervisor, I also wish to thank several other co-authors who have played an important role in this research: Bjørn Andersen, Ragnhild Eleftheradis, Jan Ola Strandhagen from NTNU, Brage Mo from MARINTEK, Camilla Langeland and Terje Skarlo from Sør-Trøndelag Univeristy College, Thor Inge Bernhardsen and Martin Kirknes from Statoil, Odd Myklebust from Sintef and Leif Tore Larsen from Hydro Aluminium.

Finally, I am forever grateful to my closest family in Trondheim for both their support and patience; my dear wife Silje and my three wonderful children Johannes, Solveig and Berit.

Summary

The increased level of complexity in production and global competition demands a reliable plant capacity. To achieve this, it is of vital importance to integrate maintenance with production planning. This PhD research develops new concepts denoted as integrated planning (IPL). In particular, sound key performance indicators (KPIs) are developed for maintenance planning. The KPIs will communicate between maintenance planning and production planning through an interaction mechanism to the environmental system which is production planning. In this thesis the overall scientific objective is develop theory and methods in IPL that balance maintenance management with other priorities related to physical assets. The main objective has been decomposed into five research objectives:

1. identify and evaluate existing models for maintenance planning strategies;
2. develop a framework for IPL;
3. evaluate and structure existing maintenance KPIs for IPL;
4. further develop KPIs applied for IPL; and,
5. demonstrate and evaluate the KPIs in the IPL framework.

The contributions to science are:

- identification and evaluation of the Deming cycle and static indirect maintenance grouping to be sound strategies in maintenance planning and suitable for further development towards IPL;
- semi-static maintenance strategy applied as a maintenance optimisation strategy in IPL;
- a framework for IPL;
- a framework for structuring KPIs;
- evaluation of overall equipment effectiveness (OEE) and maintenance backlog as two appropriate indicators for IPL;
- evaluation of the hidden factory and the need for developing the profit loss indicator (PLI);
- development of the KPIs maintenance backlog and PLI; and,
- demonstration of KPIs in different industrial contexts.

The contributions to practice apply to several sectors and industry branches. Through their industrial challenges it was possible to demonstrate KPI frameworks and PLI. This should in future contribute to reduced minor stoppages, downtime, defects, and revenue losses.

My proposal for further research in this field is modelling and development of the existing theory in IPL. There is also a need for conducting more testing in industrial cases in an attempt to bridge the gap between theory and practice. The 5C model for cyber-physical systems seems promising as a further direction after implementing PLI.

Structure of Thesis

This PhD thesis has two main parts:

- Part I – Main report: This part contains the background, research challenges and questions leading to the research objectives with defined limitations. In addition, this section describes the theoretical background together with the research methods and research design. Finally, this part presents and discusses the main results from the articles with concluding remarks and directions for future research.
- Part II – Articles: The second part is a collection of articles that represents the contributions of this research. In total 3 journal articles and 9 conference papers are included.

Overview of Appended Articles

Article 1 (Conference paper):

Rødseth, H. (2014) Maintenance Optimisation for Integrated Planning. *Safety, reliability and risk analysis : beyond the horizon : proceedings of the European Safety and Reliability Conference, ESREL 2013, Amsterdam, the Netherlands, 29 September-2 October 2013.* CRC Press. [1]

Article 2 (Conference paper):

Rødseth, H. & Schjølberg, P. (2014) Integrated Planning - A novel concept for maintenance management. *EuroMaintenance 2014.* Finland. [2]

Article 3 (Conference paper):

Rødseth, H. & Mo, B. (2015) Integrated Planning in autonomous shipping – Application of maintenance management and KPIs. *10th World Congress on Engineering Asset Management,* WCEAM 2015, September 28, 2015 - September 30, 2015, 2015 Tampere Talo, Tampere, Finland. [3]

Article 4 (Conference paper):

Rødseth, H., Langeland, C. & Myklebust, O. (2012) Integrated Key Performance Indicators - A Tool for Smarter Decision Making. *Proceedings of IWAMA 2012 - The Second International Workshop of Advanced Manufacturing and Automation.* Tapir Akademisk Forlag. [4]

Article 5 (Conference paper):

Rødseth, H., Strandhagen, J. O. & Schjølberg, P. (2015) Key Performance Indicators for integrating Maintenance Management and Manufacturing Planning and Control. *Advances in Production Management Systems - Innovative production management towards sustainable growth: Service, Manufacturing, and Resilient Value-chain.* Tokyo, Japan. [5]

Article 6 (Journal paper):

Rødseth, H. & Schjølberg, P. (2014) The importance of asset management and hidden factory for integrated planning. *Advanced Materials Research.* [6]

Article 7 (Journal paper):

Rødseth, H. & Schjølberg, P. (2017). Maintenance backlog for improving Integrated Planning. *Journal of Quality in Maintenance Engineering* **23**(2). [7]

Article 8 (Journal paper):

Rødseth, H., Skarlo, T. & Schjølberg, P. (2015) Profit loss indicator: a novel maintenance indicator applied for integrated planning. *Advances in Manufacturing,* 3**,** 139-150. [8]

Article 9 (Conference paper):

Rødseth, H., Schjølberg, P., Kirknes, M. & Bernhardsen, T. I. (2015) Increased Profit and Technical Condition through new KPIs in Maintenance Management. 10th World Congress on Engineering Asset Management, WCEAM 2015, September 28, 2015 - September 30, 2015, 2015 Tampere Talo, Tampere, Finland. [9]

Article 10 (Conference paper):

Rødseth, H. & Andersen, B. (2013) Early Warning Indicators for Integrated Planning. *In:* AUSTRALASIA, P. M. A. O. (ed.) *PMAA 2013 Conference.* New Zealand. [10]

Article 11 (Conference paper):

Rødseth, H., Myklebust, O., Eleftheriadis, R. & Schjølberg, P. (2016) Improving maintenance by profit indicators. *Advanced Manufacturing and Automation V.* WIT Press. [11]

Article 12 (Conference paper)

Rødseth, H. and P. Schjølberg (2016). Data-driven Predictive Maintenance for Green Manufacturing. *Advanced Manufacturing and Automation VI*, Atlantis Press. **24:** 36-41. [12]

Abbreviations

CLD	Causal loop diagrams
CMMS	Computerized maintenance management system
EAM	Enterprise Asset Management
ETO	Engineer to order
IPL	Integrated planning
JIPM	Japan Institute of Plant Maintenance
KPI	Key performance indicator
LCC	Life Cycle Cost
MP&C	Manufacturing planning and control
OEE	Overall equipment effectiveness
PDCA	Plan-Do-Check-Act
PLI	Profit loss indicator
PSA	Petroleum Safety Authority
RCM	Reliability centred maintenance
RQ	Research question
TPM	Total productive maintenance

Key Terms and definitions

Asset [13]:

Item, thing or entity that has potential or actual value to an organisation.

Asset management [13]:

Coordinated activity of an organisation to realize value from asset.

Key performance indicator [13]:

A metric measuring how well the organisation or an individual performs an operational, tactical or strategic activity that is critical for the current and future success of the organisation.

Maintenance [14]:

Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function.

Maintenance management [14]:

All activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics.

Maintenance plan [14]:

A structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.

Maintenance planning, based on [14] :

Creation of a structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.

Contents

Part I Main report

Part II Articles

Part I Main report

1 Introduction

"*...he who is victorious in the temple computations before battle is the one who receives more counting rods*" – Sun Zi

This chapter presents an introduction of this PhD project with research questions and objectives, and the scope of the research.

1.1 Background

The complexity and global competition in production is constantly increasing. This increases the need for a reliable plant capacity and reduced maintenance cost. To attain these goals, maintenance planning is an essential activity [15]. Unfortunately, when maintenance planning is conducted with little involvement from the production department, this might challenge the success of achieving a reliable plant capacity and reduced maintenance cost. A plausible reason is that both maintenance and production share resources such as production equipment and maintenance personnel. For instance, maintenance activities conducted in a production line might require the equipment to be unavailable for production. To illustrate with another example, a craft technician can only be available either to conduct maintenance activities or to work as an operator at the production plant. This dilemma is a challenge in maintenance planning both related to plant capacity and labour effectiveness. On one hand, maintenance activities can be carried out too frequently with no production during maintenance, whereas on the other hand maintenance can be carried out too infrequently, leading to unnecessary machine failures. Plant capacity is reduced in both cases.

As the complexity increases in production due to the contributions of multiple disciplines, the concept of *integrated planning* (IPL) is emerging. For example, an IPL system has been developed in national planning in the USA [16]. IPL is here applied in a specific context and therefore not readily subject to generalization. Nevertheless, some generic aspects from national planning can be inspirational for other bodies of knowledge that deal with planning [16]. For example, IPL benefits from viewing planning as an analytical problem solving process, from using planning guides for preparedness activities, and from using planning to deal with complexity. The focus of IPL in this PhD research is the integration between maintenance planning and production.

Figure 1.1 positions maintenance in the life cycle of a physical asset. In the operation and maintenance stage, the physical asset is capable of being operated and producing products. At the same time, maintenance planning ensures that the technical condition is under control by allocating maintenance resources, so the physical asset can perform its required function. If maintenance is not successfully managed in this stage, it can weaken the success of the intended operation in terms of increased downtime, maintenance costs and accidents.

Figure 1.1 – Maintenance planning in the life cycle of a physical asset, adapted from [17].

A *computerised maintenance management system* (CMMS) supports maintenance planning. For instance, the CMMS called SAP has been successfully implemented in several companies [18]. When the maintenance preparation is completed in CMMS, a maintenance plan should be available. This is defined as a “Structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance” [14]. Any significant negative deviation from a well-established maintenance plan may reduce the labour productivity and the plant capacity. However, the maintenance plan does not take into account what will be produced, in which quantity and sequence. This should rather be performed by the production plan and schedule [19].

To perform maintenance planning in an organisation, a sound model for *maintenance management* must be implemented. The Deming cycle (PLAN-DO-CHECK-ACT (PDCA)) will ensure continuous improvement of the work processes in an organisation [20-23]. This framework is also included in maintenance management where work processes are structured. Although earlier maintenance management models have omitted the Deming cycle in the maintenance management framework [24], newer maintenance models include this framework [25-30]. In this framework, maintenance performance is measured (DO), analysed and evaluated (CHECK), and if necessary, leads to improved maintenance planning capability (ACT) where the next work order preparation has improved prediction (PLAN).

There are several terms for expressing the measurement in maintenance performance such as “metrics” [31] and “performance indicators” [32, 33]. In this thesis the term *key performance indicator* (KPI) is used to emphasize that this is an indicator considered by the business to be more important than other indicators [31]. In particular, the standard EN 15341 [34] offers several maintenance KPIs that an organisation should evaluate for implementation. Since the maintenance KPIs affect maintenance planning, it is also obvious that failure to manage these KPIs will challenge the survival of the physical asset.

1.2 Research Challenges and Questions

The lack of coordination between production and maintenance, is a major challenge in planning resulting in sub-optimal prioritizing of activities and unnecessary downtime such as unplanned maintenance [35]. This phenomena describes the situation when departments function as “silos” and is envisaged in terms of an asset with disciplines such as maintenance and production that performs activities that affect each other [36-39]. However, due to poor coordination and involvement between these disciplines, the result in production is unwanted outcome in terms of too low production assurance and too high maintenance costs.

Although there might be different perceptions of the reality in industry and academia, literature clearly reveals the need for IPL. Despite the fact that there is a strong relationship between maintenance planning and production planning, these activities are carried out separately [40-42]. Lack of the necessary communication between these activities has also been regarded as a conflict that increases the operation costs for production and maintenance [43-45]. More specifically, this conflict is mutual where both maintenance planning and production planning are based on theoretical models that do not match the industrial reality.

Maintenance planning models on one hand assume that the production equipment is unavailable for production during maintenance execution, and tend to ignore the potential disruptions in production [40]. This unavailability affects productivity where production capacity is consumed with reduced products and deliver less value for the customer [41, 46, 47]. This will cause a conflict when production department may need production equipment that are due for maintenance [48].

Production planning models on the other hand assume that the equipment will function with its maximum performance during the planning horizon [49]. Moreover, some of these models assume production without non-conforming units [50]. Although planned maintenance activities consume time for production, postponing this activity might increase the probability for breakdowns [40]. The production department will then struggle to follow the production plan, resulting in deadlines not met [41]. For example, there is a natural interdependence between production and maintenance in the automotive industry where a failure of one machine will result in a full line stop. The effect is then delays in production, requiring significant production overtime [42]. In fact, machine deterioration is one of the main causes of reduced plant capacity and delay in customer orders in several manufacturing industries [46]. This will indeed challenge the ability to deliver value for the customer.

The remedy today is usually that maintenance planning is performed using two different approaches. One approach is to conduct maintenance planning while ignoring the production orders [42]. Then production planning is performed within the limits imposed by the maintenance plan. Another approach is first to decide when production planning should take place ignoring the need for performing maintenance [48].

In the 1990’s, maintenance was not always considered to be an issue for strategic or serious tactical judgement [51]. Despite changes in this view, production and maintenance are still planned independently; maintenance is carried out based on reliability data but not the forecast production orders [42]. One possible explanation is that production management does not understand the strategic importance of incorporating maintenance in the manufacturing planning [45].

The models that exist today, take several aspects into account in maintenance planning:

- **Time perspective:** The time horizon can include both short term maintenance planning [52] and long term decisions in strategic planning in maintenance [53].
- **Generic mathematical modelling:** Some authors investigate in new mathematical applications in maintenance planning. Examples are Bayesian network [54], grouping of maintenance activities [55], and multi-criteria decision making [56].
- **Industry application:** Some models are tailored for a specific industry context such as wind turbines [57], road infrastructure [58], pipelines [59] , railway [60] and manufacturing industry [61].
- **Logistics:** A model can also consider the logistical part such as inventory of spare parts [62].

- **Methodology perspective:** Some perspectives includes different methods and approaches such as opportunistic maintenance [63, 64], reliability centred maintenance (RCM) [65], and value-driven maintenance planning [66].

From these models it seems that strategic maintenance planning and opportunistic maintenance involve coordination of maintenance planning and other parts of the organisation. The strategic maintenance planning model elaborates the position of maintenance planning in a corporate planning system. As a conclusion, strategic maintenance planning must align the maintenance objectives with the various parts of the organisation. Opportunistic maintenance also offers a coordination of maintenance where a time window gives an opportunity for maintenance. The time window can be a result of either a machine breakdown or other factors such as no customer orders. Although both of these models are rational and relevant, they are rather interrelated than integrated [48, 67]. In interrelating planning, one parameter is decided after another is kept as a constraint. To clarify, in strategic maintenance planning the corporative objective is first decided and then the strategic maintenance planning is conducted. Although it is stated that strategic maintenance planning must be aligned with other parts of the organisation, such as production, it is not clear if this is conducted in an interrelated or integrated approach. For opportunistic maintenance, a maintenance window first occurs as a constraint leads to performance of maintenance planning.

The relationship between operation and maintenance processes for a physical asset is elaborated in the standard EN 16646 [68]. In particular, it points out that the production plan determines the required time when invasive preventive maintenance actions shall not be performed. As a standard, this should be considered to be a guide for maintenance planning in conducting coordination with other parts of the organisation. However, this standard also seems to support interrelated planning since a production plan influences when maintenance shall not be performed. It remains to investigate how maintenance management can be adjusted against other priorities for a physical asset in IPL.

Following research challenges can be highlighted from the literature:

- There are still situations today where maintenance and production planning is performed independently despite that this challenge has been known for more than 20 years by maintenance researchers.
- There are models in maintenance planning that are interrelated rather than integrated.
- A standard has been developed to describe the relationship between operation and maintenance processes for a physical asset. This is considered as an important contribution for improved coordination between maintenance and production in an organisation. However, this approach also seems to be more interrelated than integrated.

These challenges lead to the following research question (RQ):

RQ1: *How can maintenance planning be further developed and modelled to provide decision support for production planners in IPL?*

The recent models investigate different aspects of integrating maintenance and production planning:

- **Time horizon:** Integrating production and maintenance planning at a tactical level [42, 45, 47, 69].
- **Generic mathematical application:** Markov decision process model [46].
- **Industry application:** Batch size manufacturing [48, 50] and plant production with focus on a compressors [70].
- **Task specific:** Re-planning of existing maintenance plan due external disturbances [71] and minimizing the total job completion times [41].

Even though these contributions have been important, the application of KPIs in IPL is still lacking. Several authors point out the need for KPIs and propose them for IPL [72, 73]. These KPIs are applied in the oil and gas industry, but should also be applicable for other industry branches. A summary of these KPIs are presented in Table 1.1 with description and purpose.

Table 1.1 – Current KPIs for IPL [72, 73].

No.	Indicator name	Description	Purpose
1	Plan attainment	Measures the amount of work performed vs. the amount of work scheduled for the period.	The purpose is to indicate the degree of progression in the plan.
2	Estimation rate/Planned utilization	Measures the ratio between estimated work and capacity.	The purpose is to indicate to what extent the organisation is capable of estimating the work effort.
3	Planning degree	Measures the amount of work performed vs. what was planned.	The purpose is to indicate how many man-hours used by the disciplines are actually planned.
4	Actual utilisation	Measures the actual working hours for the task compared with available working hours.	The purpose is to indicate to what degree the planner utilise the allocated resources at his disposal.

However, the two most central shortcomings of these KPIs must be considered. First, it may be questioned if these KPIs actually will lead to the planned impact in the production system. How is e.g. the KPI "plan attainment" communicating the consequences of postponing the delayed work?

The second shortcoming is the sole focus on measuring the efficiency of the planning process, i.e. the amount of resources needed to execute the processes. However, when considering the industrial standard for *overall equipment effectiveness* (OEE) [74], it is obvious that the effectiveness should be measured as well as efficiency in the operation. To overcome this challenge, a KPI structure with a balanced approach of efficiency and effectiveness is needed.

From the discussion above, some challenges should be further highlighted:

- Despite that there is a solid and broad amount of different mathematical models that integrate maintenance planning with production, it seems that none of them address application of KPIs.
- Some KPIs have been identified and evaluated for IPL. However these seem to be insufficient since it is not clear what they will lead to and what structure for KPIs will ensure that they are balanced.

The challenges lead to the following research questions:

RQ2: *What existing structures and maintenance KPIs are of relevance for IPL?*

RQ3: *How can maintenance KPIs be further developed and applied for IPL?*

Figure 1.2 illustrates a conceptual model of IPL. The production system includes the physical asset and production processes. To ensure sufficient production and safety performance, the physical asset needs to be supplied with a cost effective maintenance organisation in terms of craft technicians, tools, materials and spare parts. Relevant information is also gathered and processed in for both maintenance planning and production planning.

The three research questions are positioned in the planning system of interest; maintenance planning and the IPL loop. In maintenance planning, work orders are scheduled based on a maintenance decision regarding future maintenance activities following the Deming cycle.

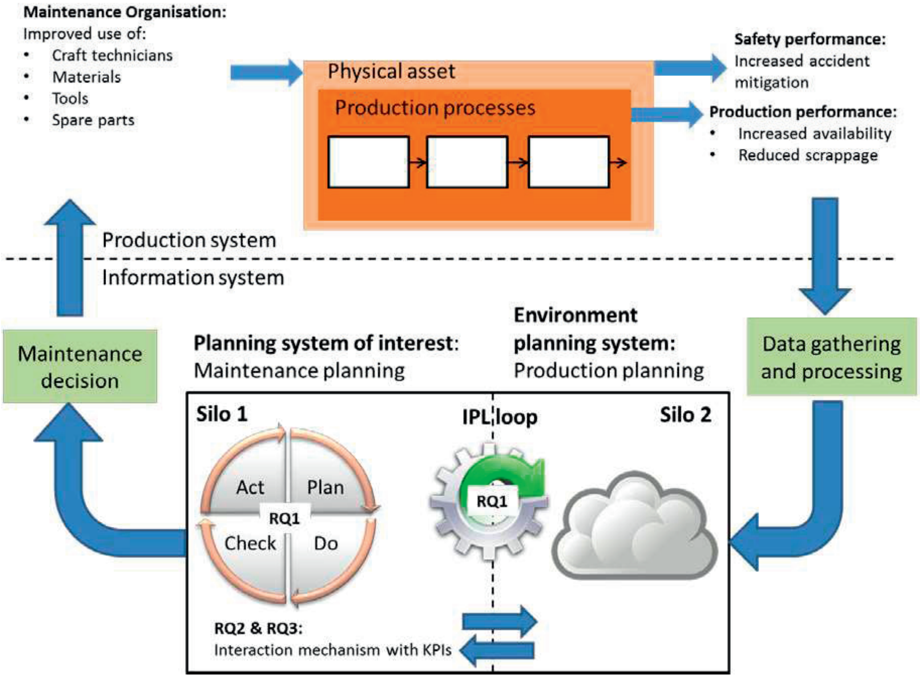


Figure 1.2 – Conceptual model for IPL.

The loop in Figure 1.2 is triggered when poor maintenance is caused by disciplines outside the maintenance organisation. By carrying out the Deming cycle in the IPL loop, continuous improvement will be performed in the organisation. However, if the interaction mechanism is poorly managed, the "silo" phenomena will occur. Research is needed to improve this interaction mechanism for maintenance planning. The expected impact of IPL is improved production performance in terms of increased availability and reduced scrappage, as well as increased accident mitigation. Moreover, it is also expected that the maintenance organisation will improve the use of craft technicians, materials, tools and spare parts.

1.4 Research Objectives

The driving inspiration of my scientific discovery leading to both new knowledge and innovation, is the need for clarification of IPL in maintenance management; the outlined research questions and the discussions with several industry branches. In addition to contribution to theory in the maintenance society, it is indeed vital that this theory will be applied in future.

The overall objective of this thesis is to:

Develop theory and methods in IPL that balance maintenance management with other priorities related to physical assets.

This main objective is further decomposed into sub-objectives that corresponds the research questions:

Research Questions	**Research Objectives**
RQ 1	**Objective 1:** Identify and evaluate existing models for maintenance planning strategies.
	Objective 2: Develop a framework for IPL.
RQ 2	**Objective 3:** Evaluate and structure existing maintenance KPIs for IPL.
RQ 3	**Objective 4:** Further development of KPIs applied for IPL.
	Objective 5: Demonstrate and evaluate the KPIs in the IPL framework.

1.5 Limitations

The scope in this thesis is limited to the body knowledge maintenance management in the operational stage of the life cycle when investigating and developing IPL. It would be beyond the scope of this thesis to include all kind of disciplines such as Manufacturing planning and control (MP&C) for manufacturing into the investigation of IPL. Furthermore, this thesis will focus on how KPIs both as theory, methods and practical applications will support IPL. In the PhD thesis, the methods are considered to be generic and are demonstrated in several types of industries. However, I do not investigate the implementation of IPL.

1.6 Structure

This thesis comprise two parts: Part I that constitute the main report of the thesis and part II that is a collection of scientific articles. The further organisation of part I is as follows:

In Chapter 2, relevant existing theory is presented and elaborated more in detail. The chosen research methodology is presented in Chapter 3. In Chapter 4 my contribution from my research in terms of main results is presented where final conclusions and recommendations are presented in Chapter 5.

2. Theoretical Background

"...I tell this story to illustrate the truth of the statement I heard long ago in the Army: Plans are worthless, but planning is everything." – Dwight D. Eisenhower

Figure 2.1 positions the theoretical background related to maintenance management aligned with the standard IEC 60300-3-14 in maintenance management [26]. The main context is the maintenance management loop (Chapter 2.1.2). Relevant topics in maintenance planning (Chapter 2.2, 2.3 & 2.4), maintenance KPIs (Chapter 2.5), the Deming cycle (Chapter 2.1.1) and asset management (Chapter 2.1.3) are presented and elaborated.

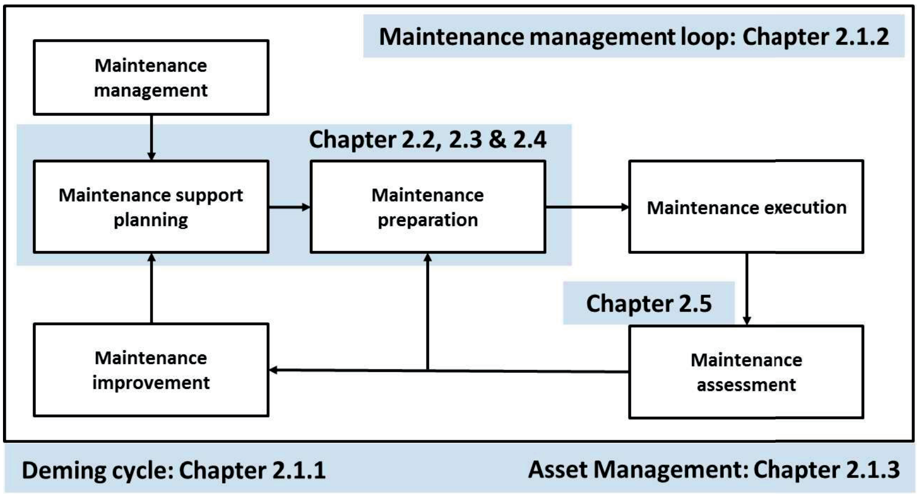


Figure 2.1 – Positioning body knowledge in thesis aligned with IEC 60300-3-14 [26].

2.1 Fundamental Principles for Integrated Planning

2.1.1 Deming Cycle as an Improvement Approach

The renowned consultant W. Edwards Deming [23] in the quality management field is known for the Deming cycle. This approach follows the activities PLAN-DO-CHECK-ACT (PDCA) and may be referred to as PDCA cycle. Deming himself used the notion Shewart cycle, since this approach has its origin from Walter A. Shewart within quality control. Nevertheless, when this cycle was used in Japan it went under the name "Deming cycle." The purpose of implementing this approach is to ensure continuous improvement of the activities in the specific business. Furthermore, this cycle facilitates learning from earlier mistakes and can be a key ingredient for sustained profitability [75]. The logic of the Deming cycle is illustrated in Figure 2.2 based on overall elaborations [20, 23, 76].

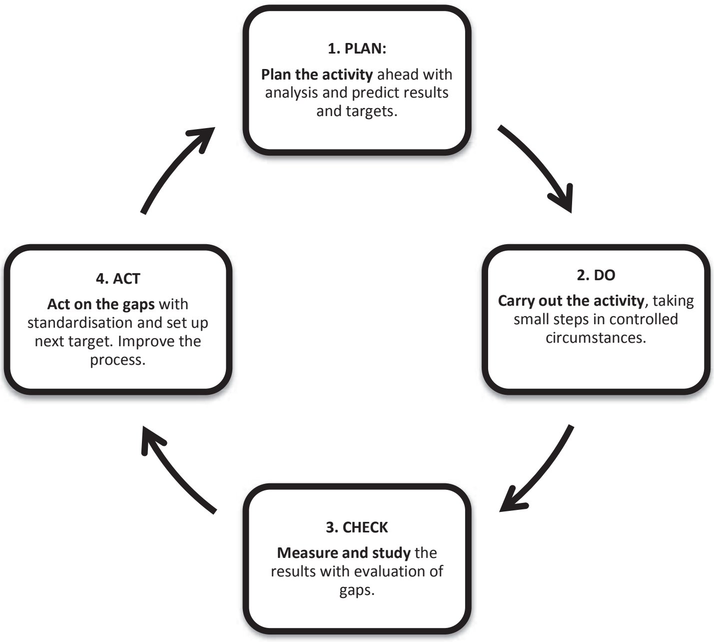


Figure 2.2 – The Deming cycle [20, 23, 76].

2.1.2 Maintenance Management

The European standard EN 13306 [14] defines maintenance as a "Combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function." Maintenance management is defined as "All activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics." The Deming cycle will in maintenance management sustain the continuous improvement of the maintenance activities.

As an alternative for IEC 60300-3-14, Figure 2.3 represents the maintenance management loop from the baseline study [25, 77]. In this figure, there is an input of resource requirements and an output of technical condition that results in an acceptable risk level and regularity.

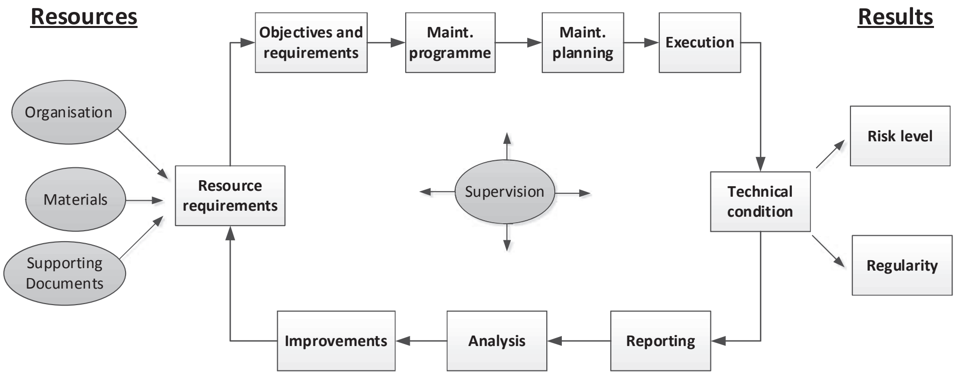


Figure 2.3 – Maintenance management loop from the baseline study [25, 77].

The further details of the maintenance work processes of both IEC 60300-3-14 and the baseline study are presented in Table 2.1 and structured according to the Deming cycle. The baseline study is mostly implemented in Norwegian companies, whereas IEC 60300-3-14 as an international standard should be applied more world-wide.

Table 2.1 – Structuring of Baseline study and IEC 60300 in the Deming cycle.

	Baseline study [25, 77]	**IEC 60300-3-14 [26]**
1. PLAN	*Objectives and requirements:* Harmonization of maintenance objectives and requirements from government regulator and companies cooperative objectives *Maintenance programme:* Development, update and improvement of e.g. RCM and risk based inspection *Maintenance planning:* Long-term & short-term, priority of work orders	*Maintenance Management:* Policy, budget & supervision *Maintenance support planning:* Task identification, task analysis, support of resources *Maintenance preparation:* Planning of tasks, scheduling & assigning activities
2. DO	*Execution:* Preparations, work permits, carrying out work, controlling, and evaluating work orders *Reporting:* Collection, quality assurance, processing and presenting maintenance related data	*Maintenance execution:* Performance, recording & procedure
3. CHECK	*Analysis:* Analysis of historical data and unwanted incidents	*Maintenance assessment:* Measurement, analysis & assessment
4. ACT	*Improvements:* Initiate, perform and follow-up improvement, establish "best practice"	*Maintenance improvement:* Improve concept, resources, procedures or modify equipment

2.1.3 Asset Management

The industry has clearly pointed out the importance of asset management. For example, in the construction industry in Canada the asset management market is large, upward $2.94 trillion of the physical asset where the maintenance and repair expenditures are on the order of $58.8 billion/year [78]. The vast annual expenditure of maintenance indicates that solid decisions in maintenance management is required. Also the manufacturing industry addresses the importance of asset management. For instance, the CEO and President of Toyota Motor Europe Didier Leroy [79] claims that "…We should always note that asset management and maintenance activities are two of the key elements to achieving competitiveness." In addition, the oil and gas industry considers asset management to be vital for improving asset availability and utilization [80].

The importance of asset management has also resulted in a Publicly Available Specification (PAS) denoted as PAS 55 [81-83]. One strength of this specification is the different types of assets:

- human assets;
- financial assets;
- information assets;
- intangible assets;
- financial assets; and,
- physical assets.

Further work within asset management has also resulted in the standard ISO 55000 [13]. This standard defines asset management as the "Coordinated activity of an organization to realize value from assets." ISO 55000 defines an asset as an "Item, thing or entity that has potential or actual value to an organization."

The fundamental key elements in asset management are as follows.

- **Value:** The purpose for an asset is to provide value to the organisation and its stakeholders.
- **Alignment:** Asset managers translate the cooperative objective of the organisation into technical and financial decisions, plans and activities.
- **Leadership:** To realize this value, sound leadership and workplace culture is necessary.
- **Assurance:** Asset management will provide an assurance that assets will fulfil the required purpose.

More specific within the maintenance field, the standard EN 16646 addresses the maintenance within physical asset management [68]. One of the reason to investigate this topic is the "silo" behaviour which keeps maintenance and other life cycle processes separated. Therefore, this standard addresses the role and importance of maintenance within the physical asset management system through the whole life cycle. EN 16646 defines physical asset management as the "Coordinated activities of an organisation to realize value from physical assets." Examples of physical assets would be components, machines, production lines, plants and infrastructure facilities.

EN 16646 also investigates the interrelationship between maintenance and other processes relevant for the physical asset. One relationship is between operation and maintenance processes, as illustrated in Figure 2.4 [68]. This relationship presents what enablers and support that is necessary between these processes [38].

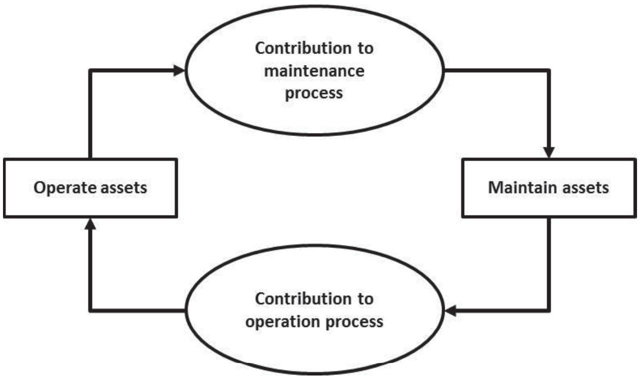


Figure 2.4 – Relationship between operation and maintenance processes [68].

The process "operate assets" provides following input to the maintenance process ("maintain assets"):

- **Production plans** that are established for the plant over a given period. They involve the operating profile of when production starts/stops and quantity of units, all of which may cause degradations. This input determines the required time when invasive preventive maintenance actions *shall* not be performed. Maintenance plans shall use this input to calculate and schedule the intervals for maintenance activities.
- **Environmental conditions** that are dependent on where and when the asset is operating and affect the failure mechanisms of the physical asset.
- **Operator involvement in monitoring and maintenance.** It is important that the operator should be involved in first line maintenance to ensure effective execution of routine maintenance actions and detection of degradations and failures.
- **Operational modes in degraded states** must be thoroughly investigated to assess the criticality of the failures**.** This can result in a non-nominal operation condition to reduce the consequences or postpone the failure. It is also important for the maintenance process to specify the acceptable thresholds (e.g. vibration levels) of the degraded state before shutdown is necessary.
- **External factors that impact the production assurance.** Examples are strikes, other social conflicts and lack of raw materials.
- **Emergency procedures.** When there are emergency situations for the asset involving maintenance tasks, these tasks should be conducted regularly to test the procedures.

- **Risk analysis.** This analysis provides important information that should be used in the maintenance process to evaluate the risk of the asset. It could e.g. result in a FMECA analysis for the equipment.

In return, the process "maintain assets" provides inputs to the production process ("operate assets"):

- **Operating constraints**. These constrains will mitigate or accelerate failure mechanisms. Some constraints are given by the production process (e.g. velocity and temperature of metal cutting tools), whereas some have to be changed based on an observed higher level of degradation than expected.
- **Times to restoration and conducting preventive maintenance**. This time includes activities for corrective maintenance such as detecting the faults, providing the logistic support, to repair, and restarting the asset. Preventive maintenance times that impact the availability or the operating mode shall be known as well. Operators will evaluate this time to manage operations during down states or degraded states.
- **Maintenance plan**. These plans are communicated to the operating team for discussion. The dates for carrying out the maintenance tasks should be fixed considering the expected operating mode.
- **Allocation of maintenance tasks**. Some of the maintenance tasks, e.g. monitoring in a control room, can be conducted by the operators who are in a better position to detect symptoms for failure modes. These activities are identified through the maintenance plan indicating which operating staff are requested to perform them.
- **Safety procedures for maintenance execution**. The maintenance personnel sends out a demand with safety procedures when a maintenance action causes a risk for the safety of individuals.

To manage the associated risk with "silo" behaviour, EN 16646 exemplifies some KPIs for this purpose:

- return on physical asset;
- external criticality of production (e.g. delivery of products with non-conformity) that directly affects the customer satisfaction;
- internal criticality of equipment that indirectly affect the customer satisfaction (e.g. bottleneck in production);
- OEE; and,
- life cycle cost (LCC).

2.2 Maintenance Planning Principles

Maintenance planning has a pivotal role in achieving the maintenance objectives and the cooperative objectives in an organisation. The term can be defined as "The preparatory work to make work orders ready to execute" [15]. Maintenance scheduling may be included in this definition depending on how it is used. When considering the term *maintenance plan* in EN 13306 [14], maintenance planning seems to have a more specific meaning. A proposed definition based on this standard is then "Creation of a structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance.” As a guide for the maintenance planner, six principles that greatly contribute to overall success of planning are presented in Table 2.2.

Table 2.2 – Planning principles in maintenance [15].

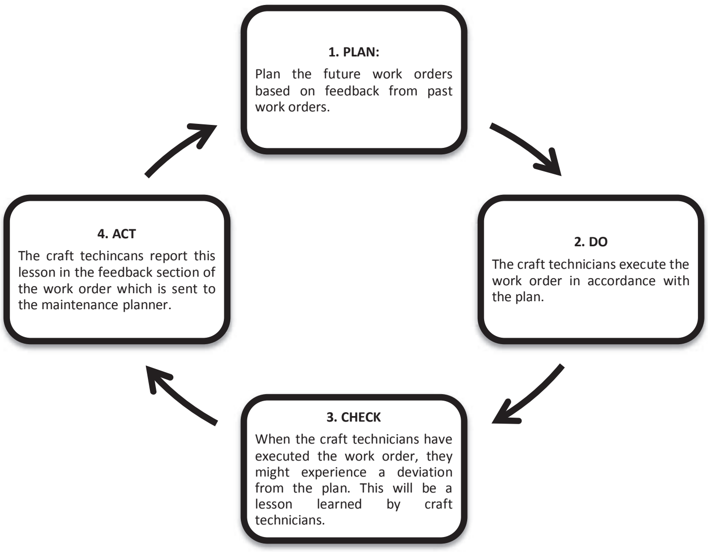
Principle	Description
Principle 1: Separate group	The planners are organized into a separate group from the craft maintenance crews to facilitate specialising in planning techniques as well as focusing on future work.
Principle 2: Focus on Future	The planning group will concentrate on future work to be performed within maintenance.
Principle 3: Component Level Files	The planning department must maintain a simple, secure archival system based on equipment tag numbers.
Principle 4: Estimates based on planner expertise	Based on the expertise from planners along with historical information, the time estimates for the work orders are established.
Principle 5: Recognize the skill of the crafts	The planner ensures that the workforce is sufficiently skilled.
Principle 6: Measure performance with work sampling	Wrench time is the primary measure of workforce efficiency.

Principle 1 endorses that the planner is not a member of the craft crew. To ensure the planner’s autonomy, the craft crew that works with maintenance execution should report to another supervisor than the planner. Although an organisational structure should sustain this autonomy, conflicting interests will still challenge the maintenance manager. The maintenance planner can have several years with experience as a craft technician and is therefore well qualified to work with maintenance execution. Since he has the role as a planner, the maintenance manager should therefore endorse him with the long-term principle “try not to use the planner in the field unless necessary.” This principle can be challenging to keep when unexpected downtime in production forces the urgent instruction: “Put that pump back on line today!” If the situation for such a downtime is highly critical for the plant, the maintenance manager might in an emergency situation sacrifice the planner function and instruct the maintenance planner to work as a member of a craft crew. However, when the organisation disables the planning function, the future maintenance work is postponed, leading to more reactive and less proactive work. If the organisation waits too long in re-activating the planning function, this can lead to a vicious circle with little predictability of allocation of future maintenance resources, as well as a trend of decreasing plant capacity. The maintenance planner is crucial and can leverage 30 technicians into 47, and thus justify savings of 17 persons [15].

Principle 2 elaborates the importance of future work. When the planner focuses on future work, he will concentrate on what has not started yet. The planner will provide the maintenance department with at least a one-week schedule of maintenance activities that are ready to be executed. During the commencement of any job, only the craft technicians or supervisors shall resolve any problems that would arise. The planner is involved after job completion when the craft crew provide sufficient feedback in terms of:

- problems that occurred during the job;
- changes in the plan; and,
- time and resources consumed.

The Deming cycle is essential in this principle where information learned in the past is used in future. Figure 2.5 portrays this approach where the work order is processed through all the four stages of the Deming cycle.



1. PLAN:
Plan the future work orders based on feedback from past work orders.

2. DO
The craft technicians execute the work order in accordance with the plan.

3. CHECK
When the craft technicians have executed the work order, they might experience a deviation from the plan. This will be a lesson learned by craft technicians.

4. ACT
The craft techincans report this lesson in the feedback section of the work order which is sent to the maintenance planner.

Figure 2.5 – Maintenance planning is a cycle of continuous improvement.

Principle 3 describes the requirement of component level records. The planning department must have an archival system with equipment tag numbers, which is secure and simple to use and where complex operations are executed. The system enables planners, supervisors, technicians and plant engineers to access equipment data, cost data and information learned during previous work. The benefit is that information related to making repair or replace decisions will be easy to access. The component level files can also be a CMMS system. This will be elaborated in more detail in Chapter 2.4.

Principle 4 endorses the planner's expertise in estimation of work orders. The time estimate for work orders is based on both the planner's experience and historical information. This estimate should reflect what a capable technician should complete in a work order without any unusual problems. When calculating the time estimates, several considerations are required:

- experience and skill of the technician;
- data quality of historical data; and,
- right amount of quality in the time estimate.

The planner's expertise is also indirectly pointed out in the standard EN 15628, that identifies and structures the qualification of maintenance personnel [84]. Table 2.3 presents this competence in more detail. A craft technician who has the role as maintenance planner would also benefit from this competence.

Table 2.3 – Competences, skills and knowledge for a maintenance supervisor or maintenance engineer, adapted from [84].

Competences	Minimum skills	Essential knowledge
To plan the maintenance tasks and define and organise the necessary resources to execute the work orders.	a) To negotiate the required maintenance works with the physical asset owner; b) To define the organisational arrangement for carrying out the work orders; c) To plan maintenance tasks, define maintenance recourses and controlling the tasks and finishing it with reporting; d) To coordinate maintenance works performed by contractors, ensure both efficiency and effectiveness of the execution, verify proper function of the equipment and hand-over to asset owner; e) To support with necessary information to craft technicians that are assigned for the work; f) Optimisation of both human (e.g. man-hours for preventive maintenance) and technical resources (level of spare part inventory); g) To conduct project leadership;	a) Communication methods and technical solutions; b) Methods and technical solutions of conducting organising, planning and project management; c) Principles, logic and parameters of operating and utilising the asset; d) Standards and operational methods of conducting maintenance work;

Principle 5 elaborates the importance of planner's capability to recognize the skill of the crafts. The planner must determine the scope of the work order. He will then plan the general strategy of the work and include a preliminary procedure if it is not already included in the file system. The technicians will also use their expertise to complete their work orders. The planner and the technicians must also work together over repeated jobs in order to improve the procedures and checklists.

In this principle, the planner should argue for choosing the specific job strategy. An example of argument could be: "Due to improper condition after cleaning the filter, the filter should be changed." In addition, the planner must also provide known legal or regulatory requirements for the job procedures of the technicians. Rules and procedures are important for maintenance, but it is difficult to produce the prefect procedures in the complex environment of today's maintenance technology. The planner must therefore find a balance between two different types of ownership of work orders:

1. technicians must execute jobs exactly as planned; and,
2. freedom for technicians to change the plan.

Principle 6 elaborates how to measure planning and scheduling. For instance, this principle measures how much time the technicians actually spend on the job site versus other activities such as traveling, waiting for parts, or otherwise being delayed. In addition, the maintenance planner should measure the losses that impede human work efficiency [85]. This will be elaborated in Chapter 2.5.3. The maintenance planner should also consider the maintenance KPIs defined in the standard EN 15341 [34] with classification of technical, organisational and economic maintenance KPIs. In Chapter 2.5 these KPIs will presented and discussed in more detail.

2.3 Estimation of Maintenance Intervals

2.3.1 Basic Principle in Maintenance Optimisation

Maintenance optimisation is finding the optimal maintenance interval with respect to maintenance costs. The basic model is illustrated in Figure 2.6, based on [60, 86]. This figure represents a graphical presentation of the model where the trade-off is between the planned maintenance costs and the unplanned maintenance costs. In sum, these two types of maintenance costs will represent the total maintenance costs.

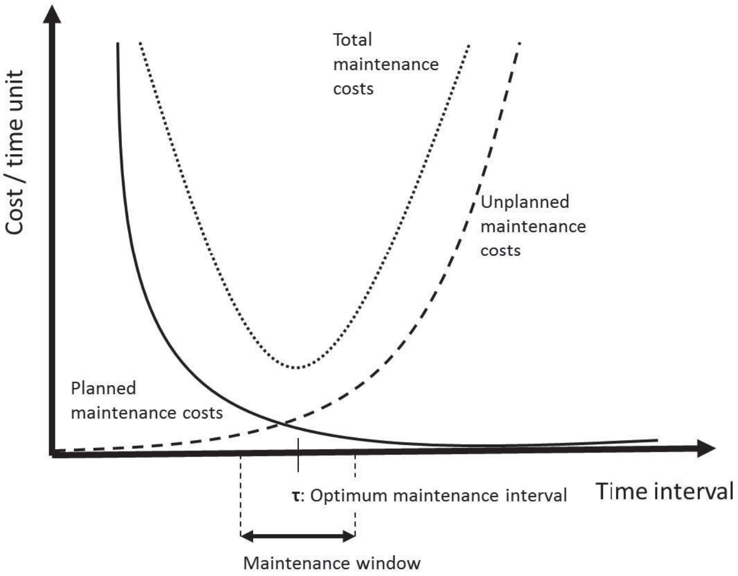


Figure 2.6 – Maintenance optimisation for establishing time interval based on [60, 86].

In this model, the preventive maintenance cost will decrease when the maintenance interval is increased due to more infrequent planned maintenance activities each year. However, when the maintenance interval is extended, this will increase the failure rate due to decreasing reliability of the component that is not maintained. In total, there will be a mathematical optimal maintenance interval. The production department should give a certain maintenance window with a sufficient time for performing the maintenance interval.

Several models have been developed for improving the maintenance optimisation in maintenance planning [56, 61]. Earlier, some challenges has been identified and highlighted by Dekker [87]:

- maintenance optimisation models are not straightforward to understand and to interpret;
- the models have been developed mainly for math purposes;
- the interest for publications in companies can be limited;
- maintenance will comprise different aspects; and,
- it is not always necessary to optimise.

Despite these challenges, it is still a need for maintenance optimisation due to two main reasons: Technological push and economic necessity.

2.3.2 Static Maintenance Grouping

Based on their planning aspects, maintenance models can be divided into stationary and dynamic models [64]. In the dynamic models, new relevant information can alter the plans during the planning horizon. Such information is e.g. new failure rate estimates and cost estimates. However, in stationary models it is not possible to alter the plan during the planning horizon even if new information is available. These models also perform grouping of several maintenance tasks into one maintenance package. The reason for this grouping is that the set-up cost and administrative cost are reduced due to economy of scale. Figure 2.7 illustrates an example when maintenance grouping is conducted.

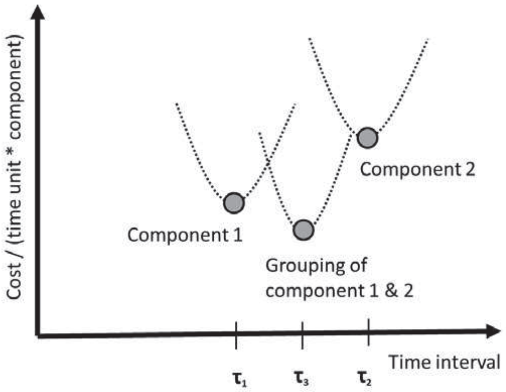


Figure 2.7 – Grouping of two components.

For each component it has been found an optimal maintenance interval for component 1 at τ_1 and component 2 at τ_2. A new maintenance interval has been decided to be at τ_3 . When preventive maintenance for both component 1 and 2 is performed, the new maintenance interval τ_3 is obtained. The time interval is not optimal at τ_3 for the components isolated. In this situation, component 1 will increase the expected unplanned maintenance costs in terms of more failures, and component 2 will increase the planned maintenance costs due to more frequent preventive maintenance. Nevertheless, when these components are grouped and performed at τ_3 the total maintenance costs is expected to decrease because some cost elements are shared with component 1 and 2. The reasons for reduced maintenance costs can be:

- administrative cost is shared of one maintenance activity instead of two;
- workshop, tools and craft technicians is shared; and,
- a planned maintenance activity will result in downtime for both components.

Within stationary grouping, two approaches can be applied: Direct and indirect grouping. The main difference between these approaches is that in indirect grouping maintenance is conducted every T time unit whereas for direct grouping the time between the maintenance activities during the plan horizon need not to be constant. Table 2.4 presents relevant notion for indirect grouping.

Table 2.4 – Notation for indirect grouping.

i	Component i.
n	The total number of components.
C_i^P	Individual PM cost.
C_i^U	Unplanned costs upon a failure including corrective maintenance and downtime.
τ_i	Individual maintenance interval for component i.
S	Setup cost.
$\lambda_{E,i}(x)$	Effective failure rate in time interval $[0, x)$. Weibull model is assumed.
MTTF	Mean time to failure.
α	Ageing parameter.
$M_i(x)$	$M_i(x) = x \times C_i^U \times \lambda_{E,i}(x)$, accumulated unplanned costs in time interval $[0, x)$ due to increasing failure rate.
$C_i(\tau)$	$C_i(x) = \left[C_i^P + S + M_i(x)\right]/x$, Average costs per time unit for individual maintenance interval for component, i.
T	Occasions for preventive maintenance with time interval, T.
k_i	Occasions for preventive maintenance for component i with time interval, $k_i T$. k_i is an integer.
t_0	Time at now.
○	Original planned maintenance activity.

For indirect grouping, there are only opportunities for preventive maintenance every T time units. The maintenance window, t_m, is not considered in this model. Further, for each component *i*, it is possible to perform preventive maintenance every k_iT time unit. In this PhD thesis, a heuristic with three stages is applied:

Stage 1: Establish values for k_i

1. Establish a cost function for each component:
   $C_i(\tau) = \frac{C_i^P + S + M_i(\tau)}{\tau} = \frac{C_i^P + S}{\tau} + C_i^U \times \lambda_{E,i}(\tau)$
2. Minimise $C_i(\tau)$ for each component.
3. Choose initial T-value to be equal smallest individual maintenance interval.
4. Calculate $k_i = \frac{\tau_i}{T}$ and round consequently either down or up to an integer. Keep the k_i-values fixed.

Stage 2: Minimize T

1. Establish a cost function where each component is maintained at time interval k_iT:
   $$C(T,\vec{k}) = \frac{S}{T} + \sum_{i=1}^{n}\left[\frac{C_i^P + M_i(k_iT)}{k_iT}\right] = \frac{S}{T} + \sum_{i=1}^{n}\left[\frac{C_i^P}{k_iT} + C_i^U \times \lambda_{E,i}(k_iT)\right]$$
2. Minimise the cost function with respect to T. In the result chapter, Microsoft Excel is used, and Solver is used as a tool for minimizing.

Stage 3: Vary k_i slightly in stage 1 to check if a better solution is achieved in stage 2.

To illustrate, k_i values will be 1,2 and 3 resulting in a maintenance plan as shown in Figure 2.8. The time horizon is assumed to be infinitive.

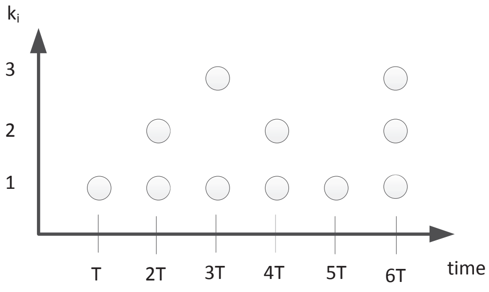


Figure 2.8 – Original plan for indirect grouping.

2.4 Maintenance Planning in CMMS

Today, most maintenance planning is performed with support from CMMS. From the CMMS called SAP, the following business processes are identified within maintenance planning [18]:

1. **Planned Repairs Business Process:** Can be planned, but not predicted.
2. **Preventive Maintenance Business Process:** Can be planned in respect to content and scheduling.

In addition, immediate repair is also a business process in CMMS, but this activity can neither be planned nor predicted.

The planned repair business process is performed in five steps [18]:

1. **Notification.** Register a technical object, date, description, damage code and priority.
2. **Planning.** The order is planned from the notification with tasks including creating maintenance activities, reserving spare parts, assigning external companies, or planning operating times.
3. **Controlling.** This activity checks the availability of material, support with required capacities and release of work orders.
4. **Implementation.** This process involves both withdrawal of spare parts from warehouse and execution of the maintenance work order.
5. **Completion.** After the technician has performed the maintenance work order, he must confirm actual required time, how the damage was processed, as well as status of the technical system. All this information is updated to history.

The preventive maintenance business process makes it possible to plan required resources in advance with respect to content and scheduling. This type of maintenance business process can in addition to content, also predetermine date of execution. To perform the preventive maintenance process, several functions are used in enterprise asset management (EAM) shown in Figure 2.9 [18]. The small arrows denote “optional” transfer whereas the thick arrows denote “compulsory” transfer.

The **maintenance strategy** of the technical equipment comprises a chronological sequence for all preventive maintenance packages either as time based (3, 6 or 12 Months interval) or performance based (1000, 2000 or 4000 running hours). The content details of the maintenance packages are left out from the maintenance strategy.

Maintenance task list provides information about the activities (operations) and contains materials and deadlines for the maintenance package.

Maintenance item describes the activities, the object list and the organisation and responsibilities for the dedicated maintenance package.

The **maintenance plan** contains at least one maintenance item and determines the maintenance dates, as well as the maintenance call in terms of e.g. order and notification.

Deadline monitoring runs automatically and ensures that the maintenance calls, such as work orders that are generated on the due date.

Finally, the **Call** would be a work order ready to be executed.

After the work order has been executed, a maintenance assessment is carried out with the purpose to support future maintenance planning in CMMS. One central element in this assessment is evaluation of maintenance KPIs. In the next chapter, maintenance KPIs are elaborated in more detail.

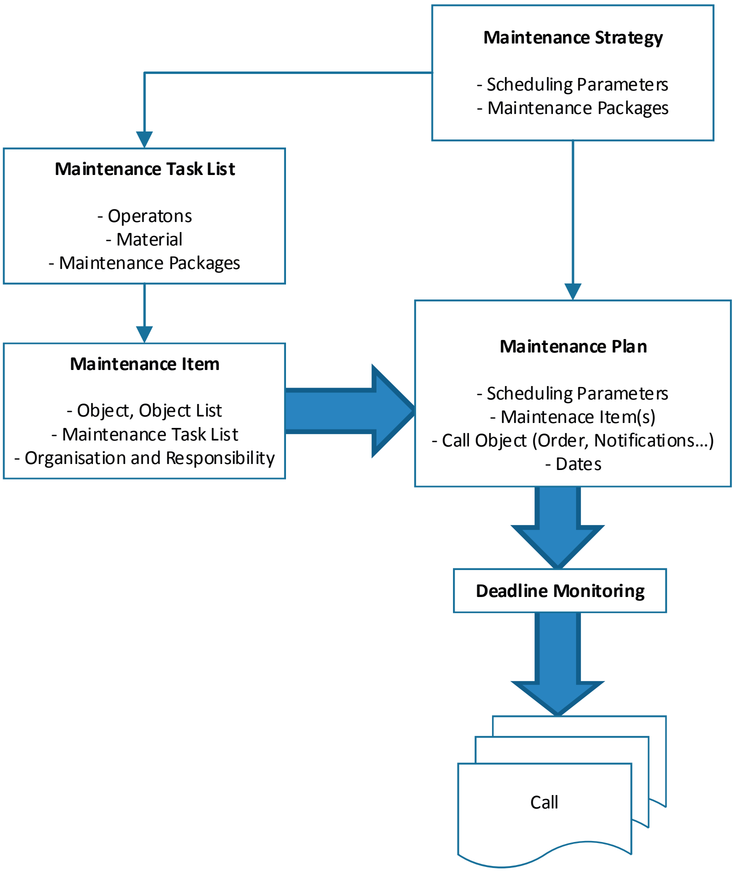


Figure 2.9 – Interrelationship of EAM Maintenance Planning [18].

2.5 Maintenance KPIs

2.5.1 Definitions and Characteristics of Maintenance KPIs

The synonym "*indicans*" represents an overall understanding of indicators and is a measure from which conclusions on the phenomenon of interest (*indicandum*) can be inferred [88]. An indicator can also have a concrete meaning and be explained as a gauge or meter of a specified kind [89]. The term indicator is often interchanged with similar terms such as KPIs [84, 90, 91], maintenance performance measure [91, 92], performance indicators [32, 93], and metric [91]. Further in this section the term indicator and KPI are investigated.

The term indicator is defined in the standard EN 15341 as "Measured characteristic (or a set of characteristics) of a phenomenon, according to a given formula, which assess the evolution" [34]. Indicators are also denoted as KPIs when applied in maintenance management. In this thesis, KPI is defined as "A metric measuring how well the organisation or an individual performs an operational, tactical or strategic activity that is critical for the current and future success of the organisation" [94].

To achieve this success in the organisation some generic characteristics of sound KPIs are necessary. Table 2.5 presents the characteristics for effective KPIs which ensure the usefulness in achieving the success in the organisation and should be applicable for maintenance. Fifteen characteristics can be identified and are adapted from the guidelines in business performance management [94] and a ISO-standard for automation systems in manufacturing industry [95]. It seems that some of the criteria in the ISO standard have included sub criteria and these two sources are compared with this in mind.

Both the guideline in business performance management and the ISO-standard for automation systems show some unique considerations. The guideline for business performance management includes two psychological considerations. Firstly, the KPIs should only be few in number due to the human cognition capability. Too many KPIs would result in lack of control of the situation for the user and would at the end affect the performance in the organisation. Secondly, the organisation can magnify the result of the performance through different incentives such as extra payment. In the ISO standard, some technical aspects are included in terms of automation of KPIs, the need for documentation, and cost-effective KPIs.

The criteria mentioned above are not in conflict with, but rather supplement each other in characterising effective maintenance KPIs. When the KPIs for IPL have been developed and implemented in the organisation, all of the 15 characteristics should be carefully studied.

Table 2.5 – Characteristics for effective maintenance KPIs adapted from [94] and [95].

Characteristics	**Business Performance Management** [94]	**ISO-standard** [95]
1. Aligned	KPIs are always aligned with corporate objectives and strategies.	The KPI affects change in relevant higher-level KPIs.
2. Owned	Every KPI is owned by a person or group in the organisation.	*Buy-in:* Teams responsible for the operation and teams responsible for upper and lower level KPIs are willing to support the use of the KPI. A challenge is to retrieve official approval by management for the KPI.
3. Predictive	KPIs measure drivers for business value and are therefore "leading" indicators of performance desired by the organisation.	The KPI is able to predict non-steady-state of the operation.
4. Actionable	The user can intervene and take actions before it is too late since KPIs are populated with timely, actionable data.	The team responsible for the KPI has the knowledge, ability and authority to improve the value of the KPI.
5. Few in number	KPIs should not be too many in number so that attention and effort is not scattered on too many things.	

6. Easy to understand	The user should have thoroughly insight of the KPI-model so that it is easy to understand the KPI.	The meaning of the KPI is understood by team members, management, and customers.
7. Balanced and linked	KPIs should reinforce and not reinforce each other.	The KPI is balanced within the chosen sets of KPIs.
8. Trigger changes	The KPI should trigger a chain of reactions and changes in the organisation.	*Trackable:* The appropriate steps to fix the problem are known, documented, and accessible. The problem is indicated by particular values or temporal trends of the KPI.
9. Standardised	KPIs must comply with a standard of definitions, rules and calculations.	*Standardised:* The standard can be plant-wide, corporate-wide, or industrial-wide and is characterized as *correct*, *complete* and *unambiguous*. *Correct:* The calculation of the KPI is computed in accordance to a standard definition. *Complete:* The definition and the calculation of the KPI covers all parts, and no more, of standard definition. *Unambiguous:* The syntax (grammar) and the semantics (meaning) in the definition of the KPI lacks ambiguity or uncertainty. *Valid:* There is a compliance between the operational definition and the standard definition. *Quantifiable:* The value of the KPI can be numerically specified. *Accurate:* The measured value of the KPI is close to the true value.
10. Context driven	KPIs is put in a context with targets and thresholds to performance so that the user can gauge the performance over time.	The KPI is comparable to a defined reference value over a period of time, and a normalized factor to express the indicator in absolute terms with appropriate units of measure.
11. Reinforced with incentives	Organisations can magnify the impact the KPIs with incentives.	
12. Relevant	KPIs can lose their relevance over time and should be evaluated and refreshed on regular basis.	The KPI enables improvements in the operation, demonstrate real-time performance, allows accurate prediction of future events and presents a record of past performance that is valuable for analysis and feedback control.
13. Automated		KPI collection, transfer, computation, implementation, and reporting are automated.
14. Documented		The documentation ensures that the instructions for implementing the KPIs are up-to-date, correct, complete, and unambiguous.
15. Inexpensive		The cost of measuring, computing, and reporting the KPIs are low and can be justified for the management.

2.5.2 Structuring of Maintenance KPIs

The main reasons for establishing of a structure maintenance KPIs in an organisation are to control and improve the maintenance function. This has become an essential part of maintenance management [92].

Both the maintenance function and applicable structures for performance measurement have been evaluated [96, 97]. The maintenance function reflects the role in the organisation and has evolved with time. The traditional view has been that the maintenance function is to fix broken items, but has fortunately changed to include proactive tasks such as routine servicing, periodic inspection, preventively replacement and inspection [97]. In fact, the role of the maintenance function concerns also strategic decisions in the organisation such as strategic planning that links the maintenance function with the corporative strategy [53]. The maintenance function can be further structured into management processes. Figure 2.10 illustrates these processes of the maintenance process adapted from [29]. This adapted version would now be more aligned with IEC 60300. Also, similar illustrations of maintenance management processes has been proposed, and they all comprise a closed loop [96, 97].

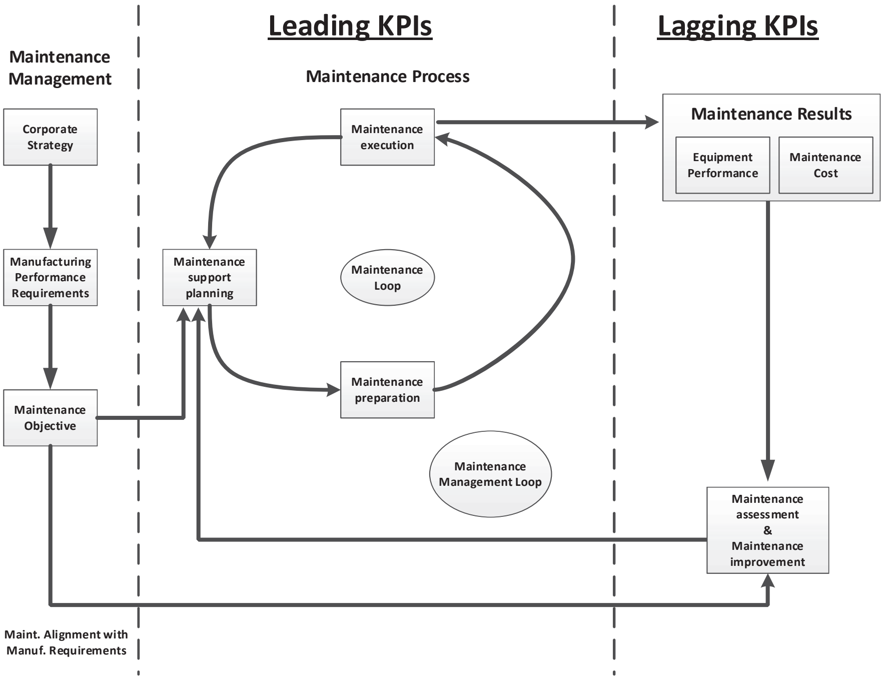


Figure 2.10 – Management processes for the maintenance function, adapted from [29].

Measuring performance in maintenance planning is important because it will ensure and verify that the maintenance activities planned and executed have given the expected results [91]. In fact, measuring this can support the maintenance manager to allocate maintenance staff and resources to particular areas of the production system that will impact manufacturing performance [29, 91].

A combination of both business specific and multi-criteria hierarchical framework has also been suggested [98]. This framework is illustrated in Figure 2.11 and consists of 5 major steps:

1. translate the generic KPI system into the specific business and industry branch with all organisational levels (i.e. strategic, tactical and operational);
2. prioritize the maintenance objectives;
3. align the business maintenance objectives into maintenance KPIs;
4. measure and control the KPIs; and,
5. perform analysis and continuous improvement.

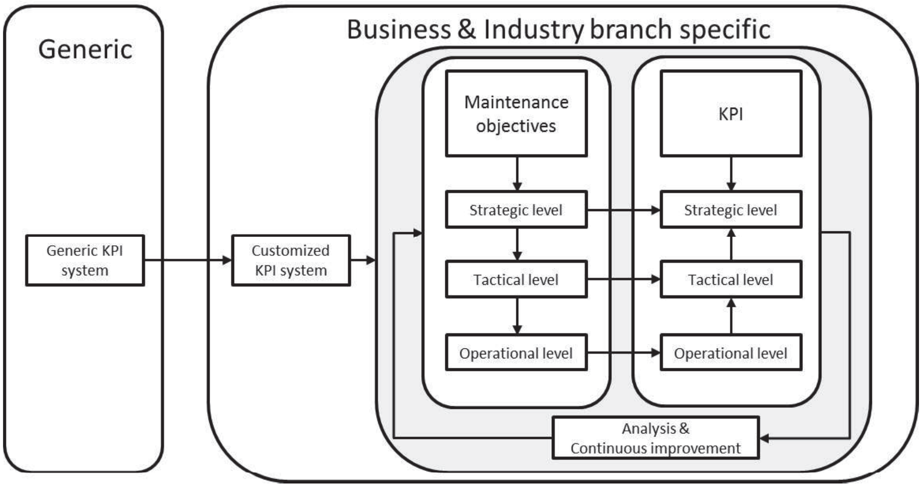


Figure 2.11 – Framework for Maintenance Performance Indicators, adapted from [98].

Today, the standard EN 15341 presents relevant maintenance KPIs [68]. To clarify, this standard describes a system for managing KPIs to measure maintenance performance in a framework of influencing factors. Figure 2.12 presents the structure of the maintenance KPIs and the influencing factors [34]. The KPIs are classified within a matrix with the dimensions of indicator level and indicator groups. The indicator level represents the most suitable level for the KPIs in the production plant. Level 1, 2 and 3 represents respectively levels of plant production, production line and equipment. Further, the KPIs are also classified into economic, technical and organisational indicators. The framework in Figure 2.12 also express a causality where both external and internal influencing factors affect the KPIs. Internal factors are within the control of the organisation, whereas the external factors are more difficult for the organisation to control.

According to this standard, the KPIs will support the organisation to define objectives and strategies that can improve the economic, technical and organisational performance. Further it will allow the organisation to:

- measure the status;
- evaluate the performance;
- compare performance;
- identify strengths and weaknesses; and,
- control progress and changes over time.

This standard can be applied at a periodic basis during preparation and follow-up of budget, or on spot basis in terms of benchmarking studies. A limitation of this standard is that neither the term maintenance KPI is defined, nor does it comprise criteria of effective maintenance KPIs. An updated version is expected in 2018. Hopefully, these limitations have then been considered with an improved version.

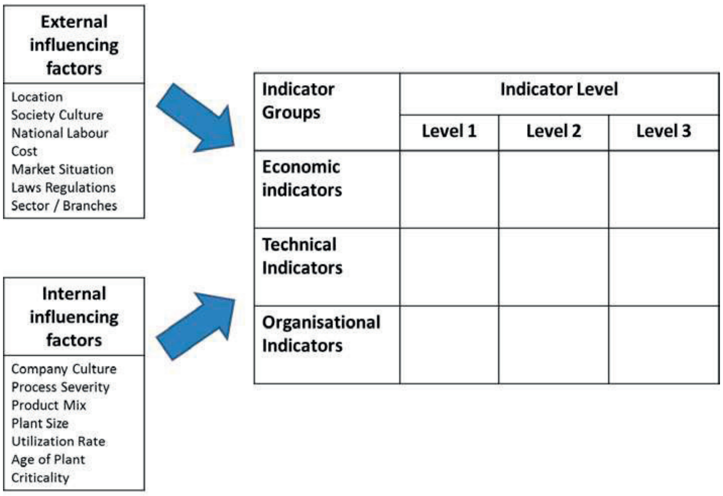


Figure 2.12 – Framework of maintenance KPIs and the influencing factors [34].

A literature study of maintenance KPIs classifies KPIs in terms of leading and lagging indicators [91, 99]. Figure 2.13 presents the overview of this taxonomy with some examples of maintenance KPIs. A more comprehensive description of the maintenance KPIs has been elaborated with tables [29]. The leading indicators are measured during the execution of the maintenance processes, whereas lagging indicators are measured when the result of maintenance management is observed.

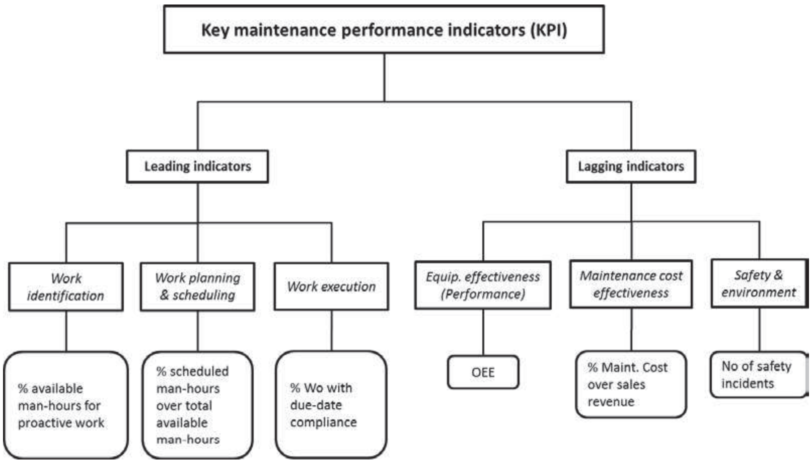


Figure 2.13 – Overview of some maintenance KPIs [91, 99].

2.5.3 Hidden Factory and OEE

The metaphor "hidden factory" can be traced back to the metaphor "gold in the mine" in the quality management field; the quality loss denotes all defects in production and are evaluated [100]. These quality losses represent unnecessary defect costs and are classified as follows:

- tangible costs related to production;
- tangible costs related to sales of product; and,
- intangible costs.

Later, the metaphor "hidden factory" has been introduced when measuring OEE and associated time losses [101]. In fact, by recognizing the "hidden factory" within, improvements in companies have contributed directly to the bottom line [102]. Both Nakajima [103] and Shirose [85] established the original foundation of OEE in the concept total productive maintenance (TPM) in the promotion organisation Japan Institute of Plant Maintenance (JIPM). The work from Nakajima in introducing TPM seems to argue that TPM is the process whereas OEE is the KPI for "unlocking the hidden factory" [101]. By measuring OEE it is possible to demonstrate the size of the "hidden factory" [102]. OEE has also been associated with other metaphors such as "hidden machines" [104]. The importance of OEE has increased due to intensified competition, resulting in demands for higher OEE value [105]. It is also claimed by Nakajima that "…*equipment effectiveness* is a measure of the value added to production through equipment." (p. 27) [103].

In addition to the time losses from OEE, the "hidden factory" is also comprehended as the eight wastes where unnecessary work such as repeated motion and rework is being carried out [106]. The eight wastes have been identified by Toyota Production System [107]:

1. overproduction;
2. waiting (time on hand);
3. transportation or conveyance;

4. over-processing or incorrect processing;
5. excess inventory;
6. unnecessary movement;
7. defects; and,
8. unused employee creativity.

The “hidden factory” also envisions the accumulated manufacturing overhead costs such as transaction costs [108]. These transactions do not contribute directly to the physical product produced, but rather exchange materials and/or information necessary to move production along. In the quality management field, the metaphor “hidden organisation” [109] or “hidden factory” [110] has been used to point out the existence of bad work carried out in the organisation such as rework of unsatisfactory parts in the factory or fixing errors in customer service. In fact, it has been stated by Feigenbaum [110] that “from an operating point of view, anywhere from about 20 % to 40 % of total capacity of many American companies is tied up in this hidden organisation.”

A similar metaphor for the “hidden factory” is the “iceberg” effect and has been applied within LCC [111]. A plausible reason for illustrating LCC with this metaphor is that the acquisition cost represents only the visible top of the “iceberg” of all cumulative costs of the product over its life cycle at point in time for investment. In addition, there will also be future costs that are hidden or difficult to calculate when deciding for investing in new equipment. Examples of such cost elements are training cost, repair cost, and retirement cost.

It seems that the guided imagination leads to several meanings of the “hidden factory”. By its definition a metaphor is a figure of speech in which a word or phrase is applied to something to which it is not literally applicable [89]. Moreover, the figure of speech is a word or phrase used in a non-literal sense for rhetorical or vivid effect. Obviously, it is not a literally a physical factory or machine hided for the organisation. Instead, a meta-understanding of the “hidden factory” should be activities with losses and waste that do not provide value for the customer. Further in this section, the “hidden factory” measured through time losses is presented.

Shirose [85] has extended OEE and introduced 16 big losses that are inherent in a production system and impedes the profit. Figure 2.14 presents a systematic overview of the 16 big losses. In addition to the equipment losses considered by Nakajima, Shirose also includes losses that both impede labour effectiveness and resource consumption. Since cutting-blade losses are included, it seems that the 16 big losses are primarily meant to be applied for fabrication and assembly industries.

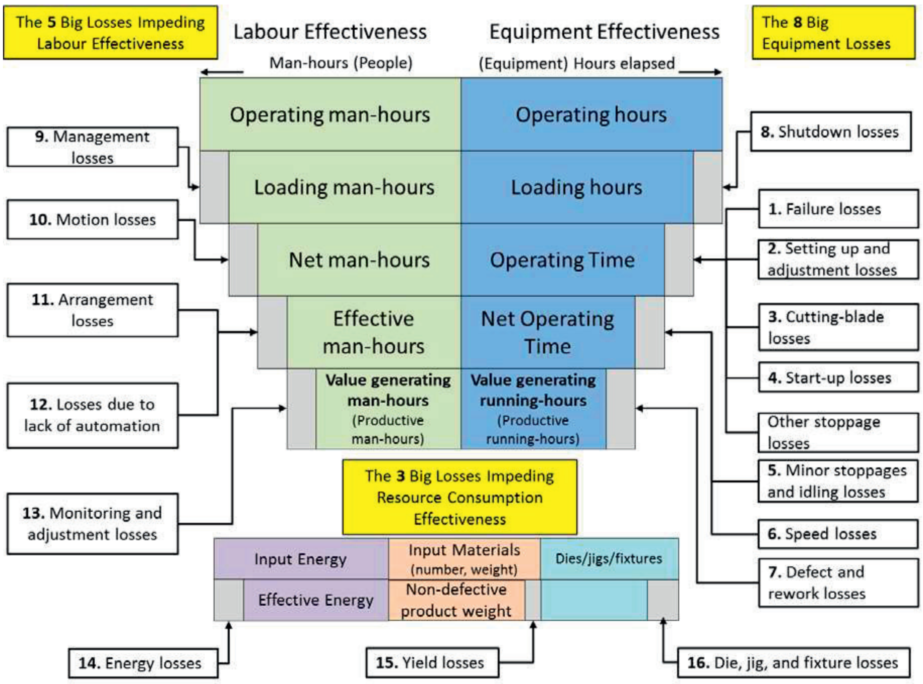


Figure 2.14 – 16 big losses [85].

Regarding the equipment losses, most of them are included when calculating OEE as described in this section. However there are some of them that are left out or reallocated to other time elements when calculating OEE. The shutdown loss of the equipment involves preventive maintenance activities such as inspection, parts replacement and overhauling. If some of these activities are taking place during the loading time when production is scheduled, this would reduce the operating time. Another reallocation is the cutting-blade loss that would be considered as a part of the preventive maintenance activity or a corrective maintenance activity that would be included as a failure loss.

There are also 5 losses that impede the labour effectiveness. The *management losses* are waiting time that occur during management, such as waiting for materials, instructions, and defect repair. *Motion losses* are due to violation of motion economy and can be results of both poor design of the layout and operator related such as skill differences. *Arrangement losses* are due to line-balance losses in production and multi-operations for the operator. The losses due to *lack of automated systems* take place when manual work is performed when an automated system would be cost-effective. This system could for instance be automated loading and unloading systems. The *monitoring and adjustment loss* is occurring when operators frequently must monitor and adjust the production process to avoid quality defects.

Finally, there are 3 big losses that impede resource consumption effectiveness. Since the *energy costs* represents a significant amount of the total operating costs, it is important for the companies to reduce the consumed energy. Energy sources include electricity, fuel as well as processing of wastewater. The *yield loss* is volume losses and is calculated in terms of the ratio of the weight of non-defective product and the total weight of raw material. The last type of losses for resource consumption is related to the *wear of tools* and requires manufacturing and maintenance.

In more recent time, an own industry standard [74] and a user guide [104] by Koch has revitalized OEE with source from JIPM. ISO 224000 also defines and models OEE as an industry-neutral framework for manufacturing operations [112]. Some local differences still exist between the ISO standard and industry standard. For example, the time for conducting maintenance that requires a shutdown will affect the availability in the industry standard, but this has been extracted in the ISO standard and will not affect availability. Despite these differences, a thorough scrutiny of these sources in combination with the practice and experience from industry should ensure a sufficient and sound basis for both implementing and operationalising OEE with accurate calculations.

As illustrated in Table 2.6, OEE is calculated based on the six big losses and comprises the time elements availability, performance rate and quality rate. The six big losses are in accordance with the loss categories from Nakajima [103]. However, in more recent taxonomy of the six big losses, the set up and adjustment losses have been replaced with waiting time [104].

Table 2.6 – Six big losses in OEE calculation.

OEE time elements	Six big losses
Availability	1. Breakdown losses
	2. Set up and adjustment losses
Performance rate	3. Idling and minor stoppage losses
	4. Reduced speed losses
Quality rate	5. Quality defects and rework
	6. Start-up losses

In summary, OEE is calculated as the product of availability (A), Performance rate (P_R) and quality rate (Q).

The calculation for availability is

$$A = \frac{T_L - T_{DT}}{T_L}$$

where T_L is the loading time and T_{DT} is the downtime measured in hours. The loading time is also denoted as the potential production time that the machine could theoretically have been in operation when there is a “demand” [104]. The time difference from the total time (365 days x 24 hours) is the unscheduled and “not scheduled” time [74]. The unscheduled time is when the equipment has an outage reasons beyond the scope of the production team. Example of these reasons are no customer orders, strike, and no supply of resources due to boycott and test production. Not scheduled time is when there are not meant to be any operations-activities going on at all. An example would be not scheduled time during the night since the production only has day-shift.

Downtime includes several time elements:

- breakdown;
- setup;
- adjustment losses;
- both preventive and corrective maintenance during loading time; and,
- waiting for technician

To increase the OEE value, it can be tempting for the maintenance planner to plan for maintenance activities outside the loading time. In fact, it has been proposed that all planned downtime should be left out from OEE calculation [101, 113]. It has also been strongly questioned that planned downtime should be deducted from loading time with for example excessively long preventive maintenance activities [114]. This approach of calculating OEE can then result in an artificial high OEE, where it is no pressure on reducing the time for preventive maintenance [74]. Therefore, it is no surprise that scheduled maintenance is proposed to be included in the "big losses" and therefore included in calculation for availability [115]. This is also supported by the mining industry that estimates OEE with a calendar time-based approach and thus including scheduled maintenance time [116].

The performance rate comprises both minor stoppages and reduced speed in production. The calculation of this rate is:

$$P_R = V_{output} \times \frac{T_L - T_{DT}}{R_{actual}} \times \frac{R_{actual}}{R_{plan}}$$

where V_{output} is the produced volume, R_{actual} is the actual production rate whereas R_{plan} is the planned production rate. An important issue for the performance rate is the maximum duration of a minor stoppage before it is classified into an availability loss. The literature is not so clear in this point with different recommendations. Nakajima [103] recommends minor stoppages to be under 10 minutes and less than 3 times/month. Koch on the other hand recommends minor stoppages to be even shorter and less than 5 minutes [104]. Shirose [85] also supports this by defining minor stoppage or idling loss to have the durations from 3 seconds up to 5 minutes. In addition, following characteristics are given to describe a minor stoppage [85]:

- a simple measure will result in functional recovery;
- minor stoppage does not require a repair or spare parts; and,
- the loss is accompanied by temporary functional stoppage.

In overall, a minor stoppage is a temporary problem such as a workpiece clogs a chute or a sensor failure causes a temporary stoppage of the machine. The measure is then to remove the stuck workpiece or restart the machine. It is also important to shed light on the planned production rate. This rate could here either be understood as the design speed rate of the existing machine, or the speed rate that is today technological possible to achieve.

Quality may be measured quantitatively as reduced number of parts classified as scrap or required for rework in manufacturing [104]. The calculation for quality rate is

$$Q = \frac{V_{approved}}{V_{output}}$$

where V_{output} is the actual produced volume and $V_{approved}$ is the volume of products that is approved and therefore free for defects.

A case study has concluded that OEE is not considered as a strategic measure for the organisation [117]. This is however in contradiction with the fact that OEE is seen as a measure of maintenance performance management for tactical decisions and middle management [118] and at a strategic level for the senior managers [119]. It is also concluded that it is necessary to link the factory capacity model with the business plan to project the required OEE [120]. OEE should also be used as a strategy in the company, i.e. including OEE as a part of the overall organisation improvement plan [121].

Based on several literature studies regarding OEE, it is a strong support for that OEE is applied for both maintenance and production department [122]. This aspect has also been mapped through a causal loop diagrams (CLD) and is shown in Figure 2.15 [122]. The diagram visualizes the causality where a plus sign in the arrow indicates an amplifying effect, whereas a minus sign indicates a weakening effect.

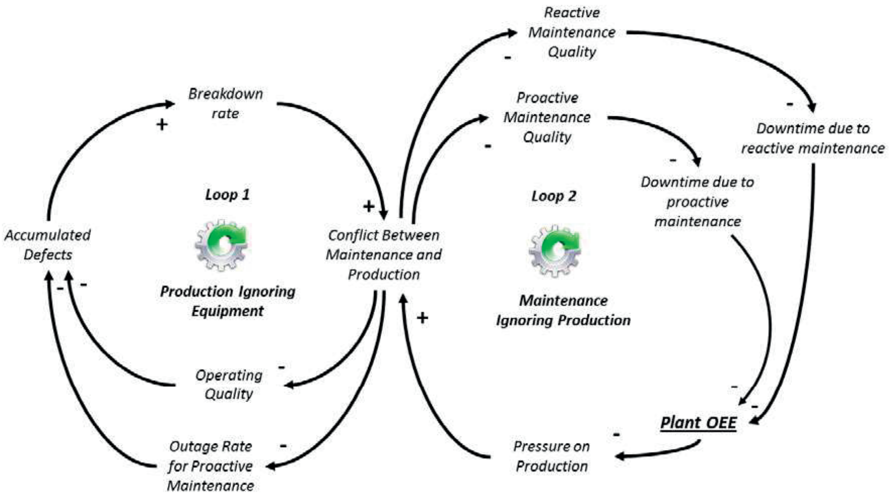


Figure 2.15 – Conflicts between maintenance and operation causes more downtime adapted from [122].

As shown in this diagram, the result is reduced plant OEE due to a silo problem. In particular, many production and maintenance employees have experienced a conflict arises when a serious breakdown occurs when production is under pressure to meet targets. This will also lead to a culture of mutual blame between the production and maintenance function. Production will blame the maintenance for unexpected breakdown and poor quality maintenance service in repairing the equipment. The maintenance department, on the other hand, will blame production for not operating the equipment properly, lack of reporting during a failure and not letting maintenance perform the preventive maintenance programme in the organisation. In sum, the CLD simplifies the illustration of these conflicts.

2.5.4 Maintenance Backlog

To control the technical condition through maintenance management, specific KPIs have been developed. The KPI denoted maintenance backlog has this function and can be measured through two different approaches.

The first approach to measure maintenance backlog, is related to the maintenance plan. In accordance to Petroleum Safety Authority (PSA), maintenance backlog is the amount of preventive maintenance that is not carried out within the due date [123]. This amount is measured in accumulated man-hours for each operator. Since maintenance backlog introduces contribution to risk, maintenance backlog has the purpose for PSA to trend risk level for oil and gas companies at the Norwegian Continental Shelf. An important consideration for this KPI is to consider how much volume in work of maintenance backlog that should be allowed for a company [124]. It is difficult to set a limit for this volume in maintenance planning. Nevertheless, it can then be questioned how well maintenance management is performed if no such limits exists.

Nuclear industry has a similar approach in analysing maintenance backlog [125, 126]. In this industry branch, the term maintenance backlog clearance is applied and defined as a percent of issued work orders that have been completed on schedule [125]. Maintenance backlog will determine the number of activities that the nuclear utility should have carried out, but for some reason have been delayed [126]. The unit for maintenance backlog is the number of activities, giving an alternative definition of maintenance backlog as the total number of maintenance activities for a given period pending execution, expressed as the number of work requests [126].

The second approach is related to measuring the technical condition of the equipment and is applied for road facilities [127, 128] . In this industry branch, maintenance backlog is defined as the amount of unfulfilled demands at a given point of time in explicit reference to the predefined standards to be achieved [127]. This definition will also comprise a monetary perception where maintenance backlog is regarded the cost of bringing the current level of technical condition back to a standard level of the technical level [128].

In summary, the differences between these approaches is presented in Table 2.7. These approaches should not be regarded as conflictual, but more as supplementary.

Table 2.7 – Comparison of activity based and condition based measurement of maintenance backlog.

	Approach 1: Work order based	**Approach 2:** Technical condition evaluation
What is measured?	- Maintenance activities that are not completed within due date.	- The technical condition of the facility. - Unfulfilled demand of functional or financial amount in the road infrastructure. - The cost of bringing the current technical condition up to a reference level.
Measuring unit	- Man-hours - Number of work orders	- Monetary form (e.g. USD) - Functional form (e.g. kilometres with road)

3 Methodology

"To produce or maintain; THIS is THE Question" – Harald Rødseth

Oxford English Dictionary defines research as "The systematic investigation into and study of materials and sources in order to establish facts and reach new conclusions" [89]. To conduct this type of investigation it is vital to follow a sound research methodology. The purpose of the research methodology is to allow others to scrutinize and evaluate the research. This chapter presents and discusses the research methodology chosen in this PhD thesis. Firstly, this chapter outlines and positions the different types of research methods chosen in my research. Secondly, this chapter describes the research design applied in this PhD thesis.

3.1 Classification of Research

Research methods can be classified according to following criteria [129]:

1. descriptive vs. analytical;
2. applied vs. fundamental;
3. quantitative vs. qualitative; and,
4. conceptual vs. empirical.

The first criterion distinguishes descriptive and analytical research. Descriptive research includes for example surveys where the purpose is to describe the state of affairs as it exists today for example in an organisation. In analytical research, instead of describing the current situation for an organisation, information already available is used and analysed to make a critical evaluation of the material. The position in my research is **analytical research**. By considering existing theory in maintenance management and reliability theory, the theoretical framework has been developed.

The second criterion evaluates if the research is either applied or fundamental. Whereas fundamental research concerns generalisation of theory, applied research aims at finding a solution for an immediate problem facing the industry. My position in the research is **applied research**. The motivation in this PhD project started with the need for developing indicators for IPL in the research programme "Center for Integrated Operations in the Petroleum Industry" [130]. However, since maintenance as a scientific field includes more than the petroleum industry, other areas were included for applied research. Through meetings and discussions with other industry branches such as manufacturing, maritime and process industry, it seemed that IPL theory was generic and was later tested through demonstrations in several industry branches. The research society and manufacturing industry in Europe also support the need for more research within IPL theory. In fact, a research topic in Europe is for maintenance to be better synchronised with production planning [131].

The third criterion considers quantitative and qualitative methods. Quantitative research is based on a measurable attributes whereas qualitative research rather concerns observable phenomena. For example, the study of human behaviour that can be difficult to quantify, and thus would be classified as qualitative research. For my thesis mostly **quantitative methods** have been applied.

The fourth criterion evaluates if the research is conceptual or empirical. Conceptual research is related to theory where the idea is to develop new ideas or models or to reinterpret existing ones. Empirical rather relies on receiving facts first-hand and then actively stimulate the production of desired information. My research is supported by the position **conceptual research**. Although experience has been important for me when developing IPL theory as a concept, it was for me not a logical approach from my experience towards the theory. This understanding is also a key element in constructing a scientific theory [132]. According to this understanding it is not possible to generalize theory from few observations. Therefore, my experience through meetings with industry is rather understood as an important creative (non-logical) approach from experience towards the concepts in IPL theory.

3.2 Research Design

When acquiring new knowledge, two basic approaches are offered [133]:

- inductive reasoning where knowledge is gained by sensory experience, i.e. empiricism; and,
- deductive reasoning where knowledge is gained by reasoning, i.e. rationalism.

Figure 3.1 portrays a model of research processes of the scientific method [134-136]. In overall, the scientific method consists of four stages. **Stage 1** starts with the inception of the idea from the researcher that is based on his experience both from his prior theoretical knowledge and his observations in his field. The idea is then formulated into a problem definition with concepts and definitions where hypothesis setting will test this idea. In **stage 2** the experiment is designed with a suitable research methodology. Further in **stage 3**, the designed experiment is conducted involving testing of the hypothesis through collection, processing and analysis of data. If the hypothesis is rejected, the researcher must re-start at stage 1 and modify it. If despite his attempts, he does not manage to falsify the hypothesis, the researcher can proceed to the next stage. In **stage 4**, the theory is refined with conclusion and highlight of contribution and further study.

The research design in my thesis is based on the scientific method. However there is one important deviation of the scientific method from my conducted research. According to the scientific method a hypothesis setting should be established. This is not the situation in my research, but instead deductive testing has been conducted within the body knowledge of maintenance management and reliability theory.

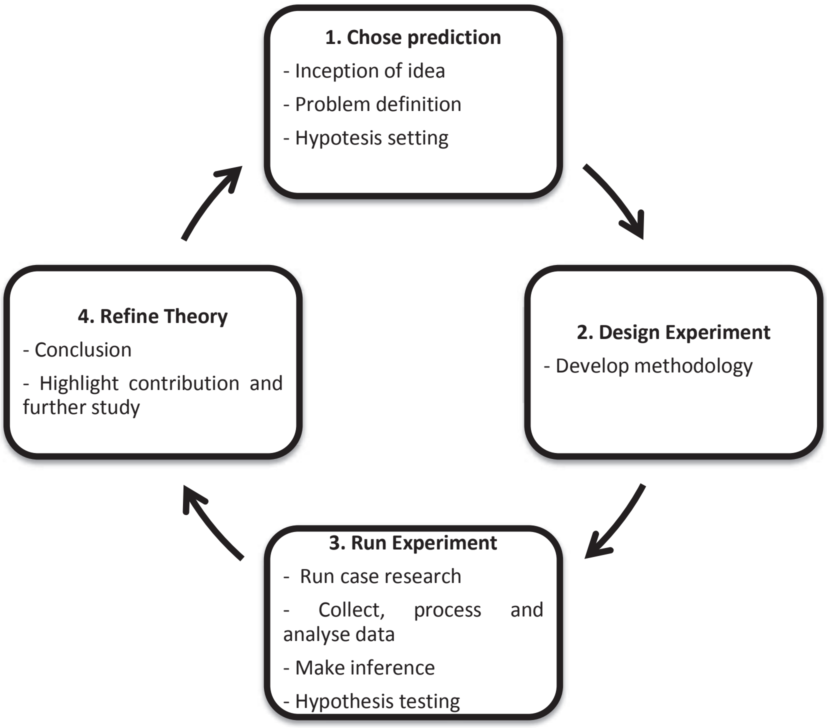


Figure 3.1 – Model of the scientific method [134-136].

A popular misunderstanding of the scientific method is to interpret it as inductive [137]. By following the inductive logic, the researcher should start the process of raw evidence in terms of simple, unbiased, unprejudiced observation and generalise a theory based on these observations. According to the scientific theory this is not possible since every act of observation we conduct is based on what we have seen in past. Instead, the scientific work should start with some expectations from the researcher. In fact, Karl Popper [138] has stated that "…The initial stage, the act of conceiving or inventing a theory, seems to me neither to call for logical analysis nor to be susceptible of it." He made it quite clear that there is no logical path from experience and towards new ideas and concepts in theory. Instead, "an irrational element" or "a creative intuition" is rather needed when starting the scientific discovery. Therefore it will not be logical path between stage 4 and stage 1 in the scientific method in Figure 3.1, but rather a "creative jump."

The chosen research design is presented in Figure 3.2. The research design has the ideal of the scientific method. Furthermore it applies case research as theory testing within the scientific method [139]. The starting point **(0)** is to conduct literature review and meeting the industry to understand their industrial challenges within IPL. The dashed arrows at **(0)** indicates that it is not a logic path towards development of theoretical assumptions **(1)** but rather based on my creative intuition as a researcher.

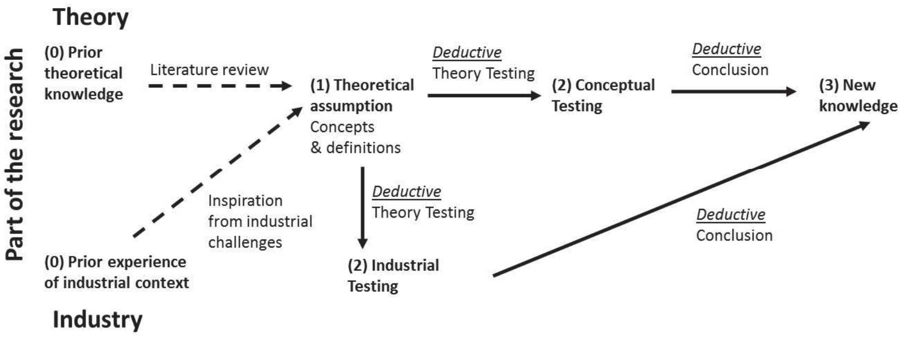


Figure 3.2 – Applied research design in the PhD thesis.

Following concepts and definitions would as examples be provided at **(1)**:

1. identification of models for maintenance planning strategies and existing maintenance KPIs; and,
2. development of a framework and KPIs applied for IPL.

The next phase is to conduct theory testing **(2)** in terms of both conceptual testing and industrial testing. The reasoning in this type of testing is deductive with explicit derivation from the theoretical assumptions. In my thesis, the following overall research activities support this testing:

1. **Conceptual testing** where existing models for maintenance planning strategies and maintenance KPIs are evaluated. Also, conceptual testing was conducted to demonstrate the developed KPIs applied for IPL.
2. **Industrial testing** where existing maintenance KPIs in the IPL framework were demonstrated and evaluated based on real industrial data. To illustrate this type of testing, a developed KPI for IPL was demonstrated based on industrial data in the saw mill industry.

The last phase is the conclusion **(3)** where the theory is refined towards new knowledge. An important aspect of the scientific method is to attempt to falsify the hypothesis. Although no hypothesis was developed and tested in my thesis, I still managed to conduct testing of the results achieved during this PhD project. The testing did not result in failures where it was not possible to perform the conceptual or industrial testing. Thus it is plausible to conclude that the scientific contribution has led to new knowledge within the body knowledge of maintenance management and reliability theory.

4 Main results and Discussions

"To produce <u>and</u> maintain; THIS is THE Answer! " – Harald Rødseth

The purpose of this chapter is to present and evaluate the main results achieved in this research.

An overview of the contributions in this thesis is shown in Figure 4.1 where the research objectives, articles and the results are structured. The research objectives were given in Chapter 1.4:

- **Objective 1:** *Identify and evaluate existing models for maintenance planning strategies.*
- **Objective 2:** *Develop a framework for IPL.*
- **Objective 3:** *Evaluate and structure existing maintenance KPIs for IPL.*
- **Objective 4:** *Further development of KPIs applied for IPL.*
- **Objective 5:** *Demonstrate and evaluate the KPIs in the IPL framework.*

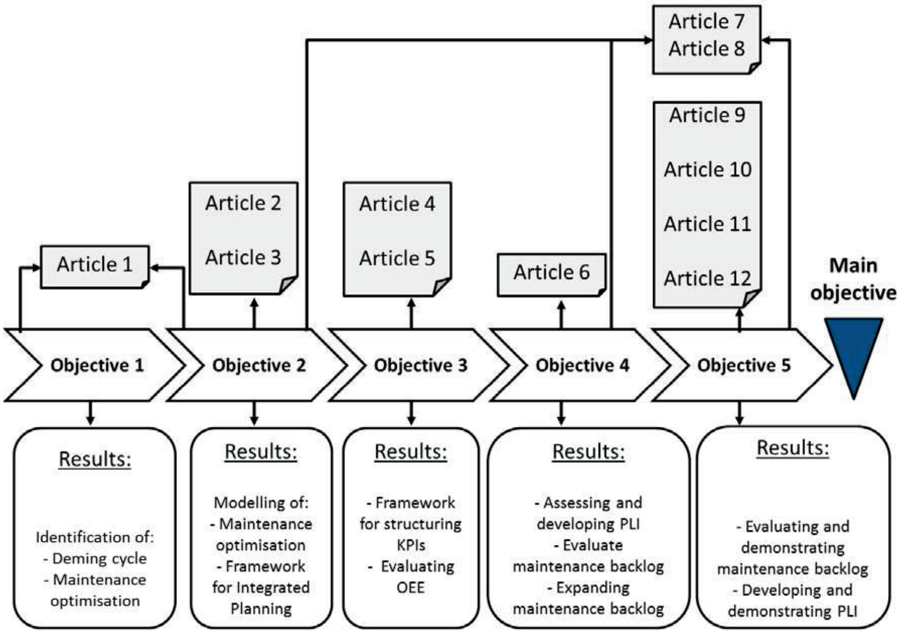


Figure 4.1 – The structure of research objectives, articles and outputs for achieving the main objective.

To achieve these research objectives, in total 12 research articles have been written and provided as results in terms of the contributions of this PhD research. The main results are two-fold. Firstly, the contribution to science is investigated for each research objective addressing the relevant research articles. Secondly, the thesis presents the contribution to practice for several industry sectors. To ensure that the theory developed holds, specific criteria for research quality is presented and evaluated for this PhD thesis at the end of this chapter.

4.1 Contribution to Science

4.1.1 Further Development and Modelling of Maintenance Planning

The research objective 1 is to identify and evaluate existing models for maintenance planning strategies. Article 1 addresses this objective [1].

An appropriate maintenance management framework needed to be identified. In addition to the general framework presented in the standard IEC 60300-3- 14 [26], an alternative identified in Article 1 is the maintenance framework developed by the Petroleum Safety Authority (earlier Norwegian Petroleum Directorate) [77]. The framework should be considered to be a basic model for the maintenance management processes for this industry sector.

What is clear from this model is that it constructs a closed loop and ensures continuous improvement with the Deming cycle. Maintenance planning in this loop will comprise different activities and application for methods [25]:

- method and criteria for planning and prioritising of both preventive and corrective work orders based on the impact on safety and production; and,
- regular monitoring and evaluation of plans in terms of achievement, maintenance backlog and efficiency.

In addition to Article 1, a recent maintenance planning handbook also advocates that planning should be included in a cycle of continuous improvement. In fact, it is stated that the objective of planning is not just to plan and then execute [15]. The intention of planning is to follow a cycle-of-improvement philosophy where the organisation ensures learning in the planning stage. Therefore, the closed-loop model will be an essential part in the maintenance planning strategy and the IPL framework.

When choosing maintenance planning strategies, two suitable maintenance strategies were identified in Article 1:

- dynamic grouping; and,
- strategic grouping.

The main difference between them is that dynamic grouping is applied when updated information of the failure rate is available whereas static grouping does not exploit new information of failure rate. Article 1 identifies the pro and cons of these two strategies. The benefit for static grouping is that it does not require as much administrative work, but the drawback is that it does not exploit new information. The benefit for dynamic grouping is that it updates based on unforeseen events but here is the drawback that such a model is difficult to implement and administer. To summarize the scientific contribution towards research objective 1 is found in Article 1:

- the Deming Cycle is a basic model for all maintenance planning strategies; and
- both static and dynamic maintenance planning strategies are suitable strategies but they have each their own strength and drawbacks.

The research objective 2 is to develop a framework for IPL. Article 1 [1], 2 [2], 3 [3], 7 [7] and 8 [8] address this objective. Figure 4.2 portrays this balance as semi-static grouping and is proposed further as a strategy for IPL from Article 1.

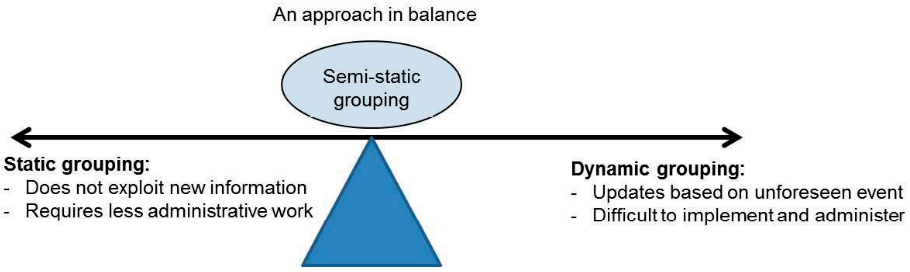


Figure 4.2 – The balanced approach in semi-static grouping strategy.

This approach should as with dynamic grouping update based on an unforeseen event and as with static grouping require less administrative work. This avoids the drawbacks from static grouping where no new information is exploited and the difficulties to implement and administer from dynamic grouping. Figure 4.3 shows the result illustrated as a dashboard.

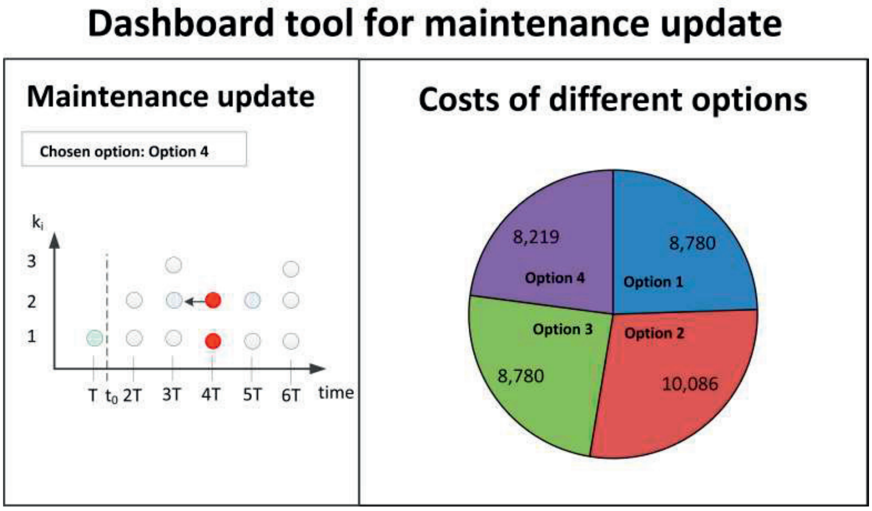


Figure 4.3 – Dashboard tool for maintenance update [1].

Also an IPL framework was developed as shown in Figure 4.4 [2]. The framework consists of three levels. At level 1 the customer influences the market through demand and supply for a product. In addition, the restrictions and requirements are also settled at this level from regulatory, owners and management. The next level is a processing plant on-shore where the raw oil or raw gas is further processed to sellable product and gas. Level 3 positions the production system located offshore representing the different organisations responsible for production. The notion of primary and support planning loops is inspired by the Porter value chain concept where activities are divided into primary and support activities, and where the planning ensures continuous improvement through the Deeming wheel. The "heart" of the IPL framework is the IPL loop. For oil and gas industry there might be occurrences where external planning is necessary. If two production companies deliver to the same processing plant it can be necessary to perform external planning in order to meet a required level of production assurance to the processing plant.

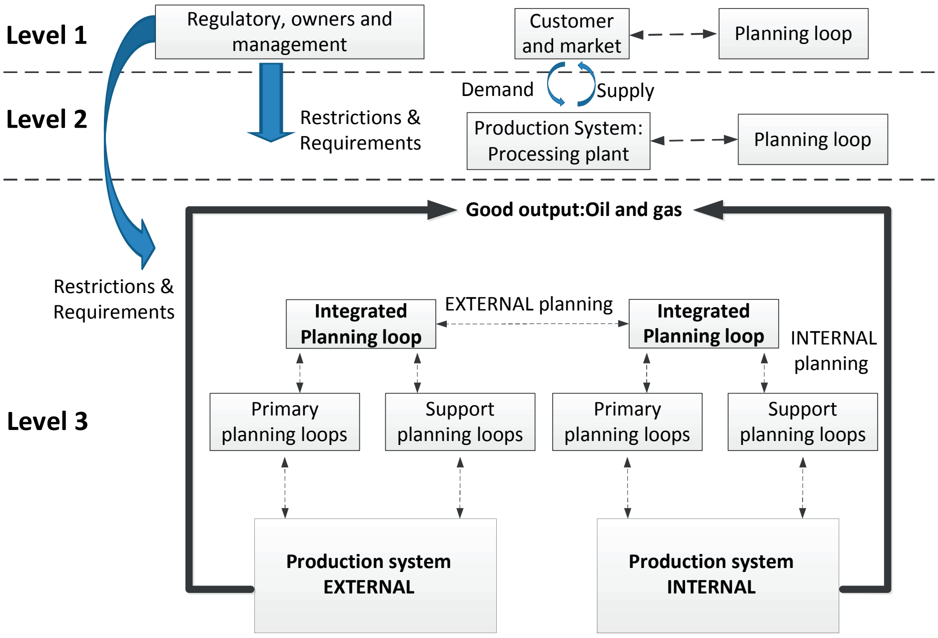


Figure 4.4 – IPL framework for oil and gas industry [2].

To ensure a higher degree of generalisation, some further updates are necessary from the IPL framework:

1. Level 2 should either be merged with level 1 or renamed to production system or warehouse.
2. Due to different contexts of market regulations, external planning at level 1 is not relevant for all industry branches such as the saw mill industry. Nevertheless it will remain since it is of relevance in the oil and gas Industry.
3. Level 3 will deliver other good output than oil and gas. Therefore it should be reframed to good output or products.

The latter point will have some implications for definition of IPL. The aim for enhanced oil and gas recovery is context driven and should therefore be excluded from this definition. The modified and generalised definition for IPL is therefore:

"Multidisciplinary decision making process that manages technical condition and results in increased production, reduced costs, improved safety. This process is performed in a manner that optimises across multiple planning disciplines through updating of objectives and

attended by the power and intention to commit resources and to act as necessary to implement the chosen plan."

Table 4.1 presents the content of the IPL loop which is in accordance with the Deming wheel [2]. This wheel should be considered to be generalized for application in any industry branch.

Table 4.1 – Content of the IPL loop, adapted from [2].

Stages	IPL loop
1. PLAN	1.1 Collect data 1.2 Processing of data 1.3 Processing of initial plans 1.4 Review of objectives and requirements 1.5 Processing of IPL
2. DO	2.1 Dispatch plans to the relevant planning disciplines: - Strategic plans - Tactical plans - Operational plans
3. CHECK	3.1 Report results 3.2 Perform analysis and regular meetings in order to exchange learning, observations and knowledge
4. ACT	4.1 Improve assessments 4.2 Prevent need for maintenance

4.1.2 Relevant Maintenance KPIs for IPL

The research objective 3 is to evaluate and structure existing KPIs for IPL. Article 4 [4] and article 5 [5] address this research objective.

When evaluating existing KPIs, a sound list of generic characteristics for effective KPIs is necessary. The list was tested on OEE and it was argued that this KPI has some shortcomings as a KPI for IPL. Also the list of characteristics points out that OEE can be regarded as a lagging KPI and that it must be balanced and linked with a cause-and-effect relationship to other KPIs. Based on a case study for a both a Norwegian and Canadian production plant for automotive suppliers, the following maintenance indicators were applied:

- OEE;
- Time for preventive maintenance/Time for maintenance; and,
- maintenance backlog measured as accumulated man-hours that has not been finished within due time.

Based on the case studies, a proposed framework shown in Figure 4.5 was developed [4]. As shown in this framework OEE is now linked with both maintenance backlog and OEE.

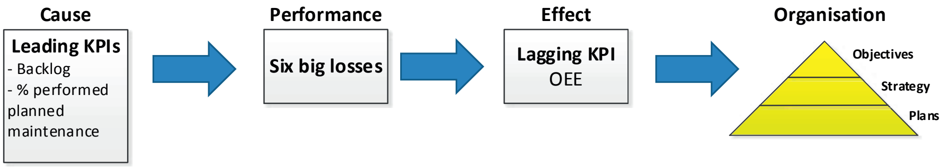


Figure 4.5 – Proposed framework for integrated KPIs [4].

Also a literature study of KPIs in maintenance and manufacturing was conducted where several literature sources were investigated:

- EN 15341 as an standard for maintenance KPIs;
- World Class Maintenance KPIs;
- KPIs for MP&C; and,
- leading KPIs for the maintenance process.

The result of integrating KPIs from manufacturing and maintenance is presented in Figure 4.6 [5]. As shown in this figure maintenance backlog is again considered to be a leading KPI and OEE as a lagging KPI. Since OEE influences the throughput time, too high maintenance backlog might at future date increase the throughput time.

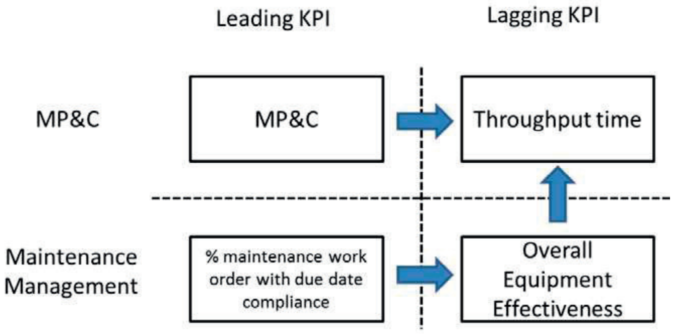


Figure 4.6 – Structure of leading and lagging KPIs for MPC and Maintenance management [5].

4.1.4 Further Development of Maintenance KPIs

The research objective 4 is to further develop KPIs that can be applied for IPL. Article 6 [6], Article 7 [7] and Article 8 [8] addresses this research objective.

In total two KPIs were further developed and are structured in a framework shown in Figure 4.7 [8]:

- profit loss indicator (PLI) as a lagging KPI; and,
- maintenance backlog as a leading KPI.

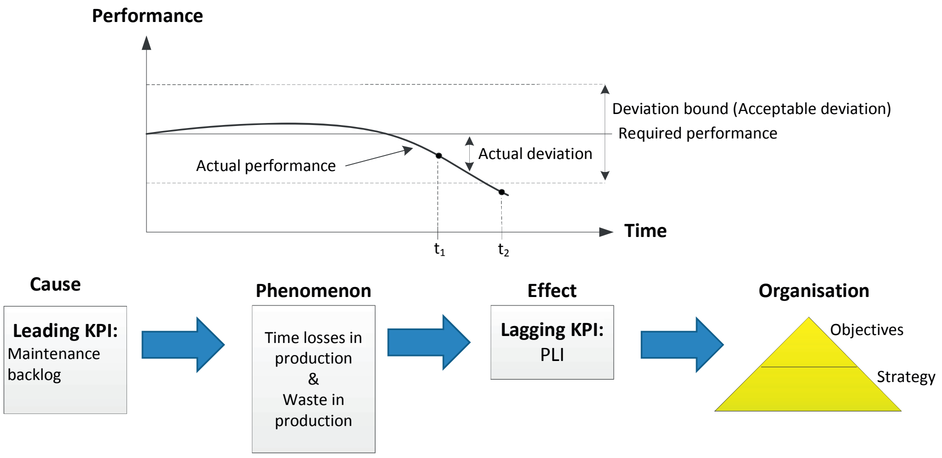


Figure 4.7 – Proposed framework for PLI and MB applied in deviation analysis [8].

The PLI is an offspring of both Asset Management and the metaphor "hidden factory". Since ISO 55000 reflects on potential or actual value in the definition of the term asset, an important question would be: What is the financial loss due to the hidden factory? When evaluating the hidden factory in terms of the six big losses as the basis from the OEE calculation, this loss was calculated for an aluminium processing plant in terms of minor stoppages and downtime such as caused by breakdowns.

The further development of the PLI resulted in structured methods for deviation analysis:

- The deviation is measured from either an ideal value or a norm value in a roadmap. The ideal value stems from Toyota Production System where the view of an ideal machine is e.g. defect free or can deliver on request without wasting materials. The norm value on the other hand considers a deviation from an "expected day" in production and from meeting the production plan.
- A structured deviation approach in five steps.
    1. Step 1, it is decided what to analyse, where variables for PLI are measured and calculated and trending a PLI value.
    2. Then it is decided how to react to the deviation and is valid for tactical and strategic decisions (Step 2). The different PLI elements are evaluated and are linked to early warning indicators (EWI) and root cause analysis (RCA).
    3. Step 3, identify why the deviation has happened through evaluating the KPIs and conducting RCA such as Ishikawa and 5-whys analysis.
    4. Step 4, decide what to do, based on step 2 recommended operational changes, or for tactical and strategic decisions it will be provided recommendations for updating the plans.
    5. Step 5, ensures that the organisation can learn through the evaluation based on a data and knowledge base.

The PLI value can be calculated with three perspectives and is expressed as the PLI cube shown in Figure 4.8 [8]. The first perspective is the accounting perspective, and is positioned where profit can be calculated by subtracting the costs from turnover in production. The indication for a profit loss is then the sum of turnover loss and extra costs in production. The second perspective is a perspective from the hidden factory where categories for time losses and waste are evaluated. The time losses are based on the OEE calculations, whereas the waste is composed of utilisation, raw material and resource consumption. The third perspective is based on the physical asset where PLI can be measured at the process level, plant level, system level or equipment level.

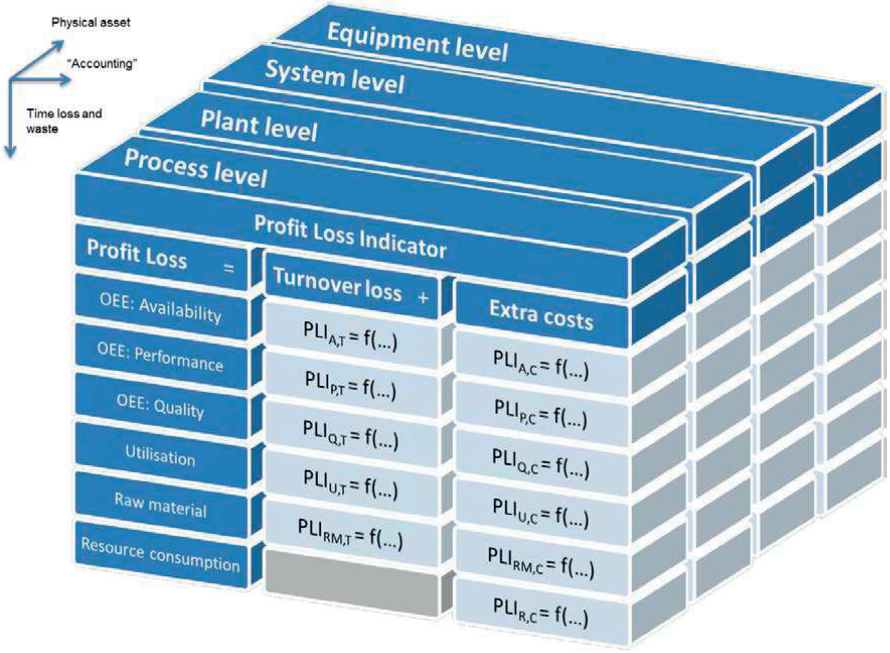


Figure 4.8 – The PLI cube [8].

When developing theory for maintenance backlog, three elements were developed:

1. *Terminology of maintenance backlog.* A terminology for maintenance backlog is developed combining and harmonizing terminology from both oil and gas industry and facility infrastructure. While the oil and gas industry considers maintenance backlog as a property of work orders and the intended maintenance activities, facility infrastructure on the other hand considers maintenance backlog as a property of the technical condition of the system. Since these considerations are dependent on whether time-based or condition based maintenance strategies have been chosen, both of these considerations are valid and are harmonized into a new definition.
2. *Process flow chart of maintenance backlog.* To manage maintenance backlog it is necessary to have a process flow chart in the organisation. This will ensure a sound management of maintenance backlog at an operative, tactical and strategic level.

3. *Maintenance backlog model.* The maintenance backlog model will provide a taxonomy since it is dependent on which maintenance strategy that has been chosen. Furthermore reliability modelling has been applied to ensure sound calculation of maintenance backlog. In addition, reliability modelling and theory of constraints has been used to model countermeasure for too high maintenance backlog.

The research objective 5 is to demonstrate and evaluate the KPIs in the IPL framework. To endorse this research objective Article 7 [7] and Article 10 [10] demonstrate maintenance backlog whereas Article 8 [8], 9 [9] , 11 [11] and 12 [12] demonstrate PLI. Table 4.2 summarises the contribution for this research objective.

Table 4.2 – Contribution of demonstration and evaluating maintenance backlog and PLI.

Level of abstraction	**Maintenance backlog**	**Profit Loss Indicator**
Generic outline of concepts and definitions	Terminology, process flow chart, maintenance backlog model, IPL framework aligned with maintenance backlog	Framework for integrated KPIs, deviation theory, PLI cube, IPL framework and IPL loop
Typical application of the KPIs (demonstration)	- Trending of maintenance backlog as EWI in a dashboard structure - Calculation of maintenance backlog based on reliability theory and risk influencing factors (RIF) - Calculation of maintenance backlog within barrier management - Operational rescheduling of maintenance plan - Guideline for Implementing maintenance backlog within IPL	- Operational application of PLI (day-to-day) decision. - Norm approach and ideal approach for PLI calculation - PLI and evaluation of Zero Defect Manufacturing - Strategic decisions of PLI (update of maintenance programme)
Case *specific* demonstration (Context specific)	- oil and gas industry case study - Pseudo case study	- Saw mill industry - oil and gas industry - Machine tool industry - Machine centre - Smelting plant

4.2 Contribution to Practical Application

Table 4.3 presents the overview of the contribution in this thesis to practical applications. As shown in this table four industrial sectors were involved; in total 10 contributions have been made; and, the theory has been tested for several industrial challenges.

Table 4.3 – Overview of practical contribution of theory developed in thesis.

Sector	Industry branch	Article	Industrial challenge	Contribution to practical application
Process industry	Aluminium processing plant	Article 6	Minor stoppages	Calculation of factors for PLI
	Aluminium processing plant	Article 6	Downtime resulting in lost production and downtime costs	
	Smelting house	Article 11	Achieving zero defect in production	Identification of drivers
	Saw mill industry	Article 8	Revenue losses in terms of reduced availability, performance and waste of raw material.	Development of PLI
Maritime industry	Transport with bulk vessels	Article 3	Problems of blow-by of piston rings in Marine Diesel Engine	Dashboard for IPL
Oil and gas industry	Oil and gas company 1	Article 9	Update maintenance programme	PLI calculation for supporting strategic decision
	Oil and gas company 2	Article 10	Need for early warning signs	Identification of maintenance backlog and development of dashboard for EWIs
Manufacturing industry	Machine tool industry	Article 11	Zero defect manufacturing	Criticality assessment of processes for defect in production
		Article 12	Zero defect manufacturing	PLI calculation of a defect in manufacturing
	Automotive supplier	Article 4	KPI not owned by the operators	KPI framework

4.4 Evaluation of the Research Quality

To evaluate the research quality of this thesis some specific criteria must be addressed. In total, four criteria have been evaluated [140, 141]. Table 4.4 presents these criteria with an overall description.

Table 4.4 – Evaluation criteria for research quality [140, 141].

Evaluation criteria for research quality	**Description of criteria**
Solidity	Relates to how convincing the research is expressed by e.g. both validity and reliability. Validity relates to what extent the research results mirror the reality. This criteria also relates to the chosen research method. Reliability tells us to what degree the research results are reproducible.
Originality	This criteria refers to degree of new and significant information within research. This criteria also relies on the researcher's capability to use his own creativity and knowledge to imagine new concepts relevant for building the theory.
Scholarly relevance	The degree of generality in the research.
Utility value	The quality in contribution to practice.

All of these criteria have been sought as an ideal during this research and my overall impression is that they have been fulfilled. Research quality seems at first glance to be contradictory; High degree of solidity in terms of scrutiny may hinder the originality where creative thought process is restricted. Also, there might be a contradiction between scholarly relevance and utility value. In this contradiction the theory is so generic that it is difficult to actually implement it in an industrial company. On the other hand, a too practical problem in industry can be difficult to extract towards a generic theory that has scholarly relevance.

Therefore, to aim for high degree in solidity, originality, scholarly relevance and utility value can be challenging. Nevertheless, I believe that the remedy for this challenge has been to follow the scientific method as an ideal. In this approach, the creative thought processes shaping new and scientific concepts and definitions has been a necessary process before it is tested and validated. Also, the scientific method makes it possible that the general theory (scholarly relevance) is tested in industrial real situations and provides an important contribution to practice (utility value).

By evaluating solidity, the research results must mirror the reality in terms of validation. As pointed out in the research design, two types of testing has been conducted; industrial testing and conceptual testing. In the industrial testing the theory was tested with realistic industrial data. As an example of this type of validation is the demonstration of PLI that was tested in several real industrial operational environments. Due to anonymity the data is not accurate but should still represent a realistic value and be fit for purpose. Ideally all demonstrations in this thesis should be presented in real industrial context where data is provided. However, the nature of maintenance has some longitude effects where several years, perhaps decades are required in the research in terms of validation. This is especially the case for the leading indicator maintenance backlog where significant extra time would be required to extract the life time data and validate the effect. Therefore, this theory is validated through a conceptual testing. The research is also considered to have high degree reliability where it is expected that others who scrutinise the research results will achieve the same results. To ensure high degree of reliability the argumentations in the thesis is well traced with references to literature. Also, the mathematical models provided in the thesis have a clear presentation of the input data, the procedure and the result.

The degree of originality is also expected to be high in this thesis. Although several researchers have worked with their own concepts of IPL, it is rather limited what exists today in relation to maintenance management models and application of KPIs as presented in this thesis. To illustrate, two original contributions have been provided in this PhD thesis. Firstly, a technical contribution is made where maintenance backlog is no longer modelled only according to the work orders, but also supported by reliability theory. Secondly, a financial contribution has been provided for both maintenance backlog and the hidden factory in PLI calculations.

Also, the scholarly relevance is considered to be high as well. The publications are included in both conferences and journals where the body of knowledge of maintenance management and maintenance modelling is either the main topic or a sub-topic for academia. The degree of generality is ensured where the IPL framework, maintenance backlog and PLI should be applied for any industry branch. This has also been an important part in the research design where the industrial testing has been performed in several sectors without restrictions from the theory itself.

The last criteria concerns contribution to practice and has been presented in previous chapter. The theory has been tested for four sectors with expected have high degree of utility. To illustrate the utility value in my research, PLI is about to be implemented in the saw mill industry Kjeldstad Trelast and it is of interest of Statoil to evaluate PLI as a further decision tool in their own organisation based on the case study.

5. Conclusions and Recommendation for Further Research

"Not everything that can be counted counts, and not everything that counts can be counted" – William Bruce Cameron

This chapter finalizes the work of this thesis with clear concluding remarks. Then this chapter also reflects on future perspectives as research topics.

5.1 Concluding Remarks

The overall scientific objective of this thesis is to develop theory and methods in IPL that balance maintenance management with other priorities related to physical assets.

This objective is further divided into five research objectives and has been accomplished through 12 scientific articles. To conclude, the three research questions in the thesis with brief answers are provided from the articles.

RQ1: *How can maintenance planning be further developed and modelled to provide decision support for production planners in IPL?*

Concluding remarks:

- **Article 1:** Proposal of semi-static indirect grouping strategy.
- **Article 2:** Proposal of IPL framework.
- **Article 3:** Storyboard demonstration of principles from Asset Management and Industrie 4.0.

RQ2: *What existing structures and maintenance KPIs are of relevance for IPL?*

Concluding remarks:

- **Article 4:** Proposal of framework integrating the KPIs OEE as a lagging KPI and maintenance backlog as a leading KPI.
- **Article 5:** Established relationship with leading and lagging KPIs in both maintenance management and manufacturing, production & control.

RQ3: *How can maintenance KPIs be further developed and applied for IPL?*

Concluding remarks:

- **Article 6:** Include Asset Management and the "Hidden factory" in the IPL loop.
- **Article 7:** Theoretical generic foundation of maintenance backlog.
- **Article 8:** Theoretical generic foundation and operational decision making of PLI.
- **Article 9:** Strategic decision making of PLI.
- **Article 10:** Maintenance backlog as an early warning indicator.
- **Article 11 & 12:** PLI in decision making in achieving Zero Defects in production and manufacturing.

5.2 Further Research

Based on the theory and methods developed in this thesis, several remarks should be of interest in terms of further research area:

- **Article 1:** Development of other grouping strategies such as dynamic grouping.
- **Article 2:** Further development of the IPL framework where elements other than KPIs are developed.
- **Article 3:** Modelling of maintenance backlog that will support route planning.
- **Article 4 & 5:** Further work that can verify the causality between leading and lagging KPIs.
- **Article 7:** Establish a solid platform in future teaching of maintenance backlog based on both terminology in EN 13306 and required knowledge for maintenance personnel provided in EN 15628.
- **Article 9**: In total four areas are of interest for further research; further development of terminology that could be verified by industry (1), the time perspective from early warning to unwanted event (2), evaluation of permanent "damages" when an indicator is yellow for long time (3), and the specific decision criteria for the early waning indicators (4).
- **Article 12:** Enabling accounting of PLI in real-time which today is challenging due to both technological and organisational factors.

Furthermore, all the 12 articles in the thesis point out the need to conduct more real case studies based on the results. The necessity for performing these case studies can be well justified by Robert Dekker's concern about the gap between academia and practice [87]; theory in maintenance can be difficult to understand and to interpret, many publications have math purposes only, and companies are not interested in publication. Future publications of IPL with involvement with industry should therefore be a clear strategy for further research.

Finally, an article not included in the thesis points out a further direction from the implementation of PLI [142]. When this KPI has been successfully implemented, the organisation should start to roll out the concept Industrie 4.0. From the body knowledge of maintenance management, further research in predictive maintenance strategy should be conducted with following topics from an architecture from Cyber-Physical System (CPS) (5C architecture of CPS):

- Smart **C**onnection Level: Sensors for both machines and maintenance logistics. An example would be RFID for spare parts.
- Data-to-Information **C**onversion level: More sophisticated models combining expert judgement, machine learning and physical models.
- **C**yber Level: Combining RFID technology with maintenance planning systems that enables better exploitation of spare parts.
- **C**ognition Level: Improved dashboards for predictive maintenance.
- **C**onfiguration Level: Development of "digital advices" that can adjust the point in time for performing the work orders based on analytics.

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Part II Articles

Article 1

Maintenance Optimisation for Integrated Planning

Article 2

Integrated Planning - A novel concept for maintenance management

Integrated Planning – A novel concept for maintenance management

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Keywords: Integrated planning, maintenance management, technical condition, planning

Abstract

Maintenance planning has been studied and recognized to be an essential part of maintenance management. However, faced with the challenges in the Oil & Gas (O&G) industry, existing maintenance management concepts need to be further developed. In the O&G industry the concept “Integrated Operations” (IO) has been established and is comprehended as a new way of doing business. When transferring this principle to the planning process results in the concept Integrated Planning (IPL). Traditionally, the disciplines such as drilling and well interventions, production optimisation, maintenance management and logistics have operated with “silo thinking” meaning little or ad-how coordination between these disciplines. This has resulted in sub-optimisation for the O&G business with different unwanted outcome such as limited resources, system failures, unscheduled maintenance, as well as subsurface surprises causing interruptions to drilling. The objective of this paper is to construct a framework for IPL. In particular indicators will be used as a tool for this framework. Based on literature study the result is a proposal of an IPL model applied in the O&G industry. In addition, relevant terminology is clarified in this paper. It is concluded that this framework will be used as a baseline for further research for IPL. In addition, further case studies from O&G industry are necessary for demonstrating this model.

1. Introducing planning as a discipline

From organisation theory, planning has been developed by the management principles from both Dr. W. Edwards Deming and Dr. Peter F. Drucker. The principles from the work of (Deming, 2000) and (Drucker, 1954) is elaborated and demonstrated in maintenance planning (Palmer, 2013).

Planning should be considered as a two-folded phenomenon. In addition that planning involves humans; it should also be understood as a tool with support of different methods and ICT solutions. For example, both (Palmer, 2013) and (Wilson, 2002) elaborates how Computerised Maintenance Management Systems (CMMS) is applied as planning tools. A typical example of a CMMS system is Psiam (Psiam, 2013).There exists also more generic planning tools such as (Promatica, 2013).

Today, planning is faced upon a phenomenon denoted be “silo thinking”. This phenomenon describes an asset with several organisations that performs activities that influence each other. However, since each organisation performs independent planning with limited involvement from the other organisations, the result of production is sub-optimal in terms of production output, safety and costs. This problem has been identified in both petroleum industry (Rosendahl and Hepsø, 2013) and land based production (Powell and Rødseth, 2013) and requires a more integrated plan. This concept is denoted as Integrated Planning (IPL).

The objective of this paper is to construct a framework for Integrated Planning (IPL). In order to propose such a framework the sub-objectives in the paper is to introduce the concept Integrated Planning (IPL) (1), Assess the research gap and problem statement of IPL (2), and propose a framework of IPL with concept and definitions (3).

Even though planning has some generic characteristics, the scope of IPL is delimitated to planning for a production system.

The remainder of this paper is structured as follows: Section 2 introduce the background of IPL. Further in Section 3, challenges in terms of lack of IPL in different industry branches are identified. In Section 4 the IPL framework is constructed and terminology elaborated in Section 5. Final conclusions are made in Section 6.

2. Introducing Integrated Planning

The Oil & Gas (O&G) industry has based been facing the prospect of increasing oil production, lowering operating costs and life extension (Ramstad et al., 2010). This has resulted in several activities for improving the ability to operate in an integrated and efficient manner in the O&G industry. This effort is enabled as "Integrated Operations" (IO) and is comprehended as a concept used to describe new way of doing business (Rosendahl and Hepsø, 2013). IO is defined according (IO Center, 2012) to be "integration of people, organisations, work processes and information technology to make smarter decisions. It is enabled by global access to real time information, collaborative technology and integration of multiple expertise across disciplines, organisations and geographical locations". Based on a report from (OLF, 2007) it is concluded that if IO is implemented successfully on the Norwegian Continental Shelf, an expected increase in revenue is estimated to be 300 billion NOK. According to (Rosendahl and Hepsø, 2013) this estimate provides a good incentive for implementing IO in the industry. The main challenge for IO can be illustrated in Figure 1 modified by the Annual report for the IO Center (IO Center, 2012). The paradigm leap expected from IO is going from "silo thinking" towards integrated operations that results in smarter decisions. Traditionally, disciplines and functions have been organised in self-contained siloes, where local decisions in each silo have resulted in sub-optimisation due to local goals. The vision of IO Center is to optimise the organisation where the different disciplines and functions are integrated to make smarter decisions and achieve common goals for the field as a whole.

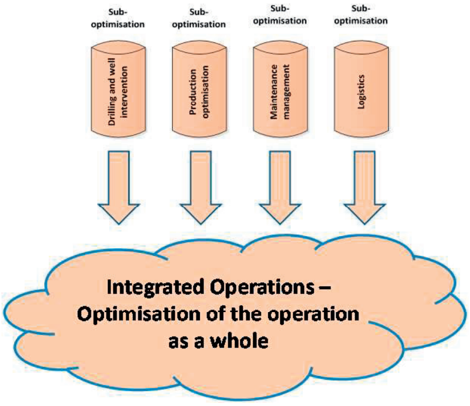

Figure 1: The vision for IO modified by (IO Center, 2012)

When transferring this IO principle to the planning domain in the O&G industry leads to the concept IPL (Ramstad et al., 2010). The challenge in O&G industry is that planning is performed in "silos", meaning each discipline has their own independent plan (Rosendahl and Hepsø, 2013). The result was lack of coordination across the disciplines resulting in sub-optimal prioritizing of plans resulting in unnecessary down-time. In fact, some of the common challenges were lack of linkage between critical information flow and decision systems, ineffective work management processes and lack of streamlined processes (Bai and Liyanage, 2010). This situation was so serious that the whole industry had difficulties to cope with the emerging future. Examples of unintended results of silo planning can be limited resources, system failures, unscheduled maintenance, unpredictable weather as well as subsurface surprises causing interruptions to drilling (Wahl and Sleire, 2009). Further, insufficient integration of the planning domains can result in problems in terms of work-related conflicts as well as cost/budget control (Bai and Liyanage, 2010). Delays of resource allocation is also a possible outcome of poor IPL that results in unexpected losses and affect the overall production volume, reduced costs and improved safety. This IPL challenge is also relevant for industry branches than O&G industry and is further elaborated in next Section.

3. IPL Challenges in Industry

The evolvement of the concept IPL has been apparent in recent due to complexity in production systems. Indeed, the integration challenges are apparent in the literature. It is stated by (Aghezzaf et al., 2007) to be a paradox that the issue of combining production and maintenance plans has received little attention. Historically in manufacturing, maintenance planning has not been regarded as an essential part of production planning. From the 1990s maintenance management was considered not on a strategic level but limited on a tactical level for manufacturing issues (Malhotra et al., 1994). Further, it was claimed that even though maintenance is important for equipment uptime it is no need for significant technical knowledge, nor for strategic or serious tactical judgement! In fact, (Al-Najjar, 1996) states that based on a literature search only eight out of 140 papers made any reference to the integration with manufacturing planning and maintenance planning. Further it is stated that, in computer integrated manufacture

(CIM) "everything" is integrated except the maintenance. This statement is also supported by (Sherwin and Jonsson, 1995) where maintenance is seldom integrated into the company's management information system (MIS). In fact, CIM systems encompass the whole product cycle from design to manufacturing but do not encompass maintenance. Based on the findings from (Wolfgang, 2012) there is also identified as a challenge with lack of coordination between asset utilisation manufacturing, asset Upkeep maintenance and Asset Design Engineering.

Based on a literature review on maintenance management several findings related to the IPL problem were performed (Garg and Deshmukh, 2006):

- Integration of various scheduling models into Maintenance Management Information Systems (MMISs) may be investigated as future research for more effective planning and scheduling of maintenance jobs.
- The Enterprise Resource Planning (ERP) systems developed or installed in many large companies during the last decade have not considered maintenance strategies.
- Maintenance management must be integrated with the other functional departments like production and quality control.

As direction for future research for this literature review, the problems related to implementation of object oriented maintenance management model and its integration to ERP was outlined. This direction is also supported by (Samaranayake and Kiridena, 2012) where existing ERP systems in aircraft industry do not provide full range of functionalities required for planning and scheduling of complex maintenance projects

It is discussed by (Aghezzaf and Najid, 2008) the problem where maintenance periods are known in advance and propose a model that integrates production and maintenance model. There are also other approaches for the IPL problem. (Yao, 2003) integrates Preventive Maintenance (PM) policies and production control policies for production-inventory systems with and unreliable machine. The limitation of this contribution is that that it deals mainly with activities at the operational level, leaving out both tactical and strategic levels for decision making in production. The PhD thesis by (Kovács, 2005) integrates the capacity and material flow aspects of production planning. In particular an aggregation formulation has been developed with focus on production planning and scheduling in make-to-order manufacturing systems. However, this formulation assumes fixed periods of planned maintenance. Thus, the IPL problem is not solved in this thesis. A more generic model is proposed by (Portioli-Staudacher and Tantardini, 2012) where the purpose is to suggest a new decision-making process for rescheduling PM interventions in the production plan due to the dynamics of the market. (Iravani and Duenyas, 2002) also investigated the IPL problem where an integrated maintenance/repair and production/inventory model is proposed. (Kazaz and Sloan, 2013) examines a single-stage production system that deteriorates and must have an optimal production and maintenance policy. (Najid et al., 2011) develops a model in terms of linear mixed-integer program where the demand shortage and the reliability of the production line is integrated. These models deal mainly with mathematical concepts. However, in the definition of IPL, the management concept is also a vital part of IPL.

The driving force for IPL is according to (Sleire and Wahl, 2008) the need to optimise the utilisation of the common resources the operations are depend on, in particular maintenance resources. Further, it is stated that maintenance is a continuous activity taking place in parallel with other operations. As an example drilling that represents an major activity on field may impede maintenance work on an installation (Sleire and Wahl, 2008). From the definition of the term maintenance (CEN, 2010) and the maintenance management model applied for O&G industry at the Norwegian Continental shelf (Oljedirektoratet, 1998, NORSOK, 2011) the result for maintenance is to achieve a desired level of technical condition. However, the planning domain in the maintenance field must ensure IPL for technical condition. In addition, partly based on an empirical study of indicators applied in IPL, it is concluded that there should be more research in order to improve application of indicators in IPL (Wahl and Sleire, 2009). Findings from audits performed by Petroleum Safety Authority (PSA) may also highlights the importance to close this research gap (Petroleumstilsynet, 2012). Their finding is that several O&G companies struggle with maintenance backlog. Further, PSA also makes it clear that maintenance backlog introduces contribution to risk and must that maintenance backlog must be under control. From IPL point of view this situation is relevant where maintenance backlog is due to prioritizing of other activities.

4. Development of IPL framework

When constructing the IPL framework it is important to evaluate existing structure of maintenance management and maintenance concepts. The maintenance management work process is illustrated in Figure 2 and is further elaborated in the NORSOK standard z-008 (NORSOK, 2011). This framework has been developed for the Norwegian Oil & Gas industry, but is considered to be generic and is also of relevance in other industry branches.

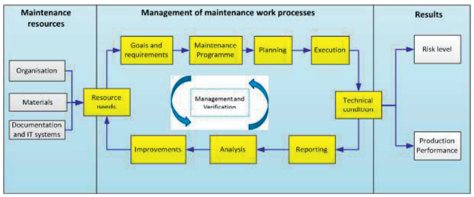

Figure 2: Maintenance Management framework

The management principle of this framework is based upon continuous improvement of the organisations activities and is designed as a closed quality loop (PLAN-DO-CHECK-ACT). This loop is also known as the Deming cycle.

In addition to have a sound management principle based on the Deming cycle, it is important to include elements for achieving satisfying results in maintenance management. These elements are illustrated in Figure 3 and are based findings performed by European Federation of National Maintenance Societies (EFNMS).

Figure 3: Maintenance elements

The starting point when constructing an IPL framework is to understand the interaction between the disciplines and the production system. Earlier literature within integrated production planning consider both production system (Ageh et al., 2010) and disciplines (Hadi et al., 2008, Fløysand et al., 2006) when dealing with IPL. In the constructed IPL framework, all the production systems are connected to relevant planning loops in a framework. The production system is located at the continental shelf and covers reservoir, well & manifolds and production facilities located both at platforms, subsea and FPSO. This production system is then connected to planning disciplines and divided into primary and support planning loops inspired by Porter Value chain categorising (Gandellini et al., 2012). The reason for this taxonomy is that planning loops are connected to a process/activity. The primary planning loops comprise disciplines that plan for activities that directly transform, commercialize and distribute the product in the production system. This planning loop comprises production planning, logistics planning and maintenance planning. The interrelationship between maintenance and operation is also of importance when considering the role of maintenance within physical asset management (CEN, 2013). This relationship is outlined in Figure 4 and reflects on what these processes should contribute to each other.

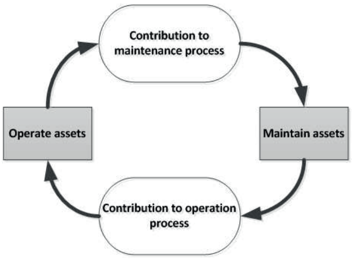

Figure 4: Relationship between operation and maintenance process (CEN, 2013).

The support planning loops comprise planning of activities in the organisation that supports the primary activities such as project planning, modification planning, maintenance planning and logistic planning.

Further the IPL framework must comprise the interaction with authorities, market and other production systems. The framework consists of three levels and is outlined in Figure 5. From level 1 the requirements and demand is given for oil and gas production. The regulatory, owners and management require that production deliver in accordance to specified volume, availability, quality, regularity and safety. Further it is a market that controls the production through demand and supply. The processing plant at level 2 receives oil and gas from all the productions systems at level 3. At level 3 it is both internal and external production systems where the distinction is different organisations that are responsible for production.

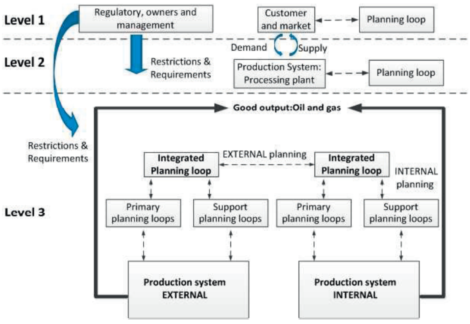

Figure 5: IPL framework

For the IPL loop in the IPL framework, following elements in planning are of relevance (Kerzner, 2009):

- *Objective.* A goal must be achieved within a certain time. For IPL, several goals that must be achieved. According to (Bai and Liyanage, 2010) IPL involves short-term (operational), medium term (tactical) and long-term (strategic) planning for satisfying the requirements.
- *Program.* The strategy that must be followed and actions taken to achieve the objectives. The actions are further highlighted as activities in Figure 6.
- Schedule. A plan showing when the individual activities will be started and completed.
- *Budget.* The planned expenditures for achieving the objective. For IPL the income for the plan must also be evaluated.
- *Forecast.* An estimation of what will happen in a certain time. In Figure 6, leading indicators will be a substitute for specific forecasts of the future.
- *Organisation.* Design of the number of positions, duties and responsibilities in order to achieve the overall objective. For IPL it is crucial that there is apposition with power to allocate resources for IPL.
- *Policy.* A general guide for decision-making and individual actions. For indicators it is important that a guideline for IPL and indicators are produced.
- *Procedure.* A detailed method for carrying out a policy.
- *Standard.* Group of performance defined as adequate.

A further description of the Integrated Planning loop from the IPL framework is shown in Figure 6.

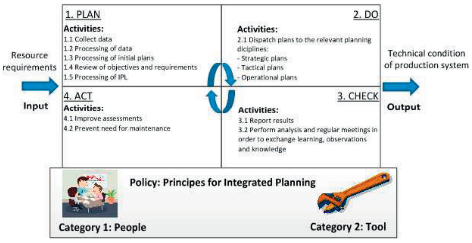

Figure 6: IPL loop

In order to have a dynamic planning loop as illustrated in Figure 6, principles for IPL is categorised into "people" and "tool". These principles will justify the model and serve as a policy for IPL, i.e. a general guide for decision-making and individual actions. The principles are based on the Integrated Planning System (Department of Homeland Security, 2009) and aspects of planning outlined by (Palmer, 2013) that are inspired by (Deming, 2000). These principles must be present all time for ensuring that IPL is successfully managed. In addition, based on the findings from (Powell and Rødseth, 2013), ICT tools should be included in category 2.

The IPL loop starts with input in terms of resource requirements. Further, the result of the IPL loop will be better control of technical condition compared with traditional maintenance management. This is due to that IPL will eliminate the silos in the organisations.

5. Terminology of IPL

In order to define IPL, following questions must be answered; what are the integrated factors in IPL (1) and what is planned for in IPL (2). To answer the first question, it is important to find literature where the notion "Integrated planning" has been applied in complex operations. Examples of such operations are urban planning (Zhang et al., 2011, Deng et al., 2012, Deason et al., 2010, Chen and Qin, 2012), spacecraft planning (Chien et al., 2009), transport planning (Integrated Planning

Work Group, 2005) and national security planning (Department of Homeland Security, 2009). In urban planning the integrated element is surface and underground urban space (Zhang et al., 2011), landscape and ecological aspects (Deng et al., 2012), river rehabilitation (Deason et al., 2010) and built-up area (Chen and Qin, 2012). Further in spacecraft planning the integration is between long-term science and engineering goals and short-term dynamic and unpredictable environment (Chien et al., 2009). For both transport planning (Integrated Planning Work Group, 2005) and national security planning (Department of Homeland Security, 2009) the integration is between relevant agencies and authorities. What is clear from all these industry-branches is that a holistic understanding has emerged from complex situations where an interdisciplinary approach in planning results in better decisions. Based on this understanding the notion “integrated” is related to the integration of production and maintenance in the O&G sector both off-shore and onshore.

The next question includes what is the expected effect of IPL. The long-term effect of IPL is increased production, enhanced oil and gas recovery, reduced costs and improved safety. This can be achieved by a main focus on technical condition. Technical condition can be defined as follows (Thorstensen, 2008): *“The technical condition is defined as the degree of degradation relative to the design condition. It may take values between a maximum and minimum value where the maximum value describes the design condition and the minimum value describes the state of total degradation”.*

The term "planning" is found in several disciplines with different definitions and explanations. From maintenance planning the definition by (Palmer, 2013) is *“the preparatory work to make work orders ready to execute. This term may involve scheduling depending on how it is used”*. From urban planning, a proposed definition proposed by (Alexander, 1981): *“Planning is the deliberate social or organisational activity of developing an optimal strategy of future actions to achieve a desired set of goals, for solving novel problems in complex contexts, and attended by the power and intention to commit resources and to act as necessary to implement the chosen strategy”*. There has also been proposed a definition of Integrated transportation planning as follows: *“A collaborative, well-coordinated decision-making process that solves the mobility and accessibility needs of communities in a manner that optimise across multiple community goals – from economic development and community liveability to environmental protection and equity”* (Integrated Planning Work Group, 2005).

In this paper the definition of IPL is defined to be *“multidisciplinary decision making process that manages technical condition and results in increased production, enhanced oil and gas recovery, reduced costs, improved safety. This process is performed in a manner that optimise across multiple planning disciplines through updating of objectives and attended by the power and intention to commit resources and to act as necessary to implement the chosen plan”*. This means that several planning disciplines affect the technical condition for O&G facilities. The challenge is actually to integrate these disciplines where maintenance management has a key role.

6. Conclusions

This paper has proposed a framework of IPL with terminology. This concept is also relevant for other similar concepts such as Physical asset management. The purpose of IPL is to have a baseline in terms of more structured approach between production and maintenance so that technical condition is better controlled and production assurance is increased. Further research should be further development of IPL and demonstrated in case studies of this framework through different tools applied for IPL.

7. Acknowledgements

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Article 3

Integrated Planning in autonomous shipping – Application of maintenance management and KPIs

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Article 4

Integrated Key Performance Indicators - A Tool for Smarter Decision Making

Integrated Key Performance Indicators – A tool for smarter decision making

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Abstract As a clear trend in manufacturing processes, the last decades have resulted in increased integration and multidisciplinary approaches such as Total Productive Maintenance (TPM), Asset Management and Systems Engineering. In order to control these holistic approaches, measuring through Key Performance Indicators (KPIs) is crucial. First, this paper elaborates this trend through a literature study and then presents a case study that deals with the holistic approach. As a conclusion, a proposed framework for integrated KPIs is established. Further work should be performed in order to verify this framework.

Keywords Maintenance indicators, integrated KPI

1 Introduction

In the last decades manufacturing processes have increased rapidly in complexity. One main trend for these processes is evolvement of a holistic view where different domains integrate. In order to manage the holistic concepts, Key Performance Indicators (KPIs) have been designed. A KPI can be defined as a metric measuring how well the organization or an individual performs an operational, tactical or strategic activity that is critical for the current and future success of the organization [Kerzner, 2011].

The objective of this paper is to elaborate the trend of increased integration in different industry branches, both through literature and case study. Based on this experience, a proposed framework for integrated KPIs is proposed.

The paper is structured as follows: In section 2 a brief description of the case study is described. Further, in Section 3, the trends of the holistic concepts are elaborated with identification of KPIs. In Section 4 the theoretical foundation of KPIs are presented whereas in Section 5, KPIs applied in the case study is presented as findings. Final, a discussion with conclusion in made in Section 6 where holistic KPIs are developed.

2 The case study

The case study was taking place during 2007-2009 where a Norwegian automotive supplier was studied. The findings from the case study comprise the Norwegian and the Canadian production plant. The company's plant in Norway was built in 2002 and a similar plant was built in Canada in 2004. The plants in Norway and Canada are both highly automated. During the case study, the factory in Canada was focused on improvement work with the objective to be the "leading plant in operational excellence", whereas in Norway, the global development of product design and process design was located; the objective was to be the "leading plant in process validation".

3 Trends of holistic concepts and relevant KPIs

The maintenance management function is continuously evolving. One key trend is further integration between maintenance and production. When looking at well-established maintenance concepts that have followed this trend, Total Productive Maintenance (TPM) is such a concept. This concept modified the American style of production in the 70's i.e. "I operate – you fix" mentality [Nakajima, 1989]. Instead, TPM endorsed a 0-vision with 0 faults, 0 defects and 0 accidents.

In order to follow this vision, TPM is designed to optimize equipment reliability and ensure efficient management of plant asset through the use of employee involvement and empowerment, by linking manufacturing, maintenance and engineering functions [Ahuja and Khamba, 2008]. This design will then sustain a production-driven improvement concept.

In particular, the integration between preventive maintenance and autonomous maintenance is illustrated in the TPM development program, see Fig. 1. Autonomous maintenance is developed for the operator administrated by the maintenance department that develops an optimized maintenance program. This integration is enabled by an education program that results in knowledge transfer where maintenance department is able to predict the remaining useful life, and the operator is able to perform autonomous maintenance. When this integration is achieved and sustained in step 4, the major time losses in industry, also referred as the six big losses, is minimized or eliminated and installation of new equipment have within start-up maintenance been designed for minimized life cycle costs. What is clear from this TPM-program, is that if this integration between maintenance department and operators fails, the 0-vision will never be achieved.

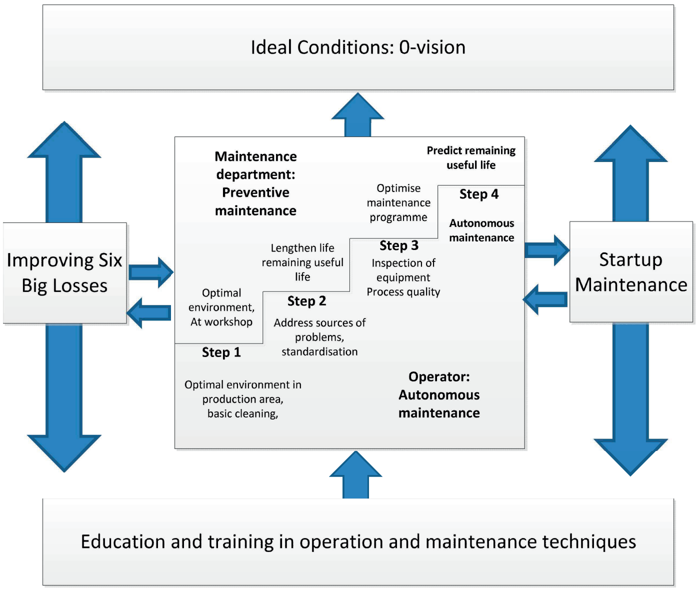

Fig. 1 The TPM development program adapted from [Nakajima, 1989]

In the TPM-program an overall indicator that measures the six big losses, denoted as Overall Equipment Effectiveness (OEE) has been developed. This indicator measures downtime, speed losses and defects [Nakajima, 1989]. An OEE standard that categorizes the losses and defines calculation set-up for OEE has been developed [Blom, 2003]. In general, OEE comprises three types of time losses and is calculated as follows [Koch & Oskam, 2007]:

$$\begin{aligned} &OEE = Availability \times Performance \times Quality; \\ &Availability = \frac{\text{Actual production time}}{\text{Potential production}} \\ &Performance = \frac{\text{Actual output}}{\text{Theoretical output}} \\ &Quality = \frac{\text{Good output}}{\text{Total output}} \end{aligned} \tag{1}$$

The need for integration has today expanded further and is documented in standards. Institute of Asset Management (IAM) has in collaboration with the British Standards Institution (BSI) developed a Publicly Available Specification (PAS) for Asset Management that is regarded as a standard, denoted as PAS 55

[British Standards Institution, 2008]. Asset management is in PAS 55 defined as systematic and coordinated activities and practices through that an organization optimally and sustainably manages its assets and asset systems, their associated performance, risks and expenditures over their life cycles for the purpose of achieving its organizational strategic plan. Further, an asset is in PAS 55 defined as plant, machinery, property, buildings, vehicles and other items that have a distinct value to the organization. In order to cope with this complex coordination, a specific asset management system in PAS 55 has been developed. In this system, the process "performance and condition monitoring" is identified and describes the need for considering the following types of KPIs; leading and lagging KPIs. The leading KPI provides warnings of potential non-compliant events of the performance of the asset management system, whereas the lagging KPI provides information about failures of the asset management system.

The need for better integration is further developed within many industrial streams. In the offshore industry the integration is denoted as Integrated Operations (IO) [IO Center, 2010], while in the automotive industry this integration management has been implemented over the years through Integrated Engineering, PDM/PLM systems, lean manufacturing and Total Quality Management (TQM) approaches [Shah and Ward, 2003]. It is enabled by using shared real time information, collaborative techniques and multiple expertise across disciplines, organizations and geographical locations.

When transferring the IO concept to the planning discipline leads to Integrated Planning (IPL) [Ramstad et al., 2010]. This discipline comprises characteristics such as planning in an IO perspective, cross-domain planning, one integrated operational plan, holistic perspective and coordinating activities and resources across the field [Ramstad et al., 2011].

Today, there are several challenges regarded IPL. One major challenge is the coordination of activities and resources between different departments and disciplines and in particular maintenance management.

Performance indicators that are of interest within IPL are *plan attainment, estimation rate* and *planning degree* [Wahl & Sleire, 2009]. Work on this topic has already started in the Norwegian offshore industry, where one tools among others within integrated planning processes is performance indicators that provide current and leading information on integrated performance [Ramstad et al., 2010].

4 The need for measuring the complexity

As a clear trend, the management systems have become more integrated, but also more complex. In order to manage and control this complexity, measuring the performance is crucial. All though several holistic concepts have been developed with suitable indicators, a theoretical approach that systemizes this holistic view should be applied. Systems Engineering (SE) is such an approach and is described to be an interdisciplinary approach and means to enable the realization of successful systems [Blanchard, 2008]. The KPIs should be in compliance with specific characteristics. One proposed list of characteristics for effective KPIs is described in Table 1 [Kerzner, 2011] with relevant examples and comments for OEE.

Table 1 Twelve Characteristics of effective KPIs adapted from [Kertzner 2011].

Characteristic	Example	Comments
Aligned	The OEE value will as a bottom line result in increased profit for the company.	The alignment can be diffuse.
Owned	The person or group that measure OEE must be accountable for the result.	Difficult to pinpoint responsible, because of addressing several disciplines.
Predictive	Maintenance indicators can be predictive and leading when they are drivers for business value.	This is a relative notion, where OEE can be lagging indicator.
Actionable	When OEE is measured and registered timely, it is possible to detect a problem before it is too late.	The sampling frequency can vary from hours to continuous with real time.
Few in number	OEE with few other KPIs in relation with other high-value KPIs that affect the overall business of the company should be preferred.	Several dashboards have been developed where OEE is one of the KPIs.
Easy to understand	Since OEE only comprises three key elements, it should be easy to understand this indicator.	Two identical OEE values can be caused by different time losses.
Balanced and linked	OEE is linked with time losses that affect availability, capacity and quality.	OEE should be balanced with a cause-and-effect relationship to other KPIs.
Trigger changes	When OEE is beneath a threshold value the company is triggered to do countermeasure such as root cause analysis.	This threshold value is always context driven and can be difficult to define.
Standardized	An industry standard has been developed for calculating OEE [Blom, 2003].	Even though an industry standard is established, several approaches for calculating exist.
Context driven	The threshold value for OEE should always be adjusted when improvements are achieved.	If the threshold value increases too much this can have a demotivating effect.
Reinforced with incentives	When improvements are well documented due to increased OEE value, the incentives can be bonus.	Bonuses can also weaken the learning potential for poor OEE results.
Relevant	If the market demand decreases, OEE should be adjusted.	Adjusting OEE to real market demand can be challenging.

Based on the comments in the table 1, careful considerations are important when measuring OEE. In particular OEE should be balanced to other KPIs. When balancing OEE with other KPIs the balanced scorecard developed by Kaplan and Norton can be applied [Kaplan & Norton, 1996]. The assumption for this scorecard is that financial measure is insufficient in order to measure the performance of the organization [Jacobsen & Thorsvik, 2007]. Therefore a cause-and-effect chain is established where measure of customer satisfaction is cause of financial measure. Internal production processes in the organization is cause of customer satisfaction, whereas ability for the organization to learn and grow is the cause of ideal production processes. This cause-and-effect relationship is also essential when describing leading and lagging indicators. As described in previous chapter, leading and lagging indicators is important to consider within Asset Management. The notion leading and lagging KPIs is further specified by [Kerzner, 2011]. He describes leading KPIs as drivers for future performance whereas lagging KPIs measure past performance. Thus it is a clear cause-and-effect chain between leading indicators, the performance and lagging indicators.

5 Maintenance indicators: Findings from case studies

The case study company is actively working on continuous improvements to increase the organization's performance and reduce the variation in product- and process requirements. This is verified through selected KPIs, such as OEE.

OEE is in the case study used to monitor and improve the effectiveness of the plants manufacturing processes (i.e. machines, manufacturing cells and assembly lines). It is not used in benchmarking, but as a tool for improvement of internal purposes. Further, the OEE is a measure on the plants performance or cells performance and used in continues improvement strategies. It is a motivation system for the entire company and a key metric that points out areas with greatest improvement potential. Additionally, this indicator trend exposes how improvements in changeovers, quality, machine reliability improvements, working through breaks and more may affects the company's bottom line.

In the case study the main difference between the two factories in their use of the OEE, was how the employees on the shop floor used the result of the measurement. In Canada the employees used the result as an evaluation of their performance as a trend in improvement and as a feedback used in the team discussion on problems in production, for example process problems, quality problems and so on. In the Norwegian plant the operators have a more distant interpretation of the OEE measure.

Improving the maintenance performance often requires a high level of participation from the shop floor, and distribution of information to the shop floor about the KPIs status to the plant is necessary. This information is presented at both plants, but to a much higher degree in Canada.

It is an important KPI for the company to increase the amount of preventive maintenance executed versus corrective maintenance executed.

Both facilities measure the percentage of different maintenance actions, with the objective to increase the amount of preventive actions and reduce the percentage of corrective maintenance. In addition, the company has a strategy to increase the percentage of preventive maintenance based on actual condition of the equipment; when maintenance is actually necessary. This has a positive impact on the company's key performance indicator OEE, because the company reduces the risk of doing unnecessary maintenance work and thereby reduces the periods when machineries must be taken out of production.

Planning is often a key aspect in the development of an effective maintenance organization, and in the Canadian facility a visual and manual planning system has provided a higher focus on the actual execution of maintenance tasks, especially on the percentage of preventive maintenance and backlog.

In summary, three maintenance indicators are applied in the case study:

1. I1 = OEE
2. I2 = (Time for preventive maintenance)/(Time for maintenance)
3. I3 = Accumulated man-hours that has not been finished within due (Backlog)

6 Discussion and conclusion

In order to develop more integrated and operational KPIs it is important to evaluate the already existing maintenance indicators described in previous chapter. When evaluating according to the 12 generic characteristics from Kerzner, there is one issue that should be discussed in order to successfully implement integrated KPIs. OEE is not considered “owned” by operators. There are several reasons for this. A possible reason within the Norwegian plant, is that working spirit is based on independence. Other reasons for lack of ownership could also be failure of the other 11 characteristics. The remedy can be to change the attitude for the Norwegian operators concering their action pattern to OEE measures, but without changing their independent working style. For example, a benchmark study e.g. between the Canadian and the Norwegian plant could help finding their best practice for using OEE. In addition, it is crucial to have a supervisor for the plants that has ownership for the OEE, and with sufficient support from top management and integrity from the shop floor.

A proposed framework for integrated KPIs is outlined in Fig. 2. Based on the discussion leading and lagging indicators it is important to identify the performance of interest, in this case the six big losses. In order to achieve the 0-vision in TPM, leading maintenance indicators are proposed. Finally, the bottom line for KPIs should be the alignment with the organization objectives and strategies.

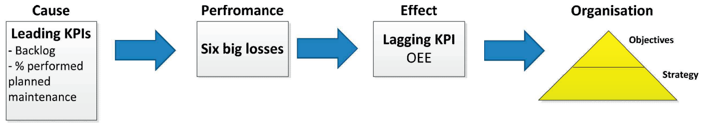

Fig.2 Proposed framework for integrated KPIs.

Further work should be performed to verify this cause-and-effect relationship and also identify leading indicators within other relevant production domains.

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Article 5

Key Performance Indicators for integrating Maintenance Management and Manufacturing Planning and Control

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Article 6

The importance of asset management and hidden factory for integrated planning

Is not included due to copyright

Article 7

Maintenance backlog for improving integrated planning

Maintenance backlog for improving integrated planning

Manuscript for Journal of Quality in Maintenance Engineering

Abstract:
Purpose – The aim of this article is to develop a novel model for maintenance backlog of physical assets and structure it in a framework for Integrated Planning.

Design/methodology/approach – Reliability theory principles for modelling maintenance backlog are used. Furthermore, to structure a framework for Integrated Planning, literature study combined with earlier case studies are used.

Findings – The framework for Integrated Planning facilitates the model of maintenance backlog. In addition to providing real-time diagnosis indicators, maintenance backlog is regarded as valuable information for decision support in Integrated Planning.

Originality/value – Development of maintenance backlog applied to Integrated Planning.

Keywords Integrated planning (IPL), key performance indicator (KPI), maintenance planning, reliability

Paper type Research paper

1. Introduction

From ancient times, planning has been regarded as an important aspect of life. Sun Zi, a general in China from around 500 BC, emphasises the importance of planning in one of the oldest military treatise in the world; namely "The Art of War". In this contribution Zi (2009) emphasise the importance of planning prior to a battle where he states that *"...he who is victorious in the temple computations before battle is the one who receives more counting rods"* (p. 79). Even today, more than 2000 years later, this treatise inspires many business people in their organisations. Planning has been regarded through time as an important issue in warfare from leaders such as Eisenhower (1957) where he states that *"...I tell this story to illustrate the truth of the statement I heard long ago in the Army: Plans are worthless, but planning is everything"* (p. 818). In organisation theory, planning has been developed by the management principles from both Dr. W. Edwards Deming and Dr. Peter F. Drucker. The principles from the work of Deming (2000) and Drucker (1954) is elaborated and applied by Palmer (2013) in maintenance planning.

Planning should be considered as involving both humans and application of a set of tools (Rødseth and Schjølberg, 2014b). Today, planning is struggling with "silo thinking" (Rødseth and Schjølberg, 2014b). This phenomenon describes a situation where different disciplines, such as maintenance and production, in an organisation perform independent planning for the same physical asset. This phenomenon is relevant in both the offshore petroleum industry (Rosendahl and Hepsø, 2013) and land based production (Kovács, 2005). In order to cope with the increased competitive pressure in production a novel concept denoted as integrated planning (IPL) is conceived (Bai and Liyanage, 2013, Ramstad et al., 2010, Powell and Rødseth, 2013).

Today a framework for IPL has been constructed (Rødseth and Schjølberg, 2014b). However, further details are required in order to operationalize the framework. In particular, key performance indicators (KPIs) should be included in IPL. The importance of a financial indicator for the "hidden factory" has been evaluated to be an important indicator for IPL (Rødseth and Schjølberg, 2014a). In maintenance management, the KPI called overall equipment effectiveness (OEE) calculates the "hidden factory" in terms of the six big losses: Machine breakdown (1), waiting time or setup time (2), minor stoppage (3), reduced speed losses (4), quality defects (scrappage) (5), and start-up losses or rework (6). Nakajima

(1989) and Koch (2007) provides a more detailed instruction of how to calculate this KPI based on information of the six big losses. Furthermore, the KPI denoted as profit loss indicator (PLI) has been developed and tested in both land-based industry (Rødseth et al., 2015b) and offshore industry (Rødseth et al., 2015a) for operational and strategic demonstration, respectively. The strength of this KPI is that there are more perspectives for measuring the hidden factory than OEE. In addition, PLI measures also a profit perspective where the hidden factory is allocated in terms of extra costs or reduced turnover. Despite a demonstration of its successful application, industry needs KPIs that are more leading in nature. In this article the authors advocate maintenance backlog (MB) to possess such a behaviour in IPL. The strength of MB as a KPI is that it can provide an early warning for PLI as illustrated in Figure 1. Maintenance backlog of preventive maintenance has also been identified as a leading KPI in IPL (Rødseth and Andersen, 2013).

Figure 1 – Measurement of Maintenance backlog as a leading KPI can reduce the value of Profit Loss Indicator as a lagging KPI.

The industrial purpose of operationalising such a KPI is to better foresee the technical condition of the production facility and control it with new maintenance scheduling methods applied in IPL. This will lead to improved capability of meeting the production demand with a reliable plant capacity and safety level at the facility. When maintenance backlog is controlled, maintenance activities may be allowed to be postponed with an acceptable increase in risk level and allowing for more production. This would also require that the risk level would be under a threshold value. From a safety perspective, the maintenance backlog will also affect the overall safety level. In particular, maintenance backlog is regarded as an indication of a significant deviation in maintenance of barriers in terms of compliance with due date of maintenance actions (Øien and Hauge, 2014).

The importance of MB is discussed in literature both in land-based sectors such as nuclear (IAEA, 1999), road infrastructure (Weninger-Vycudil et al., 2009), building infrastructure (Hopland, 2015), and the oil & gas (O&G) industry (Øien and Hauge, 2014). However, the theory of MB seems to have different meanings. For example, in the road infrastructure MB is comprehended as the cost of bringing the current condition to a predefined level and has therefore a monetary view. In O&G industry maintenance backlog has instead a work package view and considers which work orders that are not performed within due date. These views will then provide definitions and concepts that are operationalized differently. The scientific purpose in this article is to map these differences and clarify the terminology, models and flowcharts in MB. This should then be regarded as a major contribution to a generalized maintenance theory and can be applied into the different industry sectors. Furthermore, the scientific purpose in this article is also to elaborate IPL as a framework and how it is related to MB.

The main objective of this article is therefore to contribute with theory for MB of physical assets and locate it in a framework for Integrated Planning. To achieve this main objective, the sub objectives in this article are to introduce IPL where terminology, properties and framework is clarified (1), establish and demonstrate MB fundamentals (2), and map the relevance of maintenance backlog within the framework of IPL (3).

The scientific approach in this article is divided into two stages. First, a systematic literature review is undertaken within MB and IPL to clarify the state-of-the art and further development to frameworks. The second stage is construction of quantitative models where reliability modelling and theory of constrains quantifies the MB and proposes approaches for reducing the MB. To discuss the results of

MB theory in this article, the quantitative models have been demonstrated with examples. Although attempts have been made for establishing MB concepts, the contribution in this article is regarded to be novel as theory and quite interesting for the industry, at least to the knowledge and expectations of the authors.

The structure in this article is as follows: Section 2 introduces the main elements and the trends within IPL. This will then clarify important terminology and properties of IPL. The MB fundamentals is then established in Section 3, 4 and 5. In Section 3, the fundamentals for the theory is first presented with further elaboration of terminology, process flow chart and taxonomy for MB. Furthermore in Section 4, reliability modelling is established and demonstrated with the purpose of both measuring MB. The final fundamental is developed and demonstrated in Section 5 where theory of constraints is applied in a new maintenance scheduling method in order to control MB. This section also presents rescheduling options for maintenance backlog based on maintenance grouping and operational measures in production. In Section 6, presents the IPL framework and how it is related to MB theory. Finally, Section 7 systematically discuss the results of the MB theory with final concluding remarks.

2. From reactive planning towards integrated planning for technical condition

2.1 Maintenance planning

Maintenance planning can be defined as the preparatory work to make work orders ready to execute (Palmer, 2013). Depending on the context, this term may also comprise scheduling. Furthermore, the term maintenance plan is according to the maintenance standard NS-EN 13306 defined as *"structured and documented set of tasks that include the activities, procedures, resources and the time scale required to carry out maintenance"* (CEN, 2010). Today, maintenance planning is supported by both guidelines and handbooks from maintenance experts with long industrial experience (Palmer, 2013, Peters, 2015), and analytical models and literature reviews from academia (Duffuaa and Raouf, 2015, Andersen, 1999, Al-Turki, 2011, Hadidi et al., 2012, Samaranayake and Kiridena, 2012).

2.2 The silo challenge and potential for improving maintenance planning

In organisations, it is crucial that silos are identified. Indeed, it has been stated that functional silos in organisations are the third most frequently cited obstacle to knowledge sharing (Hackett, 2000). The challenge of silos in the organisation has been identified by several authors and it does not seem that this is delimited to only one type of industry branch. Several challenges of silos are identified in the O&G industry (Rødseth and Schjølberg, 2014b). In this industry it is regarded that silo planning leads to inefficient resource management of the asset as a whole leading to unnecessary downtime and reduced profit (Ramstad et al., 2010). Another challenge is the lack of integration between critical information flow, inappropriate work processes in planning, and too poor streamlined processes in order to capitalise on available production capacity (Bai and Liyanage, 2010). Additional examples of unintended results from "silo planning" include limited resources, system failures and unscheduled maintenance (Wahl and Sleire, 2009).

Likewise, the silo challenge is also evident in manufacturing. In particular, this industry branch experiences increasing complexity in the machine's technical condition and the need for more cost-effective and adaptive production and maintenance strategy (Jin and Ni, 2013). The integration between production and maintenance planning has been identified already in the 90s as a challenge (Lee and Park, 1991). In this research, a production-maintenance policy of a deteriorating production system that produced defective parts was studied. This problem continues to receive attention to model maintenance as an integrated part of production planning (Rivera-Gómez et al., 2013, Liao, 2013, Powell and Rødseth, 2013, Xiang et al., 2014, Aramon Bajestani et al., 2014). These authors call out several challenges from lack of IPL in manufacturing. Since deterioration of a manufacturing system has a negative effect on the quality of parts produced, lack of IPL can result in unacceptable defects in production. Furthermore, a usual conflict of interest in real production system happens between the production department and maintenance department (Wong et al., 2014). In this case, the silo challenge may result in a conflict between maximising productivity by running the machines non-stop and stopping the machines for planned maintenance. It is also argued that there is still a lack of tools that evaluate the production system in the presence of maintenance activities (Zied et al., 2014).

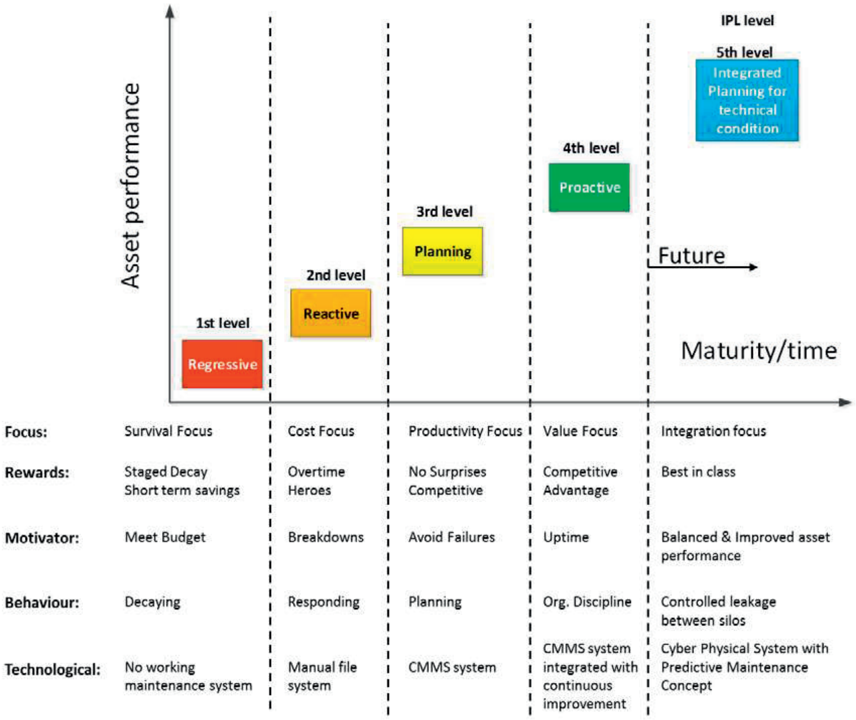
The above-mentioned challenges from both O&G and manufacturing industry have been approached by developing mathematical models and concepts. However, none of these offers KPIs as a tool for performing production planning alongside maintenance planning for a production system. KPI are the core of what is denoted as IPL from the authors' perspective. Generic models for IPL have been developed integrating manufacturing planning & control with maintenance management (Powell and Rødseth, 2013). More research remains in constructing the IPL model in generic terms that it can be applied to any industry branch. In addition, there is also a strong need for building indicators that can be used within the IPL model.

The current positioning for IPL is at level 4 in an organisational maturity model as shown in Figure 2, inspired by Ledet et al. (2005) and Sondalini (?). This paper proposes a structured framework whereby the organisation can operationalize IPL at level 5 in the future.

Level 5 is aligned with the initiatives of Industrie 4.0 (Kagermann et al., 2013). Industrie 4.0 is a strategy from the German government that promotes new and innovative ICT solutions for the manufacturing industry. As a specific technology, cyber-physical systems (CPS) will enable what is being labelled as a 4th industrial revolution. In this initiative, appropriate planning models are one key area for managing complex systems.

The maturity model shown in Figure 2 comprises specific characteristics at level 5:

- **Focus:** *Integration focus.* The focus in the organisation enables the integration of different disciplines and functions in order to achieve common goals. The integration can be internally for example the integration between the maintenance department and the production department. The integration could be externally between two organisations which produce the same product to the customer.
- **Rewards:** *Best in class.* The reward for the organisation is to be regarded as best in class for putting into practice the IPL principles.
- **Motivator:** *Balanced & Improved asset management.* The motivation in the organisation is a balance between the disciplines and continuous improved across the disciplines.
- **Behaviour:** *Controlled leakage between silos*. The organisation will still have functional departments and a clear description of which activities are performed inside the organisation. However, the behaviour in the organisation is to have controlled integration between the departments and other organisations based on ground rules established both formally and informally.
- **Technological**: *Cyber physical system with predictive maintenance*. With successful implementation of the concepts in Industrie 4.0 the future planning practice will be able to predict the future needs in maintenance thereby improving IPL.



Focus:	Survival Focus	Cost Focus	Productivity Focus	Value Focus	Integration focus
Rewards:	Staged Decay Short term savings	Overtime Heroes	No Surprises Competitive	Competitive Advantage	Best in class
Motivator:	Meet Budget	Breakdowns	Avoid Failures	Uptime	Balanced & Improved asset performance
Behaviour:	Decaying	Responding	Planning	Org. Discipline	Controlled leakage between silos
Technological:	No working maintenance system	Manual file system	CMMS system	CMMS system integrated with continuous improvement	Cyber Physical System with Predictive Maintenance Concept

Figure 2 – Maturity model for IPL inspired by Ledet et al. (2005) and Sondalini (?).

Since “balanced and improved asset performance” is a characteristic for the IPL level, the organisation should also apply Asset Management. The standard ISO 55000 defines Asset management to be “Coordinated activity of an organisation to realize value from asset” where asset is defined as “item, thing or entity that has potential or actual value to an organisation”(ISO, 2014). In this standard following fundamentals have been outlined:

- Value: The purpose of the asset is to generate values for the stakeholders.
- Alignment: The organisational objectives are streamlined of both the technical and financial decisions, plans and activities.
- Leadership: The leadership and the culture in the organisation are important factors for generating values in the organisation.
- Assurance: Asset Management will provide an assurance that the asset will fulfil the required purpose.

The integration between production and maintenance planning is elaborated in the standard NS-EN 16646 “Maintenance within physical asset management” (CEN, 2014a). In this standard a description is provided for what should be shared between the processes “operate assets” and “maintain assets”. Furthermore, this standard identifies “silo” behaviour of individual functional departments as risk that could be avoided by using KPIs. According to the “silo” challenge described in this section, this standard should therefore be applicable for IPL. Still, this standard has not specified how MB should be applied to tackle this “silo” challenge between “operate assets” and “maintain assets”.

An important question within IPL is which departments and expertise are integrated? From literature, the term “Integrated Planning” is used where complex operations are of interest and has been elaborated with examples by Rødseth and Schjølberg (2014b). Examples are found in different branches such as urban planning, spacecraft planning, transport planning and national security planning. In urban planning the integration is between surface and underground space (Zhang et al., 2011), and landscape and ecological dimensions (Deng et al., 2012), and town planning (Alexander, 1981). Spacecraft integrates long-term science and engineering goals (Chien et al., 2009). Integrated planning has also been developed in transport planning (Integrated Planning Work Group, 2005) and national security planning (Department of Homeland Security, 2009) where the integrated elements are the agencies and authorities. Lessons can be learned about setting objectives from both quality planning (ISO, 2005) and in project planning (Kerzner, 2009). What is obvious from all these examples is that an interdisciplinary approach has emerged where each discipline must be included in making complex decisions in order to achieve the overall result. With successful implementation of "integrated planning" better decisions are expected with improved bottom-line result in terms of increased profit. Based on this understanding IPL must include the disciplines from both production and maintenance department to achieve desirable production assurance with minimized costs.

Another important question is what is actually planned for in IPL? One important element that is planned for in IPL is a sufficient control of technical condition. A possible definition of technical condition can be the degree of degradation relative to the design condition (Thorstensen, 2008). Technical condition is further defined that it may take values between a maximum and minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation (Thorstensen, 2008). In addition, a definition of IPL has been developed and is adapted for the O&G (Rødseth and Schjølberg, 2014b).

Based on the definitions and different aspects of IPL in other sectors and the emphasis of technical condition, IPL is defined as *"the multidisciplinary decision-making process of future maintenance actions that manages technical condition and results in increased production, improved resource handling of raw material, reduced costs, and improved safety. This process is performed in a manner that optimise across multiple planning disciplines through updating of objectives and supported by the power and intention to commit resources and to act as necessary to implement the chosen strategy."*

3. Maintenance backlog fundamentals

In this section maintenance backlog (MB) is presented in the context of terminology, a process flow chart, and taxonomy. These aspects are shown in Figure 3 with corresponding sub-elements.

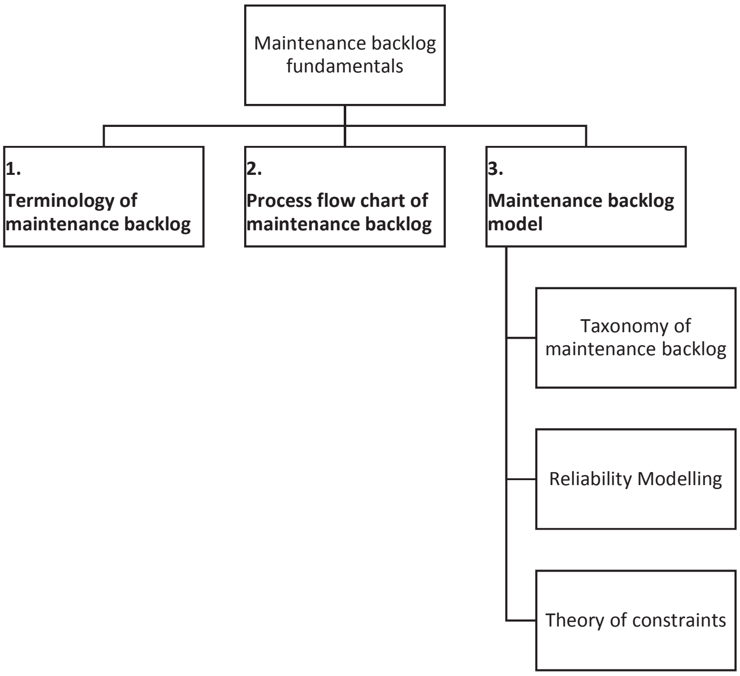


Figure 3 – Elements in maintenance backlog

3.1 Terminology for maintenance backlog

From Petroleum Safety Authority, MB is defined as amount of preventive maintenance not accomplished within due date whereas outstanding maintenance is defined as amount of corrective maintenance not defined within due date (Petroleumstilsynet, 2012). International Atomic Energy Agency (IAEA) uses the term maintenance backlog clearance, which is the percent of issued work orders that have been completed on schedule (IAEA, 1999). IAEA has also described MB as a performance indicator to determine the number of backlog activities that the nuclear utility should have carried out but has delayed for some reason (IAEA, 2006). In this industry branch, MB is defined as the total number of maintenance activities backlogged for a given period pending execution, expressed as the number of work requests. It could be for corrective or preventive maintenance (IAEA, 2006). From these definitions, both Petroleum Safety Authority and IAEA enable a common concept MB that includes the maintenance scheduling perspective. Scheduled maintenance is defined as “the preventive maintenance carried out in accordance with an established time schedule” (IEC, 1990). The systematic scheduling of maintenance tasks is identified in Reliability Centered Maintenance (RCM) that classifies scheduled maintenance tasks into scheduled on-condition task, scheduled overhaul, scheduled replacement, scheduled function test (Rausand 1998). MB will occur when there is non-compliance with these maintenance schedules. In this article, MB is comprehended as a leading KPI, which means that corrective maintenance is not included in MB since a failure is not leading in nature. Instead, corrective maintenance will be used as input data when PLI is calculated (Rødseth et al., 2015b).

The term “maintenance backlog” must not be confused with the term “backlog” which is also a term used in maintenance planning. Backlog can be defined as the amount of identified work on work orders either by number of work orders or work hours for time accounting (Palmer, 2013). The main essence in this term is that backlog is just the work that has not yet been completed (Peters, 2015). However, the due date or a threshold value has not been taken into account in the term backlog. Given that the maintenance planner would plan for all relevant maintenance activities, some of the amount of backlog is also maintenance backlog. Although the definitions from O&G industry and nuclear industry reflect important aspects of maintenance backlog in terms of maintenance labour, they do not include financial aspects in maintenance backlog.

For road transport systems, maintenance backlog has been apparent with perceptual deterioration and loss of value of road assets over time (Evdorides et al., 2012). In Norway maintenance backlog for a road infrastructure component is defined as the cost of bringing the condition of the component from its current condition to a defined condition level in such a way that it will fulfil its intended purpose for a normal life cycle period *(Sund et al., 2012)*. A more comprehensive study of road transport systems performed by ERA-NET ROAD (ENR) has proposed a trans-national definition of maintenance backlog in road research (Weninger-Vycudil et al., 2009): *"Maintenance backlog of the road infrastructure is the amount of unfulfilled demands at a given point of time in explicit reference to the predefined standards to be achieved. Maintenance backlog can be expressed in functional (non-monetary) or monetary terms and it refers to single components, sub-assets or to the whole road infrastructure asset of a given road network."*

In order to sustain these sound perspectives, following definition of maintenance backlog is proposed for use in this article:

"Maintenance backlog is the amount of unfulfilled demands at a given point of time in explicit reference to predefined standards to be achieved. The demands comprise both demands for the technical condition itself and demand in meeting the planned due dates in the work orders. Furthermore, maintenance backlog can be expressed in functional (non-monetary) or monetary terms and it refers to single components, sub-assets or to the whole asset".

3.2 Process flow chart of maintenance backlog

The process flow chart is presented in Figure 4.

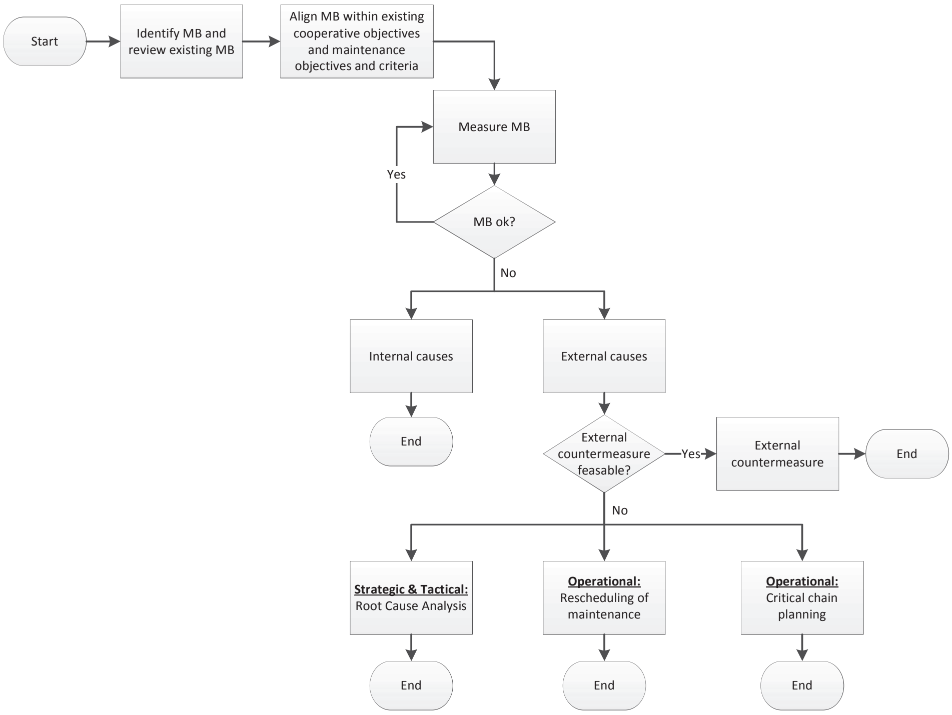


Figure 4 – Process flow chart of maintenance backlog

The start of the flow chart will be to identify MB elements and review the outstanding demands. When MB is used as a KPI, it must be aligned with the existing cooperative objectives and maintenance objectives in the organisation. When MB is measured, it is checked if the value is acceptable. If the value is unacceptable, it is necessary to evaluate if the cause is due to external factors and also an issue for IPL. If IPL is necessary, the first step is to see if external countermeasure is possible or required in the organisation. Examples for such planned counter measures could be several:

- Reduced load in operation in order to reduce the deterioration rate of the equipment.
- Production stop in order to perform preventive maintenance activity. This can be safety requirement if the safety critical maintenance is too high.
- Allocate more maintenance resources in terms of maintenance staff, tools, equipment and maintenance budget in order to reduce the maintenance backlog at next preventive maintenance activity.

When production countermeasure is not possible, the next step is to evaluate strategic, tactical or operational measures. The operational measures are presented later in this article.

3.3 Taxonomy of maintenance backlog

The proposed taxonomy of maintenance backlog is outlined in Figure 5. This taxonomy is also in alignment with the standard of maintenance terminology (CEN, 2010). However, this standard does not define maintenance backlog itself, but rather categories the maintenance activities into preventive maintenance and corrective maintenance. In this article, maintenance backlog is only identified for preventive maintenance. If corrective maintenance is not performed within due date, it is classified as outstanding maintenance rather than maintenance backlog. Furthermore, when corrective maintenance occurs this will be measured by the PLI indicator. The maintenance backlog can be aggregated from component level up to plant level.

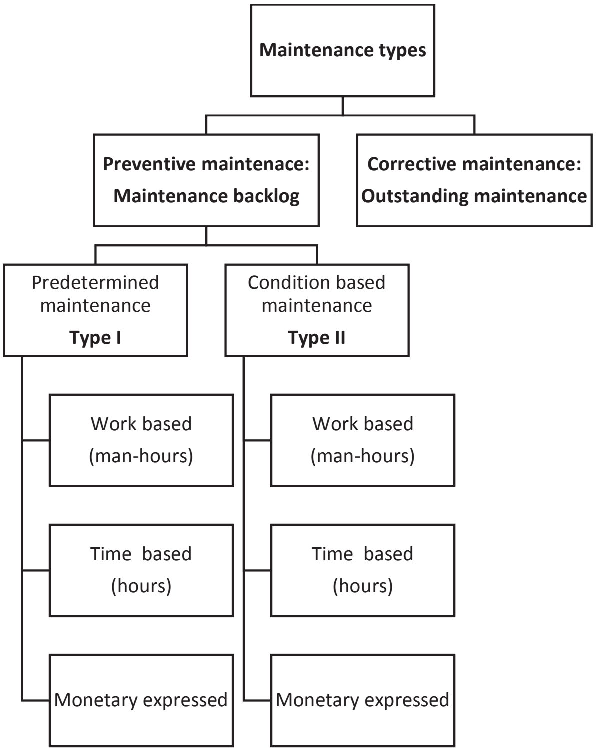


Figure 5 – Proposed taxonomy of maintenance backlog

3.3.1 Type I maintenance backlog

In monetary form, this type of maintenance backlog measures both the labour cost and the increased risk cost based on the specific failure rate model. If preventive maintenance is delayed, the actual failure rate will increase and hence the risk costs. In next chapter, this type of maintenance backlog is modelled in more detail.

The total maintenance costs will comprise the investment costs, resource costs and consequence costs (Wilson, 2013). The resource costs comprise preventive maintenance costs comprise all relevant maintenance cost for performing the specific maintenance cost. Relevant cost elements for preventive maintenance could be several:

- Maintenance service
- Tools
- Technical documentation
- Maintenance labour

When preventive maintenance is not performed within due date, the probability for unplanned maintenance cost will increase within the resource cost. This will increase in terms of corrective maintenance job costs. In addition, it will be an increase of different consequence costs due to more failures per annum:

- Cost of lost production

- Extra upgrading costs in order to increase the capacity
- Lost opportunity costs

3.3.2 Type II maintenance backlog

This type of maintenance backlog is measured in monetary form, e.g in USD, using the total costs of improving the technical condition based on what is measured through the inspections and condition parameters. This situation is shown in Figure 6. The MB limit denotes the minimum value derived from the risk costs. Based on each inspection an estimation of the risk costs is made and the cost of bringing the current condition of the asset up to a defined level where the asset fulfils the intended purpose.

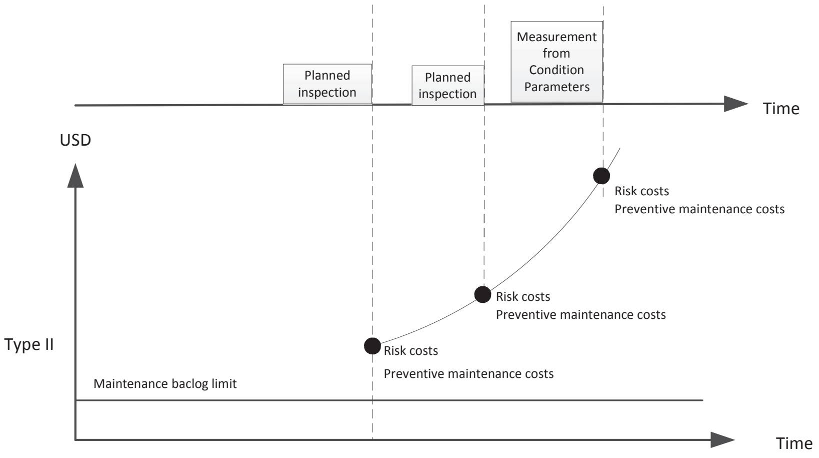
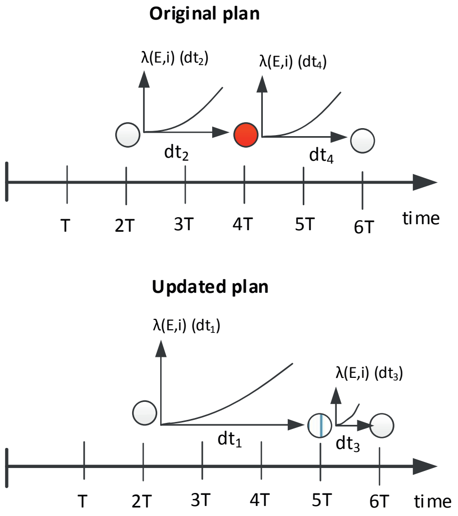


Figure 6 – Illustration of Type II maintenance backlog.

4. Reliability modelling of Maintenance Backlog

4.1 Maintenance backlog with maintenance optimisation

The maintenance optimisation modelling is elaborated by (Rødseth, 2014). Figure 7 gives an example of what maintenance backlog would be for maintenance backlog for one component. In this example maintenance is performed every 2T time unit.


Original plan

Updated plan

Figure 7 – Failure rate modelling with maintenance backlog (Rødseth, 2014)

When the planned maintenance activity is postponed with 1T time unit, the maintenance backlog can be calculated as follows:

$$\begin{aligned} \Delta C_{total} &= \sum_{i=1}^{n}\left[C_{PM,i} + \Delta C_{unplanned,i}\right] \quad ; \\ \Delta C_{unplanned,i} &= C_i^U \times \left[dt_1 \times \lambda_{E,i}(dt_1) - dt_2 \times \lambda_{E,i}(dt_2)\right] + C_i^U \times \left[dt_3 \times \lambda_{E,i}(dt_3) - dt_4 \times \lambda_{E,i}(dt_4)\right] \end{aligned} \tag{1}$$

The total maintenance backlog is composed of both planned preventive maintenance costs and expected unplanned maintenance costs. The planned preventive maintenance costs are described in previous chapter and are "waiting" to be spent. When time passes, the failure rate will change and also the unplanned maintenance costs, C_i^U. As the formula and Figure 6 shows, the failure rate will increase due to change from 4T to 5T of the planned maintenance. The next maintenance intervals are "locked" and the next planned maintenance action is performed at 6T. This will give a reduced failure rate since this time interval is changed from 2T to 1T. Thus, this will reduce the expected cost of unplanned maintenance.

Input data for this reliability model is provided as an example in Table 1, and is based on component number 1 from (Rødseth, 2014):

Table 1 – Input data for calculating the maintenance backlog.

Mean time to Failure *without maintenance* MTTF [years]	4
Ageing parameter, α	3
C_{PM} [1000 USD]	2
C_U [1000 USD]	5

The cost function for one component is given by following formula:

$$C_i(\tau) = \frac{C_{PM,i}}{\tau} + C_i^U \times \lambda_{E,i}(\tau)$$

The effective failure rate λ_E is modelled with a Weibull distribution.

The optimized value is given in Table 2.

Table 2 – Calculation of optimum maintenance interval

Ci (τ) [1000 USD/year]	1.105
τ [Years]	2.9
T= τ/2 [Years]	1.45

When the maintenance activity in 4T is postponed to 5T shown in Figure 7, following financial value can be calculated for MB according to formula 1 and is presented in Table 3.

Table 3 – Calculation of maintenance backlog

dt_1 = 3T [years]	4.35
dt_2 = dt_4 = 2T	2.9
dt_3 = T	1.45
$\lambda_{E,i}(dt_1)$	0.146
$\lambda_{E,i}(dt_2) = \lambda_{E,i}(dt_4)$	**0.083**
$\lambda_{E,i}(dt_3)$	0.023
CPM [1000 USD]	2
CU [1000 USD]	5
$\Delta C_{Unplanned,i}$ [1000 USD]	0.94
ΔC_{Total}[1000 USD]	2 + 0.94 = 2.94

The total MB is therefore in this example calculated to be 2940 USD.

4.2 Adjustment of maintenance backlog from Risk Influencing Factors

The overall schematic in Figure 8 shows how maintenance backlog is modelled. In risk modelling, the Risk OMT (Risk modelling – Integration of Organisational, huMan and Technical factors) model has earlier been developed by (Vinnem et al., 2012) and evaluated though case study by (Gran et al., 2012). In the risk model in Figure 8, a Bayesian belief network is applied to structure two levels of risk influencing factors (RIF) connected to the failure rate in maintenance optimisation modelling. The core of the Risk OMT is modelling how RIF affect the failure rate of a technical system.

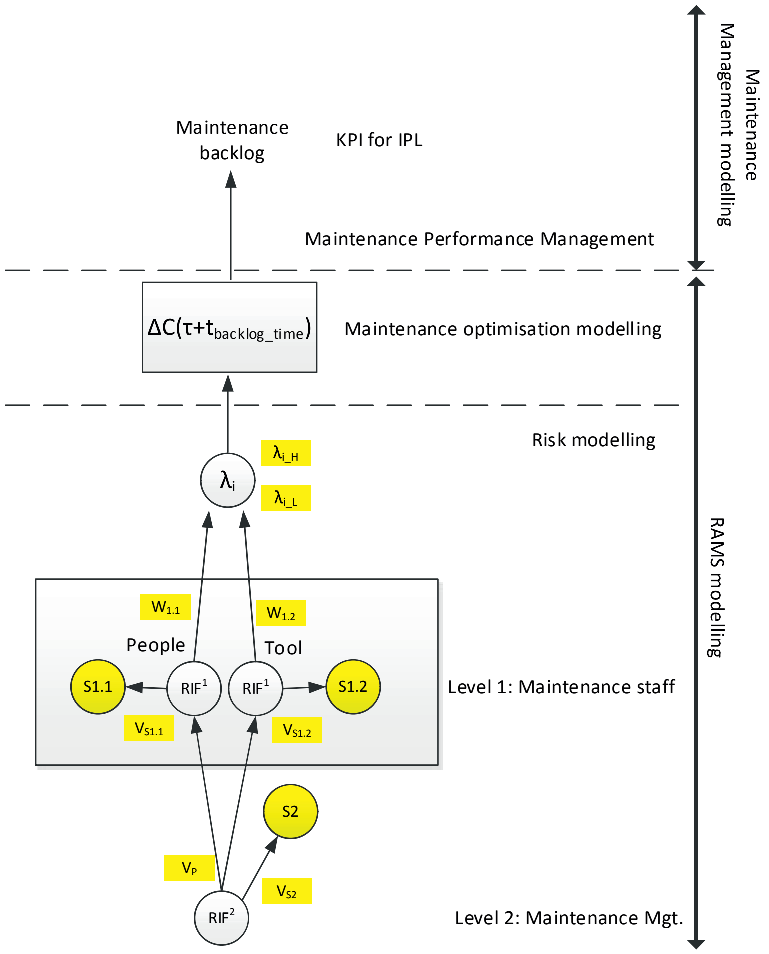


Figure 8 – Schematic modelling of maintenance backlog

Level 1 RIF

Level 1 RIF will involve both aspects from people and tool, which is of relevance in planning. At this level the operative aspect of the maintenance staff is of interest where for example technical aspects is evaluated such as how sophisticated the methods used are (tool), and the competence of the maintenance staff (people).

Level 2 RIF

Maintenance management is defined as all activities of the management that determine the maintenance objectives, strategies and responsibilities, and implementation of them by such means as maintenance planning, maintenance control, and the improvement of maintenance activities and economics (CEN, 2010). In this level these activities are evaluated and also to what extent these activities affect level 1. Further description of Risk OMT modelling is outlined by (Vatn, 2013). Following approach is used for calculating the probability of the basic event, q_i, that leads to the failure rate of the basic event, λ_i :

1. Perform an expert judgement for evaluating:

   a. Scores on level 1 and level 2 RIFs based on the scores A-F.
   b. Variances for each score
   c. Structural dependency between level 1 and level 2
   d. Weights w_i on level 1 RIFs
   e. Maximum and minimum value for qi for each basic event.

2. Map the characters into values in the interval [0,1]. Following mapping is used:
   A=[1/12], B=[3/12], C=[5/12], D=[7/12], E=[9/12], F=[11/12].
   The range is then as follows: [1/12, 3/12, 5/12, 7/12, 9/12, 11/12]

3. Calculate the posterior distribution of parents nodes based on following assumptions:
   a. The RIF distribution for the parents is based on a beta distribution.
   b. Jeffreys prior is used in the beta distribution where $\alpha_0 = \beta_0 = 0.5$ is used as prior in the beta distribution in order to calculate the posterior distribution. The beta distribution has following parameters:

$$\alpha = \alpha_0 + {}^{s^2(1-s)}\!/_{V_s} \tag{2}$$

$$\beta = \beta_0 + {}^{s(1-s)^s}\!/_{V_s} \tag{3}$$

   c. The beta distribution is calculated and following list is provided:
      Pp=[p(RIF=”A”), p(RIF=”B”), p(RIF=”C”), p(RIF=”D”), p(RIF=”E”), p(RIF=”F”)]

4. Calculate the prior distributions of child nodes based on following assumptions:
   a. The RIF distribution for the child are conditioned on the parent with the list of r values P=[1/12, 3/12, 5/12, 7/12, 9/12, 11/12].
   b. For each value in the P-vector, the prior parameters α_0 and β_0 for the child RIFs are calculated based on following equations:

$$\beta_0 = \left(\frac{p(1-p)}{V_p}\right) \times (1-p) \tag{4}$$

$$\alpha_0 = \frac{p \times \beta_0}{1-p} \tag{5}$$

   c. α_0 and β_0 are used as prior in equations (2) and (3) to calculate the posterior distributions for the child RIFs.
   d. The beta distribution is calculated and following vector is provided:
      Pcc1=[p(RIF=”A”), p(RIF=”B”), p(RIF=”C”), p(RIF=”D”), p(RIF=”E”), p(RIF=”F”)]
      Pcc2=[p(RIF=”A”), p(RIF=”B”), p(RIF=”C”), p(RIF=”D”), p(RIF=”E”), p(RIF=”F”)]

5. The weighted sum is calculated for the level 1 RIFs and the expected probability for each possible combination, *i*.

   WR(i)=w_1*Range(i)+w_2*Range(i)
   Prob(i)=Pcc1(i)*Pcc2(i)*Pp(i)

   All the combinations are distributed in a list.

6. Apply the law of total probability for calculating the basic event on following assumptions:
   a. The list contains the weighted score and the probability of each score:
      List=[WR(i) ,Prob(i)]
   b. Calculation of qi according to following formula:

$$q = \sum\nolimits_p \left[\sum\nolimits_r q_L * \left(\frac{q_H}{q_L} \right)^{\sum_j w_j * r_j} * p_R(r|P = p) \right] * p(p) \tag{6}$$

   c. In programming, the list [WR, Prob] is generated and is the unconditional distribution over the weighted sum of the level 1 RIFs. The length of the list is *n* where an element in the list is denoted as i. The q value is then calculated as follows in programming:

$$q = \sum\nolimits_{i=1}^{n} \left[\left(\frac{q_H}{q_L} \right)^{WR(i)} * prob(i) \right] \tag{7}$$

When the probability, q_i, for the basic event i is calculated, the failure rate λ_i can also be calculated according to following formula:

$$q_i \approx \lambda_i * MTTR_i \tag{8}$$

Compared with the result in Table 3, we will now assume that maintenance staff and maintenance management have been evaluated in accordance to the Risk OMT model developed in Figure 8. In Table 4 input data and result is presented as an example with comments.

Table 4 – New calculated maintenance backlog with Risk OMT model.

Input data: Based on expert judgement on procedure 1 and maintenance backlog model shown in Figure 8	**Value**	**Comment**
S2	C = 5/12	Average score. In class of average in the representing industry branch.
Vp	$0.005^2 = 0.0025$	High dependency
V_{S2}	$0.2^2 = 0.04$	Low dependency
S1.1	F = 11/12	Very bad score of the competence of the competence at the people which is a combined evaluation of experience, knowledge, skills and behaviour. In class of worst practice in the representing industry branch.
S1.2	B = 3/12	Good score.
VS1.1	$0.1^2 = 0.001$	Medium dependency.
VS1.2	$0.2^2 = 0.04$	Low dependency.
W1.1	0.3	Less important.
W1.2	0.7	More important.
λi_L [/year]	$1.0932*10^{-2}$	Best industry practice given no maintenance backlog.
λi_H [/year]	$66.91*10^{-2}$	Worst industry practice given no maintenance backlog.
Output data: Based on procedure 2-6	**Value**	**Comment**
λi [/year]	$0.0845=8.45*10^{-2}$	Very good compared to the industry branch. All though the skills for the employees was given a very bad score, average score for maintenance management and very good score for planning tool provided a good result
Increase in λ compared with Table x	0.0845 – 0.0015 = 0.0015	
New $\lambda_{E,i}(dt_1)$ [1000 USD]	0.146 + 0.0015 = 0.1475	
New $\lambda_{E,i}(dt_3)$ [1000 USD]	0.023 + 0.0015 = 0.0245	
New $\Delta C_{Unplanned,i}$ [1000 USD]	0.98	
New ΔC_{Total} [1000 USD]	2 + 0.98 = **2.98**	

With this evaluation of Risk OMT the value of MB is evaluated to be 40 USD more expensive due to poor competence at the maintenance crew for this specific maintenance activity.

4.3 Maintenance backlog within barrier management

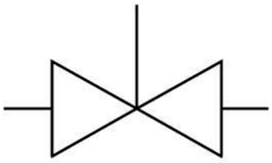
In O&G industry barriers and barrier management is regarded as important for major accident prevention. A set of principles for barrier management in the petroleum industry has been published (PSA, 2013). Furthermore, a report has also been published to increase the understanding of barrier management in practice, with emphasis on implementation in the operation phase (DNV GL, 2014). Nevertheless, barrier management has also been regarded to foster confusion with too few specific cases. In fact, it has been concluded that some of the most pressing problems within barrier management concern terminology, integration across analysis and disciplines, and implementation in operation (Johansen and Rausand, 2015). For example, there is some vagueness of what is actually meant by a barrier. A source of confusion is that both authorities and the industry are imprecise and just say “barrier” instead of being more precise and refer to the notions of barrier functions, systems, or elements. Despite this confusion, barriers are still important means in order to prevent and mitigate major accidents. There are also strong arguments that maintenance backlog will affect the barriers (Øien and Hauge, 2014). It has been claimed that maintenance is not a barrier, but rather a performance influencing factor (Øien et al., 2015). Since it is not clear what is actually meant by a barrier, the authors will not take any position about this statement but rather see how maintenance backlog will affect a barrier element such as an ESV valve. Table 5 is inspired by the ESV valve example from Øien et al. (2015). When evaluating maintenance backlog of a barrier element, it is of interest to measure how much maintenance backlog is acceptable to have and still operate within an acceptable safety level.

In this example, maintenance backlog is considered on what is allowed under the requirement of having an operational safety integrity at SIL 2. This means that maintenance backlog should be measured in absolute terms, i.e. the amount of overtime from the maintenance interval: $MB = t_l - \tau$ where t_l is the time since last maintenance action. In addition maintenance backlog should be measured relatively, i.e. the partial amount of time consumed until reaching the time limit of SIL2: $MB\% = (t_l - \tau)/(\tau_{limit} - \tau)$. When t_l has reached τ_{limit}, 100 % of the allowable time of maintenance backlog has been reached.

Table 5 – Example of maximum maintenance backlog adapted from (Øien et al., 2015)

Example and requirement

SIL	PFD
SIL 4	$10^{-5} – 10^{-4}$
SIL 3	$10^{-4} – 10^{-3}$
SIL 2	$10^{-3} – 10^{-2}$
SIL 1	$10^{-2} – 10^{-1}$



Design	**Operation with no maintenance backlog, e.g. the maintenance plan is followed.**	**Operation with maximum maintenance backlog**
Failure rate from vendor $\lambda_{DU} = 1 * 10^{-6}$ hrs	Experienced failure rate $\lambda_{DU} = 2.4 * 10^{-6}$ hrs	Experienced failure rate $\lambda_{DU} = 2.4 * 10^{-6}$ hrs
Required maintenance interval $\tau = 4000$ hrs	Maintenance interval from design **$\tau = 4000$ hrs**	Maintenance interval from design $PFD = \lambda_{DU} * \tau / 2$ $\tau_{limit} = (PFD / \lambda_{DU}) * 2$ **$\tau_{limit} = 8333$ hrs**
Design safety integrity: $PFD = \lambda_{DU} * \tau / 2 = 2 * 10^{-3}$ SIL 2	Operational safety integrity $PFD = \lambda_{DU} * \tau / 2 = 4.8 * 10^{-3}$ SIL 2	Operational safety integrity limit $PFD = 10^{-2}$ SIL 2

5. Operational countermeasures for maintenance backlog

5.1 Theory of Constraints

In production planning theory of constraints (TOC) has been developed by Goldratt and implemented in industry. TOC is based on five steps (Goldratt, 1990):

1. Identify the systems constraint(s).
2. Decide how to exploit the system's constraint(s).
3. Subordinate everything else to the above decision.
4. Elevate the system's constraint(s).
5. If, in the previous steps, a constraint has been broken, go back to step 1, and do not allow inertia to cause a system's constraint.

TOC has also been broadened by Goldratt to encompass project management in his book "Critical Chain" (Goldratt, 1997), also known as critical chain (CC) scheduling (Herroelen and Leus, 2001) or critical chain project management (Watson et al., 2007). The critical chain in a project is "the set of tasks which determines overall project duration, taking into account both precedence and resource dependencies" (Newbold, 1998). When planning for activities in a project, significant effort is used in ensuring accurate time estimates. In order to achieve a high degree of accuracy, a safety time is included in each activity. The safety time will be conservative where the estimate is significantly above the median. This will lead to a too high safety time with a planning behaviour with following waste:

- **Student Syndrome:** Not starting the task before it is necessary where the resources are not utilized in advance.
- **Parkinson's law:** Delaying completion of the task since there is no reward, but perhaps a punishment in organisation. Thus the productivity will decrease or tasks that are not necessary are performed.

In order to reduce this unwanted planning behaviour and waste, CC recommends to remove the safety time and instead insert different types of buffers:

- **Project buffer:** This buffer is put at the end of the project and is used to control the completion date. When there is a delay in the critical chain, it will consume this buffer.
- **Feeding buffers:** At the end of each set of activities connected to the critical chain will have a feeding buffer. This should ensure that the critical chain does not have to wait for a non-critical chain.
- **Resources buffers:** These buffers are set alongside of the critical chain and ensure that appropriate resources are available to work on the critical chain when needed.

As a tool, TOC in project management is regarded as essential to assist in the delivery of a successful project (Rand, 2000). As an example, the handover of a project took place two weeks early, with 99.5 % of all work completed after applying TOC. Despite documented results, this concept has drawn criticism for oversimplification and overestimation of buffers (Herroelen and Leus, 2001). Nevertheless, even after adding the buffers, the completion time of a project using CC is generally 25 % less than the time that would be estimated with other project scheduling methods (Watson et al., 2007). CC has been applied within maintenance (Bevilacqua et al., 2009), but is used for shutdown maintenance leaving out more frequent maintenance activities. Moreover, CC has not been applied within IPL or as a scheduling tool for avoiding maintenance backlog.

When further broadly encompassing TOC and critical chain into IPL, critical chain is defined to be the set of maintenance activities that require downtime and production that determines the finish date of the last maintenance activity, taking into account both precedence and resource dependencies. Figure 9 shows an example of application of critical chain scheduling for IPL. The lower part in the figure shows the plan of production and maintenance, whereas the upper part shows the status and progress.

In Figure 9, following terms from TOC is applied in maintenance scheduling:

- Non-critical maintenance: Maintenance activities that does not require stop in production, but are necessary to execute before stopping production. Examples: Preparing for maintenance resources, setup of equipment and man-power.
- Critical maintenance: Maintenance activities that require stop in production. Example: Shut-down of machine, lock out, change part, test run and start up.
- Feed buffer: The buffer in time the maintenance planner will estimate in order to avoid postponement of critical maintenance activities.
- End-buffer: This buffer in time is the estimated extra time for completing the maintenance activity without postponing the planned production after the maintenance work is completed.
- LAFD: Latest Allowable Finnish Date (LAFD). This is the date when the scheduled maintenance activity must be completed. It is also given a specific time at this date where the production will start and is also included as information in LAFD. In Figure 9, the maintenance activity must be completed at the middle of the day at Sunday.

In this example the end-buffer has been consumed due to delays in both production (50 % consumption) and critical maintenance (25 %). In addition the feed buffer of the non-critical maintenance was also consumed resulting in 25 % consumption of the end buffer. This yields 100 % buffer consumption meaning that any further delay in the critical maintenance activity will result in maintenance backlog if no compensation measures are implemented.

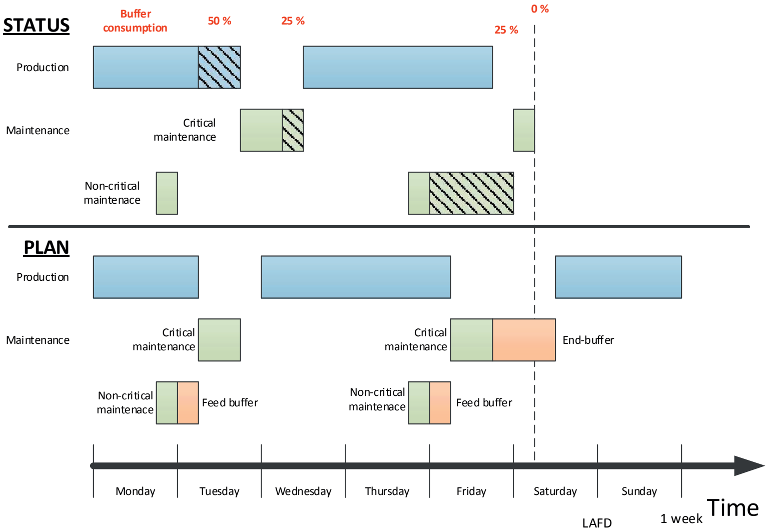


Figure 9 – Example of critical chain scheduling for IPL presenting both the plan and the status.

5.2 Rescheduling of maintenance planning

One operative measure would also be to reschedule the maintenance plan. If the maintenance backlog is known in advance, it would also be possible to enhance a maintenance activity. This was performed in an earlier article where the aim was to have a maintenance optimisation tool when performing IPL (Rødseth, 2014). Figure 10 shows an example of maintenance grouping of several maintenance activities. Each T time unit is preventive maintenance performed. When maintenance backlog is announced at t_0, rescheduling of the maintenance plan is possible. The decision criteria for rescheduling is that the extra maintenance cost will be less than the costs of lost production at 4T. In this example, maintenance activity is enhanced to 3T and one extra maintenance activity is performed at 5T.

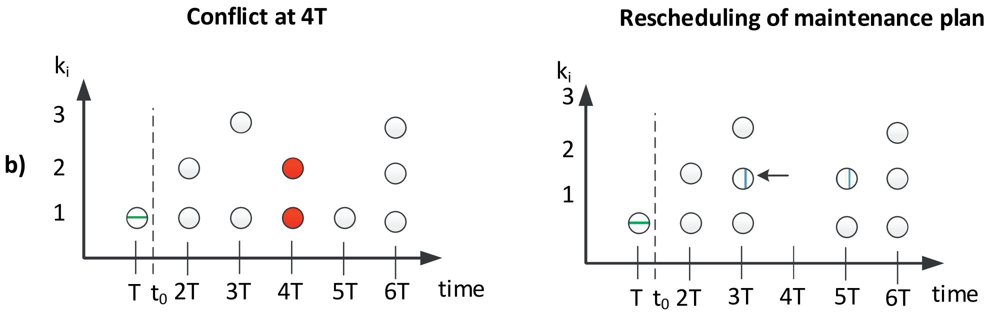


Figure 10 – Four rescheduling options for maintenance backlog at 4T adapted from (Rødseth, 2014).

5.3 Operational measures in production

Operational measures in production should be feasible, when maintenance backlog occurs. The aim would be to reduce the failure rate functions through less degradation of the equipment. However, reducing the load would result in reduced speed and increase the PLI value described in Figure 1.

6. Framework for Integrated Planning

The IPL framework was in the start developed for the O&G industry based on literature study from this industry branch (Rødseth and Schjølberg, 2014b). However, based on evaluation of IPL in the sawmill industry (Rødseth et al., 2015b), the framework should be more generic as shown in Figure 11. The IPL loop, illustrated in Figure 12 which is adapted from (Rødseth and Schjølberg, 2014b), is an important part of the framework and is located at level 3 in Figure 11.

The IPL loop starts with input in terms of resource requirements. Use of the IPL loop will be better control of technical condition compared with traditional maintenance management because IPL will eliminate the silos in the organisations.

The basis for the IPL loop is to have a well-established policy with principles for IPL. In order to have a dynamic planning loop as illustrated in Figure 12, some main principles for IPL must be established base on the main categories “people” and “tools”. These two main categories will have sub-categories as shown in Figure 12.

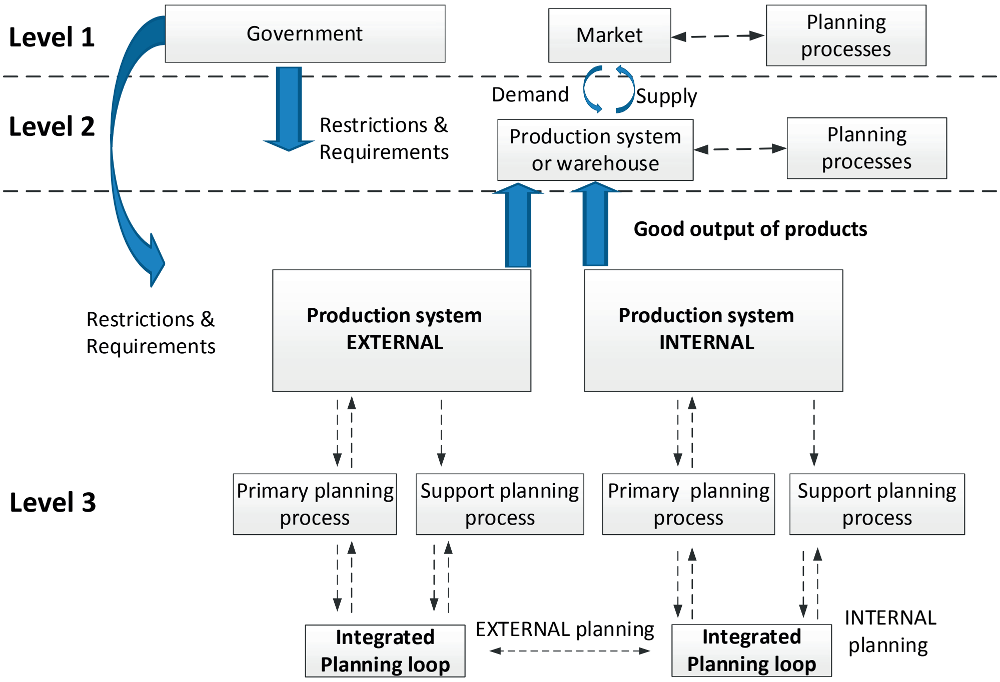


Figure 11 – IPL framework adapted from (Rødseth and Schjølberg, 2014b).

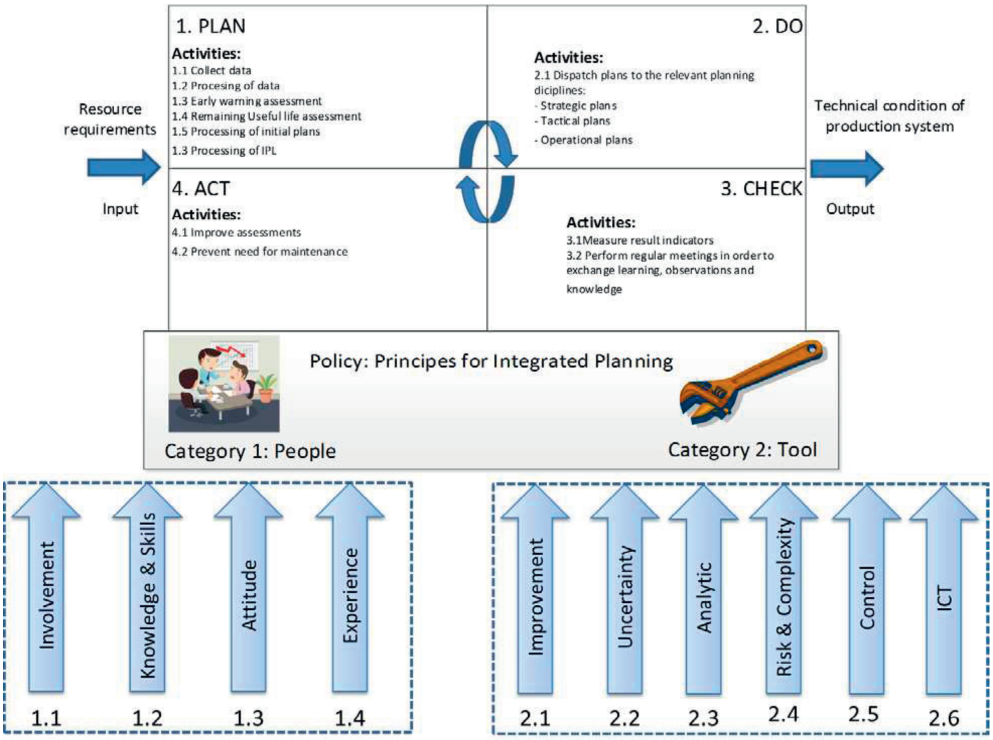


Figure 12 – IPL loop and principles for IPL adapted from (Rødseth and Schjølberg, 2014b).

The sub-principles are further elaborated in Table 6 and Table 7. These principles will justify the model and serve as a policy for IPL, i.e. a general guide for decision-making and individual actions. The principles are based on the planning fundamentals in Integrated Planning System (Department of Homeland Security, 2009) and aspects of planning outlined by Palmer (2013) that are inspired by Deming (2000). In addition, based on the findings from Powell and Rødseth (2013), ICT tools should be included in category 2 in Figure 12. These principles must be present at all times to ensure that IPL is successfully managed.

Table 6 – Principles for people working with IPL and it's relevance for MB

Principle no.	**Description**	**Relevance for Maintenance Backlog**
Principle 1.1 Involvement	*Create a constancy of purpose for improvement of managing technical condition through involvement.*	Poor involvement from other disciplines may result in a planning conflict where maintenance plan is postponed with maintenance backlog as a result.
Principle 1.2 Knowledge & Skills	*Adopt the new philosophy through training, education and self-improvement for everyone.*	The knowledge and skills from the craft performing maintenance can either improve or degrade the expected technical condition and change the degree of maintenance backlog.
Principle 1.3 Attitude	• *Drive out fear* • *Eliminate slogans* • *Remove barriers that rob people of pride of workmanship*	In order to reduce the maintenance backlog it is vital to have a closed improvement loop where maintenance planner can have feedback for why maintenance backlog is taking place and are not eliminated.
Principle 1.4 Experience	*Planning does not need to start from scratch.*	Maintenance planning should be balanced upon other priorities such as production goals in production planning.

Table 7 – Principles for IPL as a tool and it's relevance for MB

Principle no.	**Description**	**Relevance for Maintenance Backlog**
Principle 2.1 Improvement tool	*Improve constantly and forever the system of production and service.*	Maintenance backlog should follow the closed planning loop in order to sustain continuous improvement.
Principle 2.2 Acceptable level of uncertainty	*Eliminate numerical quotas for the workforce.*	Maintenance backlog is only an indicator, and not a mandate for the decision.
Principle 2.3 Analytic tool	*Planning is an orderly, analytical, problem-solving process that guides preparedness activities. Further, planning identifies the tasks and purpose, assigns tasks, allocates resources, and establishes accountability for Integrated Operations. Planning also facilitates cooperation and communication.*	Maintenance planning is modelled through several analytic tools such as Bayesian network.
Principle 2.4 Risk and Complexity tool	*Planning is fundamentally a risk management tool and depicts the anticipated environment for action. Further planning helps deal with complexity.*	Maintenance backlog will be a leading indicator and communicate the risk in the organisation.
Principle 2.5 Control of influencing factors	*Planning is influenced by time, uncertainty, risk and experience.*	Maintenance backlog is also influenced by time, uncertainty, risk and experience.
Principle 2.6 ICT tool	*Planning is supported by both an Enterprise Resource planning (ERP) system and Performance Measurement System applied at suitable facilities.*	Maintenance backlog should be implemented in an ICT tool.

7. Discussion and concluding remarks

This finial section evaluates the results of the presented work of the theory in MB, summarizes the contribution to science and industrial application, and finally concludes with remarks that indicates future research needs.

7.1 Discussion of terminology of maintenance backlog

To build a theory in maintenance it is necessary to have a specific and accurate terminology that does not confuse the research societies nor the industry. For example, European Committee for Standardization (CEN) claims that correct and formal definitions in maintenance are required in order to give the user a deeper understanding of the maintenance terms used (CEN, 2010). Unfortunately, we could not find any precise definition of MB in existing standards, so we explored this term in different sectors. By systematically elaborate definitions from petroleum sector, road transport sector and nuclear sector, we synthesised a definition for MB. This new definition should provide a more vital understanding for the user. In particular, the user of this term will now understand MB with three different aspects:

- Financial
- Technical condition
- Work orders

In addition to an accurate understanding this definition also offers a flexible understanding of the term MB. When evolving toward modelling MB, this will be reflected upon as well. The challenge with the existing EN 13306 standard is that MB is not included. Therefore, MB should be a part of the maintenance terminology in the next revision of this standard. As risk management provides a deeper philosophical reflection of the term risk (Klinke and Renn, 2002), this is also needed in MB theory since it includes the property of risk. Thus there is need to shed light on the philosophical question of realism versus constructivism (Klinke and Renn, 2002). An appropriate question would therefore be: Is MB a term in maintenance that represent an objective measure from the asset or is it instead more a subjective measure that constitute mental constructions in the mind of the planner? From the authors perspective MB should comprise both a realism and constructivism view. From the result section, the authors have presented both perspectives. For example from the taxonomy shown in Figure 5, work-based MB in terms of man-hours should from a technical point of view be possible to measure both objective and accurate in an Computerized Maintenance Management Systems (CMMS). However, the monetary expression of MB will also include a more constructionist view. For example, experts subjectively assess the MB through evaluation of risk influencing factors. Nevertheless, this should not be an unfamiliar view for the maintenance planner that today performs expert judgement of the criticality and hence prioritizing of the work orders.

Furthermore, we have also made a clear distinction from the term “backlog” and “MB”. All though we recognise in maintenance societies the confusion of these words where it is sometimes comprehended as synonyms, we still endorse the term “backlog” from Palmer (2012) and is given a different meaning than “maintenance backlog” which is presented in this article.

7.2 Discussion of process flow chart of maintenance backlog

It is also crucial to establish a clear process flow chart that presents how maintenance personnel could operationalize the MB theory. This process chart must be aligned with the existing maintenance processes in the organisation where the maintenance manager is responsible for the implementation. Likewise maintenance programmes such as Total Productive Maintenance (TPM), an own coordinator should implement the flow chart and align it to the maintenance processes.

The flow chart points out a clear distinction between internal and external causes of the MB. The internal cause is then investigated further in existing maintenance processes and can be due to several causal factors within the responsibility of maintenance management:

- Lack of organisational knowledge of controlling and understanding the effects of MB
- Lack of support from top management in controlling MB

- Poor planning of maintenance activities
- Poor quality in performing the maintenance activities
- Lack of measurement with suitable maintenance KPIs for MB
- Poor attitude for performing the maintenance plans

However if the cause is external, the maintenance management in the organisation is believed not to have the main cause of the MB. Instead, the cause is external and found in the production department. The next decision is then to evaluate if external countermeasure is possible or if a maintenance activity should be performed at a strategic, tactical or operational level. The benefit for such a process flow chart, is that a rational approach accurately distinguish if the maintenance processes (internal cause) or the Integrated Planning loop (external cause) should be performed due to too high MB. However, the process flow chart must also tackle some challenges during operation. Firstly, there might be situations where the cause of too high MB can be both internal and external situations. It will then be a pivotal task for the organisation to sustain an unambiguity and unbiased analysis of the causal factors of MB, thus avoiding an unclear result of the analysis or "all blame" for one discipline. Another challenge is also to ensure that external countermeasure has been thoroughly evaluated by the production department. It is believed by the authors that this would be the best decision in several occasions, and by just simply jump over this decision would be more costly for the organisation.

7.3 Discussion of Maintenance backlog model

The MB model provided three theoretical elements; taxonomy, reliability modelling and theory of constraints. The taxonomy positioned MB only to concern preventing maintenance. The benefit for the proposed taxonomy is that three perceptions for MB is established: Work based, time based and monetary expressed. Each perception would be measured and modelled differently, thus providing the maintenance personnel and academia a more comprehensive theory for MB. The challenge for this taxonomy is that there might be more categories or sub-categories that has not been developed yet.

The reliability modelling of MB supports maintenance optimisation theory for IPL presented by Rødseth (2014) which is shaped by solid theory within maintenance grouping by Wildeman (1996). The reliability model first presents how MB is measured financially. The first approach calculates the expected extra costs in existing maintenance optimisation models due to postponing the optimal maintenance activity. This would often require a predefined failure rate for the specific component that should be maintained. The next step would be to introduce risk influencing factors to adjust the failure rates to more accurate estimates. The Risk OMT model introduces evaluation from experts regarding both technical aspects (tool) and user aspects (people) in maintenance planning that affects the failure rate. A pivotal challenge in implementing this model is that the experts can have different perception for the score and hence provides a "wrong adjustment" of the failure rate.

The next application area for reliability modelling was within safety critical maintenance. In this context it is not allowed to cross the deadline for the maximum maintenance interval τ_{limit}. In this sense MB includes a buffer of remaining time to complete the overdue maintenance activities. The benefit for the industry in applying such a model is to have a buffer that yields more flexibility in the maintenance plan. A challenge in this model is that the buffer would approximate zero if the maintenance interval were approaching τ_{limit}.

Reliability modelling is also applied as a countermeasure for tackling MB. The strength of such a model is that it is not difficult to administrate and at the same time should be in accordance with existing CMMS such as SAP where maintenance is performed at fixed time intervals. The model developed by Rødseth (2014) was thus a semi-static maintenance grouping strategy where maintenance activities only can be performed each T time unit. All though this model is more dynamic than a clear static maintenance grouping strategy, it will still lack the full dynamic functionality which is sustained in dynamic grouping. Nevertheless, a dynamic grouping strategy would challenge administrative effort in a CMMS system where in practice maintenance could be performed at any time in future with this theory implemented.

Theory of Constraints was also applied as theory for maintenance scheduling. It was shown that in this theory the maintenance schedule would have an extra time buffer that would avoid trespassing the due date for the maintenance activity. The benefit is that the maintenance planner can have more control in terms of a feed buffer and end-buffer in time. The challenge with this theory is when the original maintenance plan is kept and no time buffer is consumed. If it is then not possible to assign the maintenance resource to other tasks, the organisation would suffer from waste in non-productive time.

7.4 Discussion of Framework for Integrated Planning

The IPL framework developed by Rødseth and Schjølberg (2014) will also apply the MB theory. When performing the process flow chart of MB the IPL loop will be applied when the cause of MB is external. In the PLAN-stage of the IPL loop the KPI MB will be registered and evaluate whether external countermeasure or if a strategical, tactical or operational activity should be performed. In the DO-stage the countermeasure for tackling MB will be performed. This paper presented only operational plans in terms of maintenance grouping and theory of constraints within maintenance scheduling. A challenge in the further performing the IPL loop is to validation of the CHECK-stage and ACT-stage due to longitudinal effects of losing control of technical condition due to MB. An appropriate measure to explore these stages would be to demonstrate them through specific industrial case studies.

A list of principles for IPL and the relevance for MB was presented. The benefit for such tables is that it can be provided as a guideline in the organisation when operationalising MB in IPL. However, the challenge could be to relate it to the specific industry context. Nevertheless, it is believed by the authors that such principles will increase the awareness of MB in the organisation.

7.5 Scientific and industrial implications

The scientific contribution in this article invites challenging questions. In the discussion of scientific implications, the author will systematically answer these questions followed up with discussion.

Is the terminology of maintenance backlog in conflict with existing definitions?
No. The definition from Petroleum Safety Authority and IAEA regards MB as compliance of a maintenance schedule which can be classified according to RCM. Furthermore, the road authority has an understanding that MB is a financial measurement based on unfilled demand of the technical condition. With the new definition, all of these perspectives are included and should provide a better understanding of the term MB.

Will maintenance backlog support IPL theory?
Yes. In the flow chart of MB it is a clear procedure of operationalizing MB when the cause is external, i.e. another discipline than maintenance is affecting the maintenance plan. The flow chart points out if the countermeasure should be external, or if it should be performed internally either at an operational, tactical or strategic level.

Is the proposed taxonomy of maintenance backlog clarifying?
Yes. It is now a clear taxonomy of the different aspects of MB. In addition, it is also a clear scope where corrective maintenance is not a part of MB.

Can the financial estimation of maintenance backlog from the reliability model be large for one planner and smaller for another?
Yes. The assessment of a financial value of the MB is based on the expert judgement in evaluation of scores for the risk influencing factors. This implies that the value of the financial number has a position in constructivism where it is the judgement and the subjective evaluation from the planner that affects the magnitude of MB. Factors from the judgement is further based on his experience and attitude.

Will TOC ensure that there is no waste of maintenance resources?
No. The buffer will be established based on the expert judgement or rules of thumb. If the maintenance plan is not affected by any issues of MB, the maintenance resources will be idle with no work and should be regarded as waste of time for the craftsmen.

Is the list of principles described of the IPL loop considered to be finial?
No. This should in this article be considered to be a first approach for establishing a guideline for the planners within IPL. Further research with interviews and surveys should be considered when developing the list of principles.

When further elaborating the industrial implications, it is of highly relevance and importance to evaluate if this article bridge the gap between theory and practice. Malik (1979) has pointed out that: "…there is more isolation between practitioners of maintenance and the researchers than in any other professional activity". This isolation has established a gap between theory and practice in the maintenance field. Dekker (1996) points to six specific areas that must be addressed in order to decide if this gap is larger than normal. Rausand (1998) also supports these statements by addressing the importance of bridging the gap between the maintenance practitioners, the reliability engineers, and the statisticians and operation researchers who develop maintenance optimisation models. Likewise his consideration, the authors in this article also see the MB theory as a way to reduce the isolation between practitioners and academia in the maintenance society. Table 8 presents the areas identified by Dekker and elaborates how the contribution in this article contribute to close these gaps. In overall, all of these contributions in the article should support in closing the gap between practitioners and the researchers within maintenance.

The new knowledge in MB presented in this paper is also of high relevance in teaching of maintenance. The authors plan to include the topic of MB at European Federation of National Maintenance Societies (EFNMS) and propose to include definition of MB in EN 13306 (CEN, 2010). This should then provide a solid ground in teaching in universities within MB. In particular, MB should be included in qualification of maintenance personnel in EN 15628 (CEN, 2014b). In this standard, the maintenance supervisor or engineer has the role as planner. However, the specified knowledge of MB in this standard is very absent. To support his skills and competence in maintenance planning, it is crucial that knowledge of MB is included in the list of essential knowledge.

Table 8 – Area for closing the gap between academia and practice

Area for closing the gap	**Contribution in article**
Maintenance optimization models are difficult to understand and to interpret.	The rescheduling of maintenance planning (Figure 10) in reliability modelling is grounded on static grouping, leaving out dynamic grouping which may be more difficult to understand and not so rather straight forward to administer in a maintenance system.
Many papers have been written for maths purposes only.	This article include new knowledge that also include terminology, process flow chart and taxonomy for maintenance backlog. This contribution should provide a wider meaning for how to operationalize this knowledge, not only by a mathematical understanding.
Companies are not interested in publication.	The authors does not share this understanding. With interest from Norwegian companies in different sectors, the plan is to have further publications with significant contribution from industry. This contribution will ensure further demonstration of the maintenance backlog theory.
Maintenance comprises many different aspects and it is not rather straight forward to generalize.	This theory contribute with more than one aspect of maintenance backlog. For example, it offer both reliability theory and theory of constraints in order to tackle too high maintenance backlog.
Optimization is not always necessary.	Maintenance backlog has already as a premise that optimisation is not obtained since the original maintenance plan is not followed. Instead, maintenance backlog will more express for the user what will be the best alternative when the original maintenance plan is no longer followed.
Optimization models often focus on the wrong type of maintenance.	Maintenance backlog theory does not take into account how to choose the most appropriate maintenance activity. Instead, if the maintenance activities is not performed as planned for, this theory will provide support to the planner to evaluate how serious is the situation financially and which counter-measures are recommended.

7.6 Concluding remarks

Control of plant capacity is an essential part in maintenance planning. In IPL it is a crucial decision process to evaluate if MB should be allowed and, if so, to what extent. This article contributes with a sound theory for MB that supports IPL. The theory validates its application through illustrative and quantitative examples. This should provide both confidence and a deeper understanding for the maintenance planner when implementing the new theory in their organisation. From the authors' point of view, there exist today no solid theory of MB that covers more than one industry branch. Hence, we have in this article shed new light of this theory by establishing MB fundamentals, which should be regarded as branch independent.

The industrial impact is expected increase in control of the plant capacity and safety level. This would then increase the capability of meeting the production demand. Instead of an ad-hoc manner where the maintenance planner struggle to keep up with the original plans, the maintenance planner is now supported with solid and new maintenance theory in MB that should result in more rational decision making in IPL.

To bridge the gap between theory and practice in MB theory, future activities requires involvement by both practitioners and researchers within maintenance. Maintenance managers and planners should start demonstrating the theory fundamentals of dedicated case studies in industry. By adjusting the examples in this article to their industrial context and support from researchers, it would be feasible to measure the impact of this theory. In parallel, academia with support from researchers need to update existing standards within maintenance. By including the definition of MB in EN 13306 and specification of the required knowledge for maintenance personnel in EN 15628, a solid platform should be present in future teaching. In long term for the industry, the production assurance should increase.

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Article 8

Profit loss indicator: a novel maintenance indicator applied for integrated planning

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Article 9

Increased Profit and Technical Condition through new KPIs in Maintenance Management

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Article 10

Early Warning Indicators for Integrated Planning

EARLY WARNING INDICATORS FOR INTEGRATED PLANNING

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Abstract

To improve the efficiency of offshore oil and gas installations, the concept of Integrated Operations (IO) has been developed, and later the IO principles have been extended into the planning domain (Integrated Planning, IPL). This concept comprises a holistic perspective where all the relevant planning domains are harmonized into one overall plan. The objective of this paper is to develop an approach for Early Warning Indicators (EWIs), both for the project and operation phases. Besides outlining a 7-step process for this purpose, the paper reports from the application of the EWI approach based on data from GDF SUEZ E&P Norway.

Keywords: Performance indicators, early warning

Introduction

In the oil & gas (O&G) industry, there has been identified a need for increasing the oil and gas recovery rate, accelerating production, reducing operational costs, and enhancing safety and environmental standards (Rosendahl and Hepsø, 2013). Indeed, it is a challenge that planning in the O&G industry is performed in "silos", i.e. each discipline has their own independent plan (IO Center, 2012; Rosendahl and Hepsø, 2013). This silo thinking, with lack of coordination across the disciplines, results in sub-optimal prioritizing of plans, producing unnecessary down-time. These challenges have partly resulted in the concept of Integrated Operations (IO). It has been estimated that a value increase of 300 billion NOK in 2015 will be the result if IO is implemented successfully (Ramstad, Halvorsen et al., 2010). When planning in an IO perspective, the term Integrated Planning (IPL) is used. IPL has the following characteristics:

- Planning in an IO perspective (Ramstad, Ose et al., 2011)
- Cross-domain planning (Ramstad, Ose et al., 2011)
- One integrated operational plan (Ramstad, Ose et al., 2011)
- Holistic perspective (Ramstad, Ose et al., 2011)
- Coordinating activities and resources across the domain (Ramstad, Ose et al., 2011)
- Supporting and making operational decisions on behalf of other disciplines (Sleire and Wahl, 2008)

This planning aspect results in a complex situation that has to be dealt with in order to meet the needs in the O&G industry, see Figure 1 (Rosendahl and Hepsø, 2013).

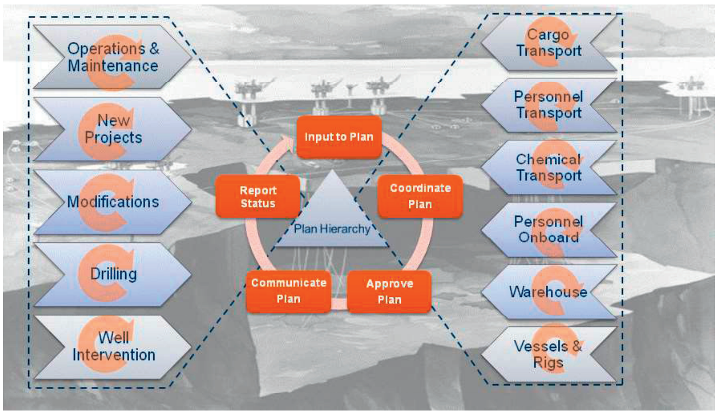


Figure 1 – Visualizing the complexity of IPL (Rosendahl and Hepsø, 2013).

In particular it has been highlighted by (Bai and Liyanage, 2010) that the major part of the O&G industry sector seems to agree that complex work planning must be integrated and obey principles of efficient design and application of indicators. In order to achieve the full learning potential for IPL, it is claimed by (Wahl and Sleire, 2009) that indicators in terms of performance measurement must be a part of the IPL concept. Further, it is concluded that more research should be done in order to improve indicators for plan performance. In fact, work on this topic has already started in the Norwegian offshore industry (Ramstad, Halvorsen et al., 2010). In this paper, indicators that provide early warning information, denoted as early warning indicators (EWIs), are further elaborated.

Despite sparse literature about indicators designed for IPL in the O&G industry, planning indicators have been identified (Wahl and Sleire, 2009). These indicators will be elaborated further in Chapter 2. Even though these indicators have been implemented in the O&G industry, it can be questioned whether these are sufficient for providing early warning information for an unwanted IPL event.

The main objective of this paper is to develop an EWI approach for IPL. In order to achieve this, the following sub-objectives were defined:

1. Identify existing indicators applied in IPL and evaluate what remains unsolved
2. Define early warning indicators and identify criteria for these
3. Propose an approach for early warning indicators
4. Demonstrate (parts of) this concept based on empirical data

Evaluation of current indicators for Integrated Planning

Based on a study for oil and gas companies, three indicators used for planning has been identified by (Wahl and Sleire, 2009). These indicators are structured in Table 1.

No.	Indicator name	Description	Purpose
1	Plan Attainment	Measures the amount of work performed vs. the amount of work scheduled for the period	The purpose is to indicate the degree of progression in the plan

2	Estimation Rate	Measures the ratio between estimated work and capacity	The purpose is to indicate to what extent the organization is capable of estimating the work effort
3	Planning Degree	Measures the amount of work performed vs. what was planned	The purpose is to indicate how many man-hours used by the disciplines are actually planned

Table 1 – Current indicators for IPL

All these indicators are geared toward efficient resource utilization. However, these indicators may have two shortcomings. First, it is not certain that these indicators actually lead to the wanted effect. When considering the ratio between efficiency, effectiveness and productivity, the model from (BLOM, 2003) can be considered, see Figure 2. The current indicators will give an overall indication of the efficiency. The effectiveness of IPL will be measured trough the fulfillment of the identified goals in IO, namely increased oil and gas recovery, accelerated production, reduced operating costs, and enhanced safety and environmental standards.

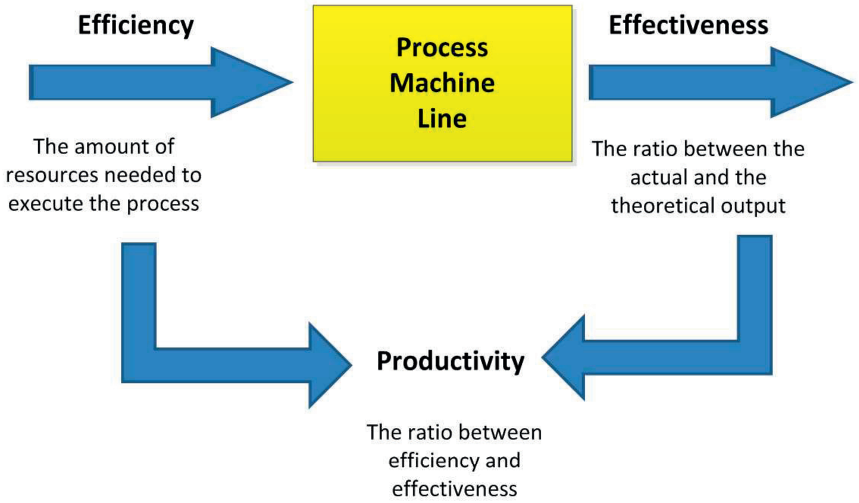


Figure 2 – The efficiency, effectiveness and productivity for a process, machine, or line

For achieving high effectiveness it is important to have indicators that are leading in nature, meaning they can predict drift from the desired IO goals, leading to unwanted events. It is not clear if these current indicators have this property. Second, these indicators measure only in the operational phase. However, events and conditions in the project phase may also lead to unwanted events in the operation phase.

To summarize, these indicators are both suitable and necessary categories for constructing IPL indicators. However, they are not sufficient to cover all the important properties for EWIs. This leads to a broader perspective outlined in Figure 3. This perspective will result in an EWI approach where EWIs are measured both in the project phase and the operational phase. The purpose is to provide warning of unwanted events in the operational phase that are relevant for IPL. The indicators for both project and operational measurements are developed in the engineering stage.

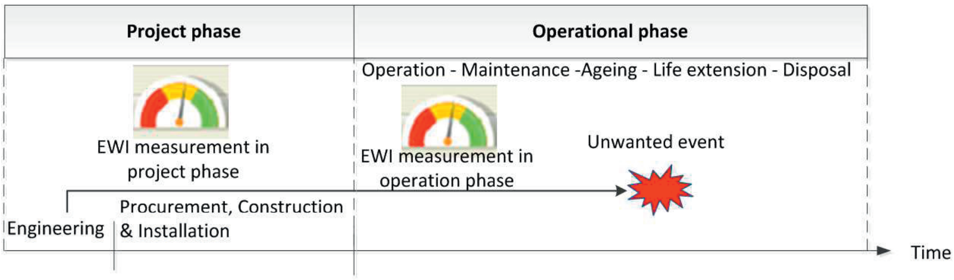


Figure 3 – Engineering IPL indicators for both the project and operation phase

Early warning indicators – context and criteria

In both science and policy, the term "indicator" is frequently used. Despite great demand for clear definitions, the meaning of an indicator is still ambiguous in different fields, such as ecology (Heink and Kowarik, 2010). In safety science the situation is similar, with no agreement neither on definition nor use (Herrera, 2012).This situation has led to further analysis of this term both in ecology (Heink and Kowarik, 2010) and in safety science (Oien, Utne et al., 2011). In ecology, the term indicator is perceived as an "indicant", i.e. a measure or component from which conclusions can be drawn on the phenomenon of interest (the indicandum) (Heink and Kowarik, 2010). This perspective is further supported in the safety science where a broad definition of indicator is as follows (Oien, Utne et al., 2011): "An indicator is a measurable/operational variable that can be used to describe the condition of a broader phenomenon or aspect of reality."

This definition is also used further in this paper. Even though this definition is generic, the development of indicators is context specific. It has been stated that there is no such thing as a universal model for developing indicators, but perhaps a combination of several methods would yield the best result (Oien, Utne et al., 2011). Therefore when developing an application of indicators, elements regarding indicators and their generic dimensions and model of context must be understood and ensured, see Figure 4.

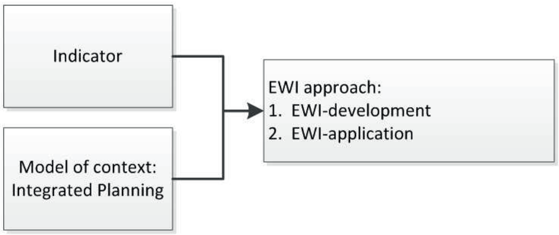


Figure 4 – Structure of application of indicators and their context

Regarding the model of context, IPL must be defined. When the IO principle is transferred into the planning domain, this leads to the concept of IPL (Rosendahl and Hepsø, 2013). An important question in IPL is what shall be controlled in the plan in order to avoid the unwanted event outlined in Figure 3. In this context, technical condition shall be under control, i.e. all the disciplines that affect the technical condition shall integrate their plans into IPL. The term technical condition is defined by (Thorstensen, 2008) to be defined as follows: "The technical condition is defined as the degree of degradation relative to the design condition. It may take values between maximum and minimum value, where the maximum value describes the design condition and the minimum value describes the state of total degradation”.

Inspired by (Integrated Planning Work Group, 2005) and (Alexander, 1981), the following definition is proposed for IPL: "Integrated Planning is a multidisciplinary decision-making process that manages technical condition and results in increased production, enhanced oil and gas recovery, reduced costs, and improved safety. This process is performed in a manner that optimizes across multiple planning disciplines through updating of objectives and attended by the power and intention to commit resources and to act as necessary to implement the chosen decision".

Based on the generic definition of indicators from (Oien, Utne et al., 2011) and the context of IPL, EWI is defined as follows: “An early warning indicator is a measurable/operational variable applied in the project phase or the operational phase to describe the condition factors that are likely to result in insufficient control of technical condition of the system. The purpose is to provide insight into future events so that countermeasures can be taken”.

When further elaborating the criteria for EWI, it is of interest to look into similar definitions for leading indicators, see Table 2.

No.	Indicator name	Definition	Comment
1	Leading indicator	“A leading indicator is a measure for evaluating the effectiveness of how a specific activity is applied on a project in a manner that provides information about impacts that are likely to affect the system performance objectives”. Source: (INCOSE, 2010)	The effectiveness is measured as the outcome of the activity and can be described as the ration between the actual and the theoretical output (BLOM, 2003). Since this effectiveness provides information about the impact, this definition is based on a cause-and-effect relationship.
2		“A measure or combination of measures that provides insight into an issue or concept. Indicators are often comparisons, such as planned versus actual measures, which are usually presented as graphs or tables. Indicators can describe the current situation (current indicators) or predict the future situation (leading indicators) with respect to an issue”. Source: (Rhodes, Valerdi et al., 2009)	The prediction of the future requires a cause-and-effect relationship.
3	Leading indicator	“A mathematical composite of relevant, quantifiable, product,	This definition highlights the importance for communicating.

No.	Indicator name	Definition	Comment
		project progress or process attributes (measures) taken over time that communicate important information about quality, processes, technology, products, projects, and/or resources”. Source: (Rhodes, Valerdi et al., 2009)	
4		"Leading indicators address the (possible) causes of a specific condition or event, and are the basis for the development of preventive maintenance programs". Source: (Knight, Akinkunmi et al., 2010)	The cause-and-effect relationship is communicated.
5	Proactive indicator	“Indicate the performance of the key work processes, culture and behavior, or the working of protective barriers between hazards and harms, that are believed to control unwanted outcomes”. Source: (Johnsen, Okstad et al., 2010)	The cause-and-effect relationship is highlighted since the factors of harms can be controlled to avoid unwanted outcomes.
6	Precursor	“A person who or thing which precedes another as a forerunner or presage; a person who or thing which heralds the approach of another; (now esp.) a thing that comes before another of the same kind as a forerunner, predecessor, or prototype”. Source: (Saltmarsh, Saleh et al., 2012)	Not so clear cause-and-effect relationship.
7	Precursor	“Conditions, events, and sequences that precede and lead up to accidents”. Source: (Saltmarsh, Saleh et al., 2012)	The cause-and-effect relationship is present since the events lead up to accidents
8		“An operational event or plant condition that is an element of a postulated accident sequence”. Source: (Saltmarsh, Saleh et al., 2012)	Postulate: Ambiguous cause-and-effect
9		“Events that must occur for an accident to happen in a given	Scenario: Ambiguous if the cause-and-effect is relevant for

No.	Indicator name	Definition	Comment
		scenario". Source: (Saltmarsh, Saleh et al., 2012)	the real situation.
10	Accident pathogen	"An adverse latent condition or hazardous state, which compounded with other factors, can precipitate and accident or aggravate its consequences". Source: (Saltmarsh, Saleh et al., 2012)	In this definition the cause-and-effect relationship is clearly specified (Saltmarsh, Saleh et al., 2012).
11	Near miss	"A broad chain of events from an accident sequence that is truncated towards the end before serious consequences occur". Source: (Saltmarsh, Saleh et al., 2012)	There is no clear description of cause-and-effect relationship in this term.
12	Early warning signs	"An early warning sign is an observation, a signal, a message, or some other form of communication that is or can be seen as an expression, indication, proof, or sign of the existence of some future or incipient positive or negative issue. It is a signal, an omen, or an indication of future developments". Source: (Klakegg, 2010)	The cause-and-effect relationship varies from strong relationship (proof) to more weak relationship (expression). Nevertheless, the causality is always present.

Table 2 – Terms similar to EWI

An important issue for the listed definitions is whether the cause-and-effect relationship is present. Both the terms "leading indicator", "proactive indicator" and "accident pathogen" imply the important element of cause-and-effect. "Early warning signs" also comprise the cause-and-effect relationship, but it can fluctuate dependent on the specific indicator. The terms "precursor" and "near miss" do not comprise causality. Nevertheless it should not be argued that silence with regard to causality in definition actually means that the precursors are not specified with this dimension (Saltmarsh, Saleh et al., 2012). If this argument holds, it could be questioned if precursors had any relevance for the decision making at all! There has been discussion to what extent leading and lagging indicators make sense (Herrera, 2012). A challenge for developing early warning indicators is to define what an unwanted event is.

When elaborating the criteria for early warning indicators, both generic criteria for indicators and criteria for early warning indicators must be described. The result is presented in Table 3 and comprises both generic and specific criteria. The generic criteria is based (Herrera, 2012) and is a result of literature review, interdisciplinary discussion and lessons learned. In order to make the criteria more relevant to IPL, the term "production and safety" is replaced with "technical condition". The specific criteria are present due to the context of the early warning indicators and the context of IPL, i.e. large time frame, low causality, high uncertainty, and high complexity.

No.	Generic/Specific variables	Criteria	Description
1	Generic	Meaningful	Indicators are relevant to technical condition and can be used to address what is happening to the system in a specific context. Indicators provide information which guides future actions.
2		Sensitive	Indicators provide a clear indication of changes over a reasonable period of time.
3		Reliable	Indicators lead to the same interpretations when used by different people for the same situation. The interpretations are related to the system and its operational context.
4		Measurable	The values of indicators can be rendered in a concise manner, either quantitatively or qualitatively.
5		Verifiable	It is possible to confirm the correctness of the value or description of the indicators.
6		Inter-subjective	Indicators are understood in the same manner by different people, either from the same technical community or from society at large.
7		Operational	The indicators can be used to support concrete actions within the operational context.
8		Affordable	The cost of obtaining and using the measures is affordable vis-à-vis the benefits.
9	Specific Specific	Time perspective	The time from designing these indicators to the actually unwanted event has a large time frame. The project phase can be several years and the life time of and O&G facility is 20 years or more on the Norwegian shelf.
10		Causality	A proposed definition from (Webster, 1976) is as follows: “The interrelation of cause and effect; principle that nothing can exist or happen without a cause”. The causality is also present for early warning indicators. However, due to high degree of uncertainty, the degree of causality is rather low.
11		Uncertainty	If the unwanted event is taking place at the end of life it is reasonable to expect a high degree of uncertainty. A proposed definition of uncertainty is from (Christensen, Andersen et al., 2003): “Imperfect knowledge about the individual aspects of a system as well as the overall inaccuracy of the output determined by the system”. For early warning indicators there will be imperfect

No.	Generic/Specific variables	Criteria	Description
			knowledge and inaccuracy about the unwanted event. Nevertheless, when these indicators are identified and designed in the engineering phase, sufficient attention will be given to the unwanted event.
12		Complexity	There will be several disciplines both in project phase and operation phase that have a role for the early warning indicators. This will result in a complex coordination task. Therefore an early warning indicator comprises a high degree of complexity. The notion complexity is defined by (Johansen and Rausand, 2012) as follows: "A state of difficulty in determining the output of a system based on knowledge about individual inputs and given out current knowledge base". The difficulty for early warning indicators is situated in the coordination role.

Table 3 – Criteria for early warning indicators

Proposed approach for early warning indicators

In this chapter both an overall approach for developing a system for IPL is presented and further what is specific for the approaches for EWI in the project and operational phases. The application of EWIs is outlined in Figure 5.

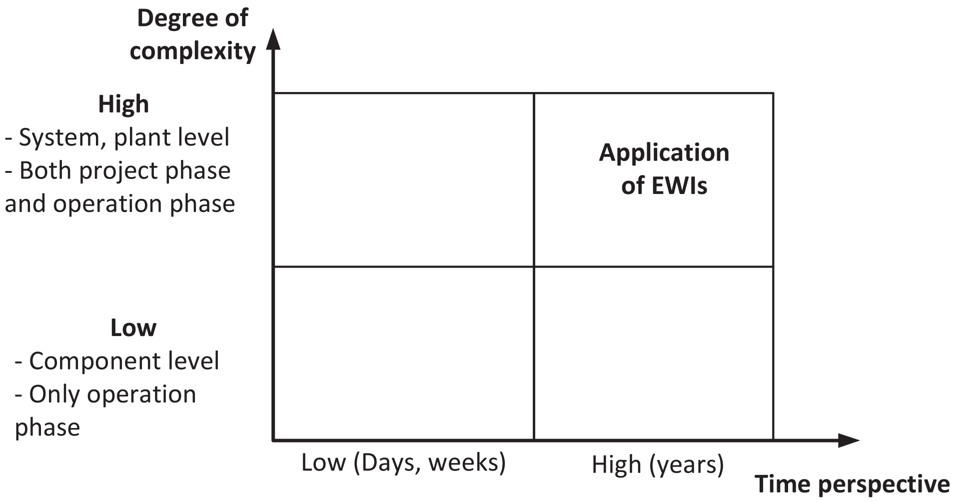


Figure 5 – Application of early warning indicator system

A proposed indicator approach for this situation is an aggregation tool for developing Technical Condition (Steinebach and Sorli, 1998). This approach has been further developed to the concept of Technical Condition Index (TCI) (Nystad and Rasmussen, 2006; Nystad, 2008; Nystad and Rasmussen, 2010). The early warning indicator system will be based on this aggregation principle. Further in this chapter, a generic approach is elaborated with additional details for the project and operational phases.

Generic approach

The generic approach consists of seven steps, outlined in Figure 6. Since this concept is novel and has not been implemented yet, this paper will not outline steps 4 and 7 any further. These steps can be further developed when empirical data is available.

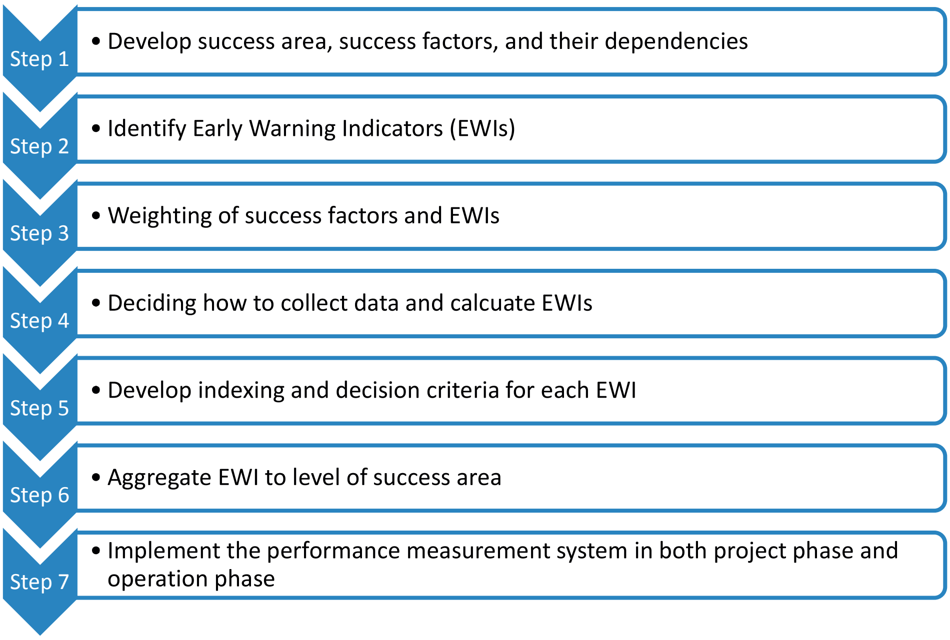


Figure 6 – Proposed steps for developing EWIs

Step 1: Develop success area, success factors, and their dependencies

To identify early warning indicators, a systematic approach is required. In this report the following assumption is made:

“If there is no drift from the success factors, the early warning indicators will be measured to be 100%, i.e. no early warning”.

In project management literature, project success factors are according to (Müller and Jugdev, 2012) one component of project success. Project success factors are defined to be (Müller and Jugdev, 2012):

“The elements of a project which, when influenced, increase the likelihood of success. In addition, these are the independent variables that make success more likely”.

The understanding of project success has evolved during the last decades. From the period in the 1960s-1980s, project success was perceived in terms of the iron triangle (Müller and Jugdev, 2012). The term “iron triangle” comprises measures of time, cost, and quality. Even though success is easy to measure through the iron triangle, both research and practice has departed from this view of project success (Toor and Ogunlana, 2010). Today the understanding of success is broader and comprises both the project and product life cycle (Müller and Jugdev, 2012). In this approach, success factors that influence the technical condition in the operational phase will be further elaborated. However the term success factor is now given a broader definition to comprise both the project phase and the operational phase:

“The elements of the project and operational phases which, when influenced, increase the likelihood of success in the operational phase. In addition, these are the independent variables that make success more likely”.

In this definition, the meaning of success is related to avoidance of unwanted events in accordance with Figure 3.

According to (Fortune and White, 2006) the inter-relationships between the success factors are at least as important as the success factors themselves. Therefore it is important to find a structured approach for this issue. (Salazar-Aramayo, Rodrigues-da-Silveira et al., 2012) have in a study elaborated factors in the petroleum industry that influence exploration and production (E&P) project management success. The method used was a structural equation modelling (SEM) method. In the proposed approach for EWI, the logic of constructing the success area in a path diagram are followed further, see Figure 7. First the success area is identified, next their interactions, and then the success factors for each success area.

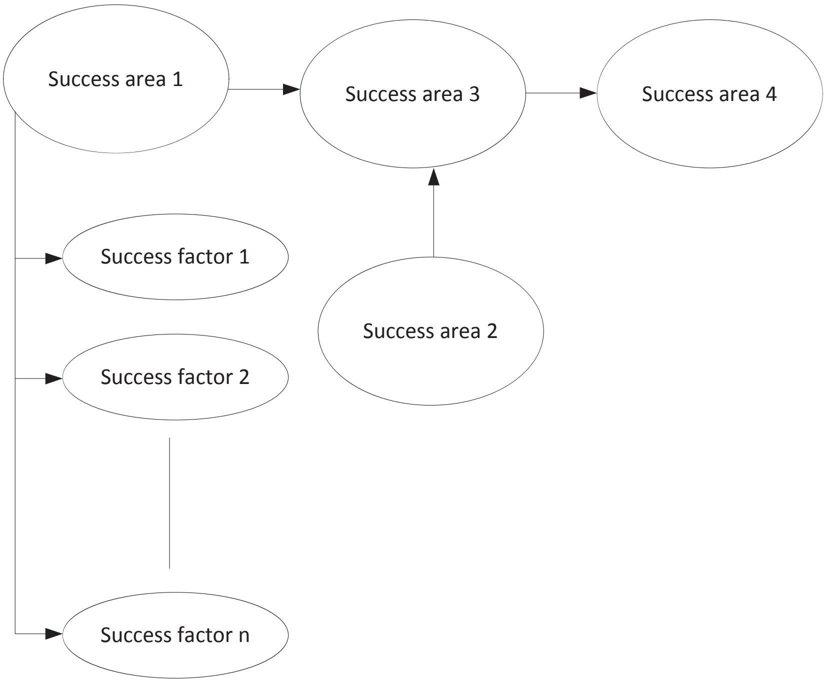


Figure 7 – Success area and their dependencies

Step 2: Identify Early Warning Indicators (EWIs)

The next step is to identify EWI from success factors. The logic is that the EWI represents measured attributes from success factors. These indicators should be structured in accordance with Table 4.

Success area Level 1	Success factor Level 2 and impact on technical condition	Measured EWI Level 3
Success area 1	Success factor 1.1 Brief description of how each success factor affects the technical condition	EWI 1.1.1
		EWI 1.1.2
	Success factor 1.2	EWI 1.2.1
		EWI 1.2.2
Success area 2	Success factor 2.1	EWI 2.1.1
		EWI 2.1.2
	Success factor 2.2	EWI 2.2.1
		EWI 2.2.2

Table 4 – Structure of success area, success factors and EWI with their expected impact on technical condition

Step 3: Weighting of success factors and EWIs

In this step, both each success factor category and EWI are weighted based on expert judgment. (Herrera, 2012) recommended eight criteria for indicators. These criteria have in this paper been assumed to be generic. If these criteria are fulfilled, it is assumed that these indicators have high quality. This quality shall be calculated as wi for each EWI. Based on expert judgment, each indicator is assessed with a quality evaluation form outlined with an example in Table 5. The maximum score is 24 possible points. The quality of success factors are also evaluated through weighting, but without a criteria list. This then gives wi = 3/3 for "high", wi = 2/3 for "medium" and wi = 1/3 for "low".

To what extent is EWI fulfilled by following criteria?				
Criteria	Definitions	High=3	Medium=2	Low=1
Meaningful	Indicators are relevant to technical condition and can be used to address what is happening to the system in a specific context. Indicators provide information which guides future actions.	X		
Sensitive	Indicators provide a clear indication of changes over a reasonable period of time.			X
Reliable	Indicators lead to the same interpretations when used by different people for the same situation. The interpretations are related to the system and its operational context.	X		
Measurable	The values of indicators can be rendered in a concise manner, either quantitatively or qualitatively.	X		
Verifiable	It is possible to confirm the correctness of the value or description of the indicators.	X		
Inter-subjective	Indicators are understood in the same manner by different people, either from the same technical community or from society at large.		X	
Operational	The indicators can be used to support concrete actions within the operational context.		X	
Affordable	The cost of obtaining and using the measures is affordable vis-à-vis the benefits.			X
	Total weight for indicator EWI	18/24 = 0,75 wi = calculated sum/24		

Table 5 – Example of filled-in quality evaluation form

Step 4: Develop indexing and decision criteria for each EWI

The calculated EWI values are transferred into indexed EWI values based on a transfer function as illustrated in Table 6. The transfer function can be both linear and non-linear dependent on the property of the indicator. It is important that experts agree upon the threshold values. In Table 6, the decision criteria are stated with a linear transfer function.

(Fortune and White, 2006) emphasize the importance of not treating the success factors as static. Therefore the threshold value may change with time.

Color code	Decision criteria	Threshold value
GREEN AREA	No early warning. The technical condition is under control. Only further monitoring is necessary.	$66\% < \mathrm{EWIIndexed} \leq 100\%$ $< \mathrm{EWIcalculated} \leq$
YELLOW AREA	Early warning. Further analysis should be performed in order to have control of the technical condition.	$33\% < \mathrm{EWIIndexed} \leq 66\%$ $< \mathrm{EWIcalculated} \leq$
RED AREA	Alarm. The technical condition is unacceptable and immediate action must be taken.	$0 < \mathrm{EWIIndexed} \leq 33\%$ $< \mathrm{EWIcalculated} \leq$

Table 6 – Indexing and decision criteria for each EWI

Step 5: Aggregate EWI to the level of success area

This step will aggregate the EWI up to the level of success factors and success area. (Nystad and Rasmussen, 2006) propose following "weighted sum" aggregation principle:

$$\mathrm{EWI}_{\mathrm{Parent}} = \frac{\sum_{i}^{n} \mathrm{EWI}_{i} w_{i}}{\sum_{i}^{n} w_{i}}$$

This principle is based on the weights wi that is provided from the stakeholders. Figure 8 shows the overall structure of EWI. First, the success area is identified. Further the success factors are identified with its relevant EWIs. Then the EWIs are aggregated up to the level of success factors and finally the success area.

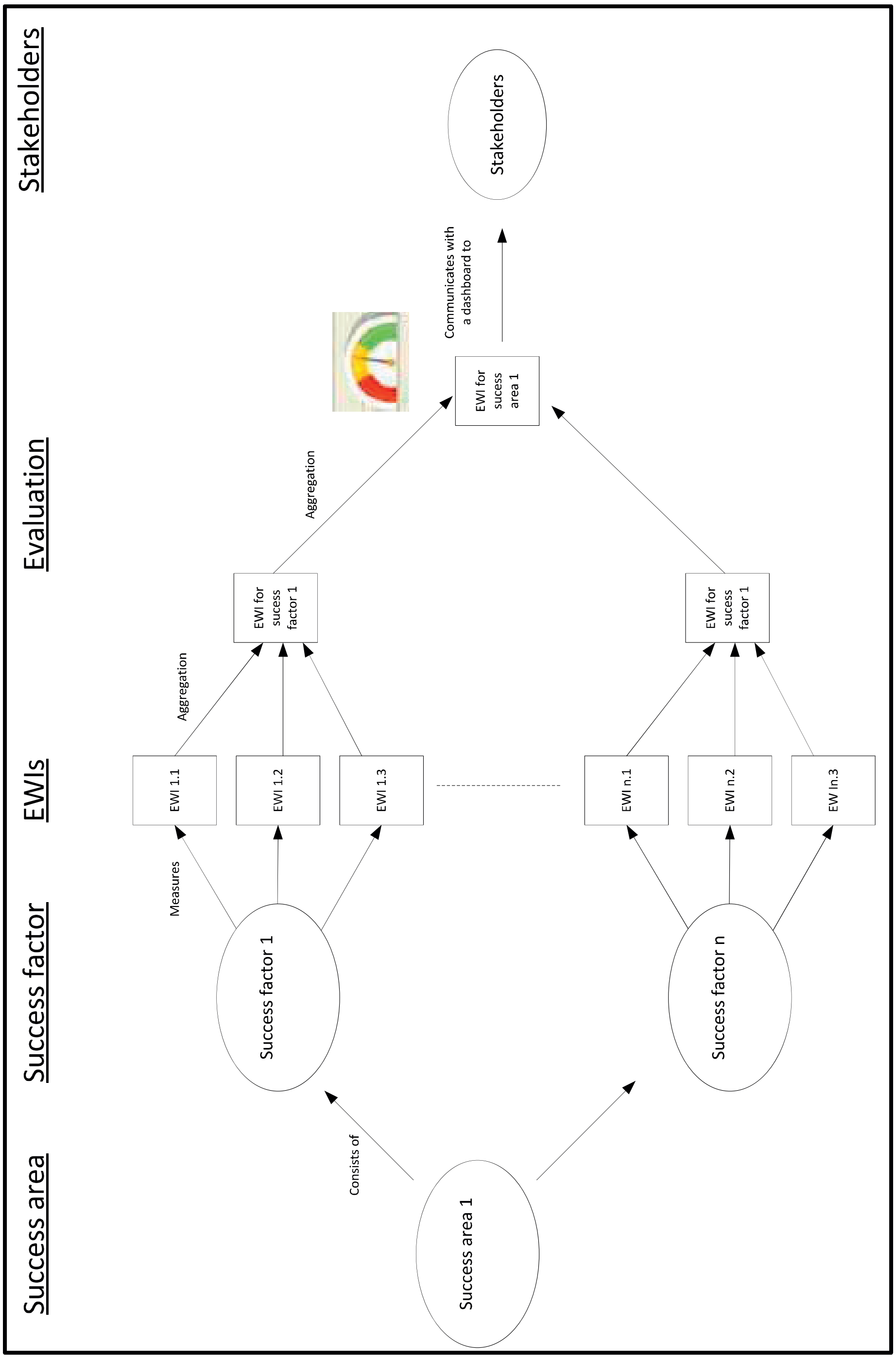


Figure 8 – Structure from success area to information to stakeholders

EWIs for the project phase

Step 1: Develop success area, success factors, and their dependencies

For the project phase, the construct is outlined in Figure 9 and motivated by the construct proposed by (Salazar-Aramayo, Rodrigues-da-Silveira et al., 2012). Project team, planning and control, quality and scope are success factors that were outlined to be areas that affected project management success and further corporate financial performance. In Figure 9, the two latter success areas (project management success and corporate financial performance) is replaced with project success in terms of technical condition. Further, it is also distinguished between the project phase and the operational phase, in accordance with Figure 3.

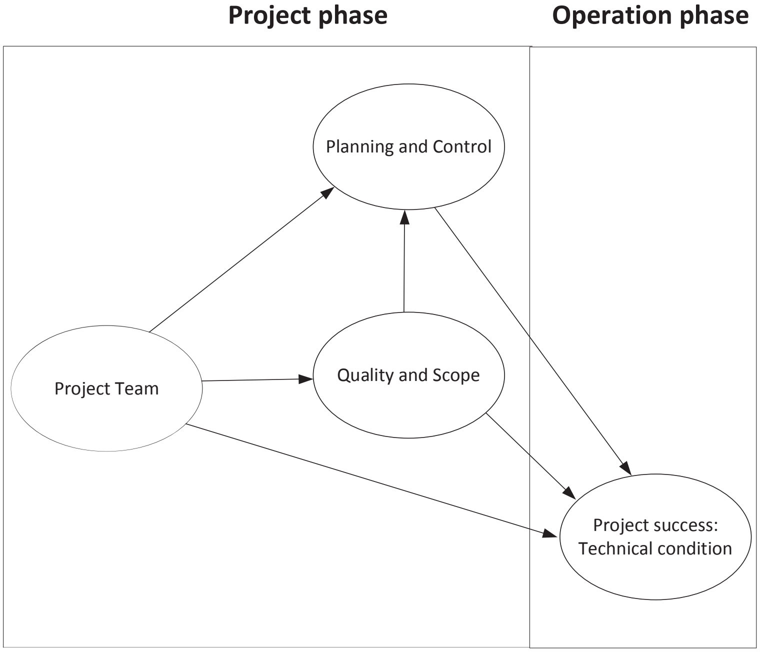


Figure 9 – Success areas for IPL in the project phase, motivated by (Salazar-Aramayo, Rodrigues-da-Silveira et al., 2012).

Step 2: Identify Early Warning Indicators (EWIs)

Table 7 outlines an example where the form of success area, success factors, and EWIs are filled in. Even though the success factors are only meant to be examples, they should be regarded as initial success factors and evaluated for further refinement by expert judgment.

Success area	Success factor and impact on technical condition	EWIs
Project team	Technical expertise in team. The technical expertise will provide knowledge to the team for the effect decisions in projects will have for the technical condition for the asset at the end of the project and during the operation phase.	1. Average age of technical personnel 2. Turnover of technical personnel
	Involvement in team. The involvement in team is important in order to achieve commitment from the rest of the project team for planning for technical condition.	3. Proportion of involved technical personnel 4. Number of overruled proposed solutions concerning technical conditions
	Coordination of project. When several interfaces that must be coordinated with the project team and number of disciplines in the project team increases, it will be more challenging to "harmonize" the language in order to plan for technical condition.	5. Number of interfaces in project team 6. Number of disciplines in project team
	Team communication. Team communication will be important to achieve a shared situational awareness for technical condition.	7. Evaluation of questionnaire of how good technical personnel communicate in the team 8. Number of published bulletins regarding technical condition
Planning and Control	Planning and control for technical condition. The planning indicators discussed in chapter 2 will show the "progress" for achieving sufficient control of technical condition.	9. Backlog of approved technical drawings. 10. Backlog of inspection activity of the technical condition of the facility 11. Inspection results of the technical condition
Quality and Scope	Documentation for operation. Documentation shows if the project team has achieved control for technical condition in the project phase.	12. Technological Readiness Level 13. Quality for maintenance program 14. Quality of Early warning indicators for operation phase

Table 7 – Example of filled in form of with structure of success area, success factors and EWIs

EWIs for the operational phase

Step 1: Develop success area, success factors, and their dependencies

For the operation phase, the construct in Figure 11 is proposed.

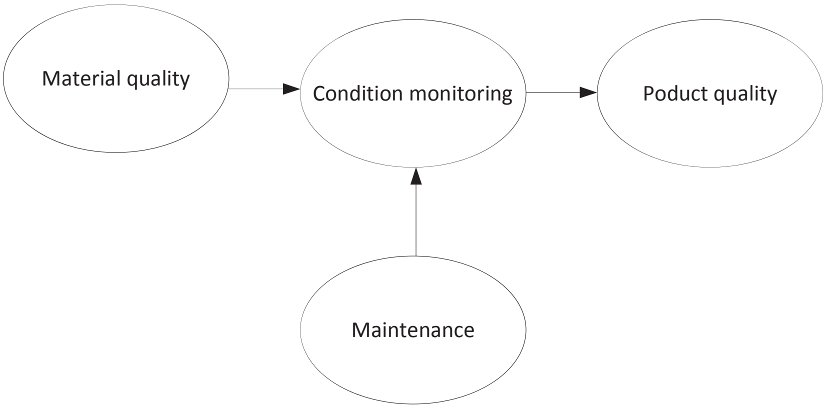


Figure 10 – Success areas for IPL in the operation phase

Each of the success area has different relevance for the technical condition:

- Material quality. The input material for the process will affect the technical condition. If the quality of the input material is poor, it must be expected that this affects the technical condition.
- Condition monitoring. This factor is the measurement of the technical condition itself. There exist several methods for condition monitoring. In this paper the condition monitoring methods are structured based on the approach proposed by (Utne, Brurok et al., 2012). This approach categorizes condition monitoring with the terms analysis, process monitoring, performance monitoring, inspection, and functional testing. These terms will be used as success factors.
- Product quality. The term product is reflecting the output of the process. This involves deficiencies in terms of scrapping and rework, but also other time losses such as reduced capacity and availability.
- Maintenance. If maintenance is not performed as planned and delayed, there will be a backlog and the technical condition will decrease.

Step 2: Identify Early Warning Indicators (EWIs)

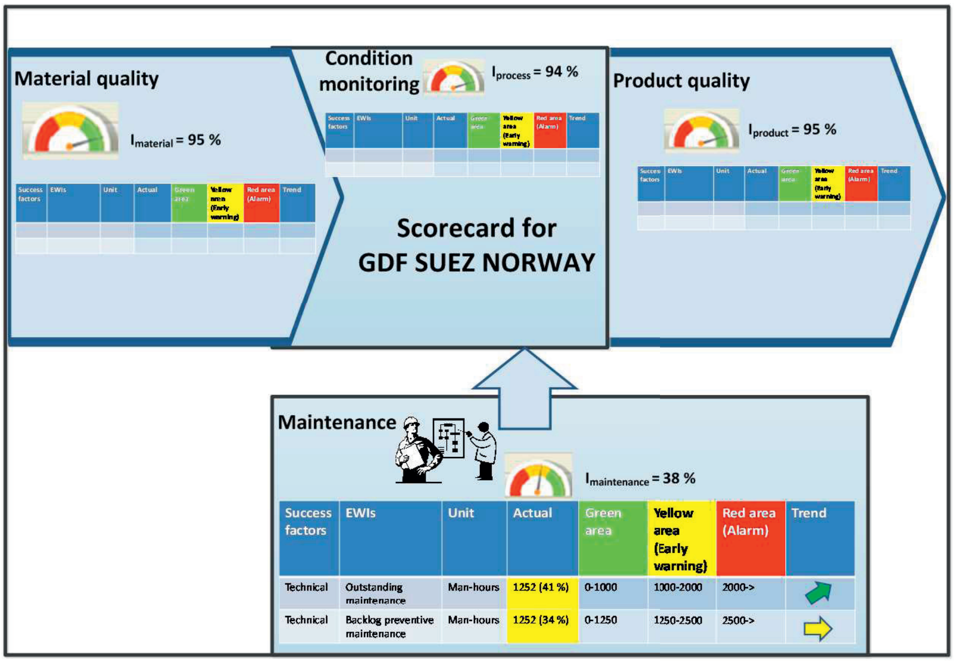
In the operational phase, the structure from success area to EWI is outlined in Table 8, filled with examples for success factors and EWI. Even though these are examples, the success factors for condition monitoring and maintenance is proposed to be final. This is due to the classification of condition monitoring proposed by (Utne, Brurok et al., 2012) where these categories are assumed to cover all condition monitoring methods. Further, the success factors for maintenance is structured in accordance with the maintenance standard for maintenance key performance indicators (CEN, 2007) and should also be regarded as generic factors applied for all assets. Poor maintenance and condition monitoring is expected to provide an early warning of insufficient control of technical condition. The success factors material quality and product quality could comprise several success factors since it is dependent on the type of asset. In Table 8 examples of EWIs are related to the O&G industry.

Success area	Success factor and impact on technical condition.	EWI
Material quality	Impurity of raw material. Raw oil which contains acid and sand particles can result in more determination than planned.	1. Amount of H2S in raw oil import at the facility 2. Concentration of sand particles in raw oil import at the facility
Condition monitoring	Analysis.	3. Result of analysis
	Process monitoring.	4. Corrosion monitoring in pipes
	Performance monitoring.	5. Efficiency of pump curve
	Inspection.	6. Measurement of wall thickness.
	Functional testing.	7. Number of failed function tests
Product quality	Scrap production. If the raw oil could not be sufficient processed due to e.g. deteriorated separator, the product has no longer the properties requested by the customer.	8. Amount of scrap production
Maintenance	Economic.	9. Budget maintenance cost/Actual maintenance cost
	Technical.	10. Backlog of preventive maintenance 11. Outstanding maintenance 12. Lead time of spares
	Organization.	13. Turnover of maintenance personnel 14. Average age of maintenance personnel

Table 8 – Structure of success area, success factors, and EWI with their expected impact filled with examples

Demonstration of concept

In this chapter, the EWI approach is demonstrated in terms of an EWI application with a proposed dashboard configuration shown in Figure 12. The construct of the dashboard is in accordance with the construct of success areas and their interactions. The empirical data is based on material from GDF SUEZ E&P Norway (GDF SUEZ, 2012). In the demonstration data of preventive maintenance and outstanding maintenance the company's decision criteria for green and red area are used.



Success factors	EWIs	Unit	Actual	Green area	Yellow area (Early warning)	Red area (Alarm)	Trend
Technical	Outstanding maintenance	Man-hours	1252 (41 %)	0-1000	1000-2000	2000->	↗
Technical	Backlog preventive maintenance	Man-hours	1252 (34 %)	0-1250	1250-2500	2500->	→

Figure 11 – Dashboard for early warning indicators in operation phase

For outstanding maintenance, the company has set the red area to be above 2000 man-hours and green area to be beneath 1000 man-hours. Further, for backlog preventive maintenance the red area is set to be above 2500 man-hours and green area to be below 1250 man-hours. The company does not specify a yellow area in their material for those indicators, but in the proposed approach, the current indicators for outstanding maintenance and backlog preventive maintenance is in the yellow area set to be 41 % and 34 %. In the dashboard it is assumed that these indicators have the same weight, thus the indicator Imaintenance is aggregated to be 38 %. In addition, it is possible to see the trend in the dashboard. For the user it might be of interest to analyze the EWI “backlog preventive maintenance” further due to the yellow arrow indicating no improvements during the last period. From the dashboard configuration it could then be possible to have an interface for the specific trends for each EWI. Figure 13 outlines the trend developed by GDF SUEZ E&P Norway. Even though the EWI is yellow and per definition an early warning, it seems to have been stable for four registrations. However, as long as this indicator is yellow it must be treated as an early warning indicator.

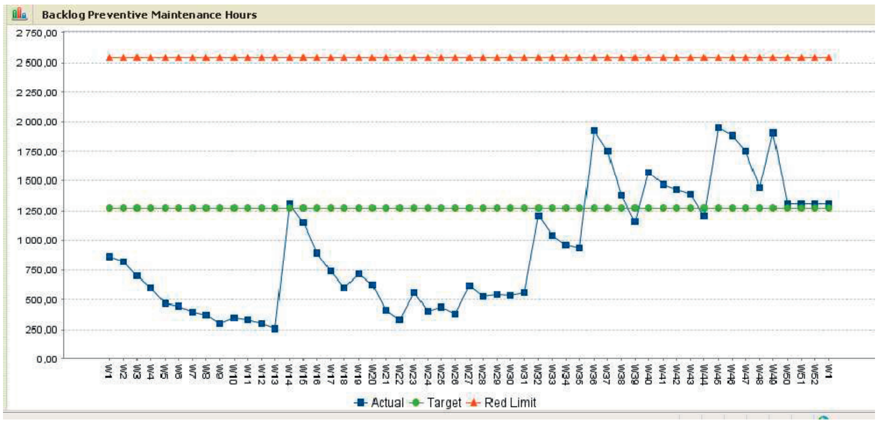


Figure 12 – Backlog of preventive maintenance measured in man-hours.

Conclusion

This paper has proposed a concept for EWIs for IPL. However, since this concept is novel in the O&G industry, it is expected that other scientific contributions could further develop this topic in the future. Aspects that should be further evaluated could be:

- Established terminology for early warning indicator. Could this be further verified by industry?
- What is the time perspective from early warning to unwanted event?
- Are there any permanent "damages" when an indicator is yellow for long time?
- How specific is the decision criteria from early warning indicators?

Finally, future research for this topic should be empirical case studies that can verify the concept and further elaborate the steps, especially step 4 (how to collect early warning indicators) and step 7 (implementing the performance measurement system in both the project phase and the operational phase).

Acknowledgements

This paper has proposed an early warning performance measurement system for IPL. The data material that has demonstrated the concept is based on the maintenance history from GdF Suez. The authors would like to thank Erik Winge from GDF Suez for this contribution and comments. In addition, the authors would like to thank for the funding from the research programs “IO2 – Integrated Planning and Logistics” and “T3 – System Integrity and Dynamic Risk Assessment” in the IO Center (Center for Integrated Operations in the petroleum industry). The contribution in this paper is expected to yield benefit to both of these research programs.

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Article 11

Improving maintenance by profit indicators

Improving maintenance by profit indicators

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Abstract

With the challenges of "silo thinking" in production and manufacturing, several disciplines and departments perform activities that affect each other, which can lead to suboptimal results in production with respect to extra costs and lack of production assurance. For maintenance management, silo thinking may result in unplanned maintenance activities, which may impede production plans. As a remedy to avoid this challenge, a key performance indicator (KPI) for maintenance management has been developed and is denoted as profit loss indicator (PLI). The purpose of this research was to investigate how this indicator can be further developed with more perspectives of concepts of Toyota Production System and Six Sigma. In particular, this PLI is evaluated for a relevant example in the industry with a case study. Results from both literature and case study are used to build further on the PLI concept.
Keywords: profit loss indicator, maintenance management, zero defects.

1 Introduction

When the production department provides feedback to the maintenance department, there arises a need for an integrated planning (IPL) concept, which avoids the two departments' functioning as "silos." This phenomenon occurs when an asset with several disciplines and departments performs activities that affect each other [1]. Owing to poor coordination between the maintenance and the production department, the overall result may be suboptimal in terms of production volume, safety, and costs. A key performance indicator (KPI) has been developed for operating IPL. This KPI, denoted as profit loss indicator, (PLI) is based on a structured approach for measuring the financial loss due to a hidden factory in production [1].

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Hidden factory is an analogy for time losses in production and is calculated for the maintenance KPI of overall equipment effectiveness (OEE) [2]. These time losses, denoted as six large losses, are categorized into availability losses, which include (1) machine breakdown, (2) waiting period, (3) performance loss in terms of minor stoppages, (4) reduced speed, (5) quality loss in terms of scrap, and (6) rework [3]. In particular, quality losses were of interest in this research. Although the PLI concept has been partly tested in a case study for the saw mill industry [4], quality losses have not been tested and demonstrated [4].

In production, industry needs to meet specific requirements of its stakeholders – market and authorities. One particular requirement of different stakeholders is compliance with zero defect manufacturing (ZDM). In fact, the requirement relates to the quality of not only products but also management systems [5]. This has been coped with in traditional quality management programs such as the Six Sigma methodology, which systematically gets as near as possible to “zero defects” (ZD) [6]. However Wang [7] claims that this is not sufficient for reaching ZD in manufacturing. The reason is limitation in the program in dealing with complex and dynamic data sets. This can be partly explained by the dynamic and complex nature of current production. It is, therefore, necessary to have a toolbox that can gather and process data and present the processed data in real time. The result is faster and better decision-making in production. However, aiming for the application of real-time data is not in conflict with existing management programs, and should be regarded as inclusive instead.

The aim of this article is to evaluate how ZDM is related to the concept PLI, partly based on literature study and partly based on discussions with managers in the machine tool and smelting plant industries. It is common to these industries that they have both worked systematically with approaching ZDs in production.

The structure of the remaining article is as follows: In Section 2, the concept of ZDM is discussed in detail and its relation to Toyota Production System is provided. Further, in this section, the hidden factory is presented with the maintenance KPI OEE and how it is related to ZDM is discussed. In Section 3, PLI is evaluated on the basis of discussions in the industry, and the final conclusion is drawn in Section 4.

2 Toward ZDs and minimizing PLI

In addition to the concept of Six Sigma, the concept of ZDs is found in other traditional concepts such as total productive maintenance (TPM) [2], quality management, and ZDM. Quality measurement can be provided by statistical indexes like process capability index and minimum process capability index typical of statistical process control (SPC). SPC is based on the idea of monitoring a variation in a feature to distinguish between natural variability and variation due to assignable causes; the detected variation due to assignable causes is meant to be eliminated and provides hints for further process improvements. As its name reveals, SPC is based on statistics and requires a certain number of measurement values/products to achieve statistically significant statements on which decisions can be based.

Therefore, companies that produce in small batches struggle to provide demanded statistical indexes and assure the quality of small-batch production; to help these companies in coping with these issues the process needs to be stable. A stable process is one that is only subject to random causes or one in which the controlled quality feature follows a time-invariant distribution. Second, a process is capable if a stable process has demonstrated to realize a quality feature that fulfils the requirements. The application of control charts is a common method to keep a process capable.

From TPM perspective, Nakajima [2] stated that ZD is a US concept that is an individual activity and became popular in Japan in 1965. The first Japanese firm to implement it combined it with Japanese-style quality circle and small group activities. Japan Institute of Plant Maintenance (JIPM) endorses small groups that are autonomous based on the ZD model advocated by Professor Emeritus Kunio Odaka of Tokyo University [8]. This is also in accordance with recent literature study of TPM by Ahuja and Khamba [9], who support autonomous maintenance as a TPM pillar. In addition, they list quality maintenance as another pillar that fosters an operator's skills in terms of achieving ZD. Therefore, it should be no surprise that in the concept of ZDM, a methodology has been developed that considers the manufacturing industry as a sociotechnical system [10]. The methodology, called SEISMIC (stabilize, evaluate, identify, standardize, monitor, implement, and control), has been tested successfully for a complex automotive part; it significantly reduced defect rates and produced anecdotal results in terms of greater job satisfaction and ownership of work.

In ZDM approach in manufacturing, it is important to specify the terminology for the word "defect." It has been claimed that the definition of ZD is zero failures during operations in the field, but not necessarily zero imperfections, blemishes, or nonconformities [11]. This is also supported by Tils, who explains ZDs as products without perceptible failure or malfunction during operation by the end user [12]. The word "failure" has been defined according to IEC 50191 [13] as the termination of the ability of an item to perform a required function.

Six Sigma can be regarded as a philosophy and a statistical method. The philosophy comprises a proven, data-driven suite of improvement methodologies, where tools support this philosophy with measurements and improvement tools for both processes and products [6]. The term sigma is a statistical term that indicates how far a process deviates from the desired measure. An important essence in Six Sigma Philosophy is that by reducing this variation, one can eliminate defects in production. The consequences of a successful application of Six Sigma in production are increased customer satisfaction, reduced operating costs, and reduced time loss in rework, which provides a bottom line of increased profit. If a company actually reaches a statistical six sigma level, the production process produces less than 3.4 Defects Per Million Opportunities (DPMO) and is considered to be a target in Six Sigma. Obviously, some variables in the industry may influence the realism of this target. One recent project that mainly focused on ZDM is the EU project IFaCOM (intelligent fault correction and self-optimizing manufacturing systems).

In Fig. 1, the IFaCOM concept is shown, which is adapted for the maintenance of an asset. Cognitive signal analysis, simulation, and behavior support the maintenance function of a company.

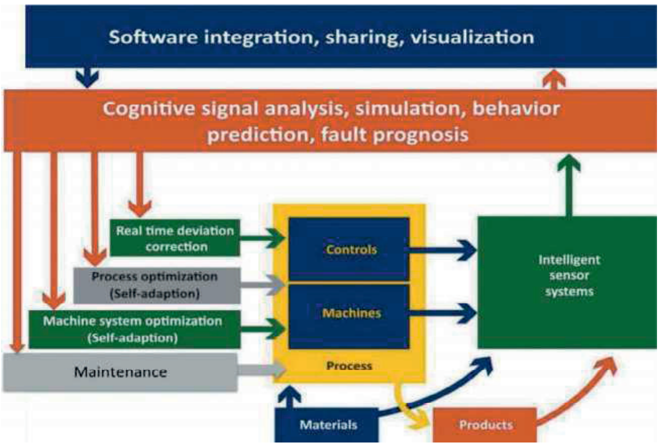

Figure 1: Adaption of IFaCOM for maintenance of an asset.

The framework is operationalized at the following three levels:

1. Short term: Closed-loop control based on in-process real-time measurement
2. Medium term: Process tuning and optimization
3. Long term: Machine system optimization

The framework also specifies that IFaCOM is vital for providing accurate and rapid feedback to maintenance. Overall, several maintenance types and maintenance concepts should be developed together with IFaCOM to establish the best practice in maintenance management in order to be a world-class maintenance company. The ZDM system in IFaCOM enables new opportunities in different approaches of maintenance by providing technological opportunities with real-time access to data from sensors. It also bears a clear relationship with Toyota Production System regarding wastes in production. One important type of waste is defects [14]. When a defect occurs, this might require repair or rework of the product and wasteful handling in terms of extra inspection.

The metaphor “hidden factory” can be traced to Nakajima, a former Vice Chairman of JIPM, who stated that OEE is a measure for “unlocking the hidden factory” [15] and provided a specific calculation approach for OEE [2]. In recent times, the OEE has been associated with a similar metaphor “hidden machine,” promoted by Koch [3]. Koch extends the definition to argue that availability losses should also comprise planned downtime such as breaks and preventive maintenance. Although this updates the OEE calculation, it should still be considered a part of the "hidden factory". This category comprises time losses when an equipment is stopped for planned maintenance. An overview of different classifications of time losses in the hidden factory is shown in Table 1 [3].

Table 1: Time loss categorization for OEE calculation [3].

Time category	**Parameters**
Availability	1. Machine breakdown
	2. Waiting period
Performance efficiency	3. Minor stoppages
	4. Reduced speed
Quality losses	5. Scrap
	6. Rework

As described in previous chapter, Six Sigma focuses on the following improvement process of Define, Measure, Analyze, Improve and Control [6]. More specifically, Motorola identified and measured extra costs of defects in terms of rework for postrelease defects. Hence, Six Sigma has a financial measure for DPMO. It can be mathematically expressed as the relationship between OEE and DPMO [15]. More specifically, quality losses in OEE can be calculated as follows:

$$\mathrm{DPMO} = \frac{\text{Number of rejected parts}}{\text{Total number of parts produced}} \times 1{,}000{,}000, \tag{1}$$

$$\mathrm{OEE}_{\mathrm{Quality}} = 1 - \frac{\text{Number of rejected parts}}{\text{Total number of parts produced}} \times 1{,}000, \tag{2}$$

$$\mathrm{OEE}_{\mathrm{Quality}} = 1 - \mathrm{DPMO} \times 10,000. \tag{3}$$

3 Demonstrating PLI through ZDM strategy

The PLI concept has been developed and tested earlier partly in the saw mill industry [4]. In this article, the PLI cube is evaluated with an adopted version shown in Fig. 2. Further, in this section, PLI is evaluated on the basis of discussions with the industry related to the quality part of OEE.

ZDM is influenced by the maintenance function of a company. This is also supported by discussions with a maintenance manager within the machine tool industry. For this industry, a case study is performed for a machine, where PLI calculation is planned for demonstration. In this case study, unplanned downtime of a machine is evaluated. The result is corrective maintenance, and the following assumptions are made; a failure in a machine requires corrective maintenance, production personnel might be required to work overtime, time loss might cause some delay in product delivery to the customer, and the downtime in the machine might affect other machines in the process.

From a maintenance perspective, this situation first affects the availability, part, and resource consumption of the PLI cube. The first aspect that calls for the calculation for PLI is labor costs for maintenance personnel and resource consumption in terms of spare parts and tools. The next aspect that might need to be looked into is standby cost for production personnel. This situation occurs when production personnel have no other tasks to perform during machine downtime. Furthermore, the downtime might cause a delay in production, which requires production personnel to work overtime. If, despite the overtime, the products are not made within the due date of delivery, a penalty might be imposed by the customer. This means that the customer would not be willing to pay the same price for the products and is then considered to be a turnover loss in availability.

The extent to which unplanned downtime is correlated to ZDs in manufacturing has been discussed. This depends significantly on the stage in which process unplanned downtime occurs. If this takes place in the first stage (i.e., the processing of raw material), this correlation is considered minor. At this stage, a machine has a robust system that does not cause a defect when unplanned downtime occurs. However, this situation is not the same in the end processes for finished goods. This correlation is believed to increase significantly in the end process. At this stage of the manufacturing process, unplanned downtime and corrective maintenance would be indicators of future defects in manufacturing.

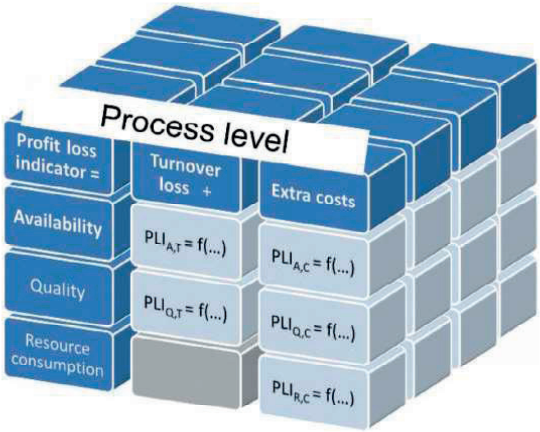

Figure 2: PLI cube adopted from Rødseth et al. [4].

Although ZDM is unique for a specific industry, the ZDM strategy has some synergies with other industries such as the process industry. In particular, discussions were carried out with a casthouse manager at a smelting plant and valuable feedback gathered. Overall, PLI is a valuable planning tool, but other tools are also necessary to cover the needs of the planning function. In addition, it is important to consider carefully how PLI will be applied together with existing KPIs in the company. In a ZDM strategy, it is necessary to have leading KPIs for PLI that are considered to be the drivers of the PLI value. In a process plant, process variability would be such a driver. In addition, it is important to understand the requirements in production. For a smelting plant, high volume is one of the requirements and must be balanced with the requirement to reduce defects in production.

4 Concluding remarks

In this article, the relationship between ZDM and the PLI concept has been evaluated. On the basis of literature study, the relationship between DPMO and OEE is clearly established. Furthermore, maintenance activities, such as machinery breakdown, might cause defects in production. In particular, discussions with a maintenance manager in a machine tool industry support this correlation. The process industry, for which the ZDM approach is also relevant in terms of having ZDs in production, might be pressurized to produce high volumes, which may compromise ZDs in production. Further research would require more field studies for these two industries, where PLI is demonstrated in combination with leading KPIs and drivers such as process variability.

Acknowledgments

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Article 12

Data-driven Predictive Maintenance for Green Manufacturing

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Data-driven Predictive Maintenance for Green Manufacturing

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***Abstract*—With the current situation of high demand of sustainable manufacturing, different stakeholders have clear expectations for more environmental manufacturing and at the same time minimizing the operational costs. The role of maintenance plays a key role in the path towards sustainable manufacturing. For achieving green manufacturing, more data-driven predictive maintenance strategies is needed and is expected to reduce energy consumption, maintenance resources in terms of spare parts, and reduction of consumables in terms of example lubrication. The overall bottom-line for the predictive maintenance strategy is increased availability, reduction of maintenance hours in terms of reactive maintenance activities, and increased profit for the manufacturing business. For a predictive maintenance strategy, it is crucial to develop Key Performance Indicators (KPIs) for the maintenance management. Today, common KPIs such as availability and different indicators for maintenance cost has been developed. When aiming for more green manufacturing, a more integrated application of maintenance KPIs are needed. Today, the KPI Profit Loss Indicator (PLI) has been developed and demonstrated in the saw mill industry and is regarded to support a more integrated approach in terms of Integrated Planning (IPL). The aim of this article is develop a structured approach for data-driven predictive maintenance aligned with the concept of PLI. Through a case study, the approach is partly demonstrated for the manufacturing industry. The results in this demonstration shows that the data-driven maintenance strategy will have a positive impact of the PLI value and provide a sustainable manufacturing in long-term.**

Keywords*—*Green Manufacturing; Integrated Planning; Maintenance Management; Predictive Maintenance

I. INTRODUCTION

In today's manufacturing companies, there has been an increased pressure to think beyond traditional economic measure and also evaluate environmental effects of the business [1]. From the European Commission it has been set up a target of sustainability [2]:

1. 20 % of energy from renewables
2. 20 % increase in energy efficiency

Furthermore, it is through an overall objective in the research programme Factories of the Future to promote the targets within EU 2020 for a smart, green and inclusive economy [3]:

- Energy- and resource-efficient manufacturing processes.
- Socially sustainable, safe and attractive workplaces.
- High-tech companies involved in innovative manufacturing.

The role of maintenance should affect all these targets with implementation of predictive maintenance. A possible definition of sustainable manufacturing can be [4]: *"The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound."*

The role of maintenance is crucial in green manufacturing. For example in the aerospace industry, it is through life cycle assessment (LCA) found that the environmental impact of the maintenance phase is of importance and can not be ignored [5]. It is further concluded that although this industry has the highest reliability and safety requirements, there is more challenges in order to have a sustainable approach at the design stage. Also, an value stream mapping approach for the maintenance process in this industry has been performed [6]. Based on this analysis, it was possible to calculate an indicator for sustainability. The value from the indicator and the graphical representation of mapping of the value stream makes it is possible to identify the potential problem area and apply a so-called 6R method for improving the sustainability. This method considers 6 different approaches for improving sustainability [7]. In addition to Reduce, Reuse and Recycle of products, this methodology also focuses on Recovering, Redesigning and Remanufacturing of the products during the lifecycle. If scrappage occurs of the end product, redesign of the machine center could be an option in the design stage. Furthermore, sustainable machining technologies is considered to be an important sustainability principle [7]. As an example for such technology is dry machining where analytical modelling of predicting tool-life is applied.

Another example of industrial application of sustainable maintenance is a joint maintenance decision-making and energy management method [8]. In this method the optimal maintenance interval from a reliability perspective is adjusted towards a time window when there is a peak-period for electricity cost. As a result, the electricity cost of manufacturing system can then be reduced. This method was further successfully tested in an auto assembly line.

From the project Green Monitor, the authors endorse predictive maintenance as an important strategy for sustainable manufacturing [9]. In this project, it is for example investigated how consumption of hydraulic oil of a machine tool can be reduced. The plan in this activity is to change from traditional time based preventive maintenance towards predictive maintenance. By measuring relevant variables such as water content and degree of particles in the hydraulic oil, it is possible to calculate the remaining useful life (RUL) of the hydraulic oil and change it later than the conservative maintenance interval given from the supplier. When the hydraulic oil is changed only when necessary, it is assumed that it will be a substantial savings in waste of lubrication oil. Predictive maintenance strategy has also been demonstrated of its effectiveness in the semiconductor industry [10]. In this industry, RUL estimation for lenses was performed where the estimated and actual RUL values where compared. This predictive maintenance strategy would more optimally schedule the maintenance activities, resulting in reduced waste of energy and materials and hence increase the sustainability. Within predictive maintenance, application of Soft Sensors is also of interest where computer programs supports sensors to be more predictive in nature. An interesting class of Soft Sensors is data-driven [18].

A green and sustainable maintenance system model has been established in order to achieve the purposes of green maintenance [11]. The objective for green maintenance is among others to reduce energy and save resources. These objectives can be achieved by implementing several types of measures:

- Legislation law from authorities
- Technology measure
- Management measure

In a green maintenance system model several topics are of interest in order to achieve green maintenance [11]:

- Maintenance process
- Maintain equipment
- Consumption of energy
- Consumption of material
- Maintain material

In addition, a Venn diagram has been developed for visualizing the green maintenance concept model [12]. This model is shown in Figure 1 and covers the traditionally conceptual model of sustainability with environmental, societal and economic factors.

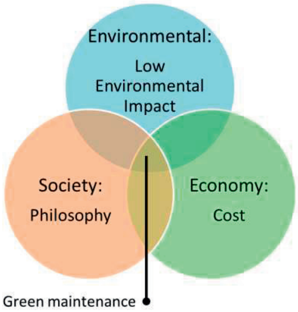

Fig. 1. Green maintenance conceptual model [12].

It has also been proposed a concept of sustainable maintenance management (SMM) and is defined as [13]: *"…all required processes for ensuring the acceptable assets condition by eliminating negative environmental impact, prudent in using resources, concern for the safety of employees and stakeholders, while at the same time economically sound."* One challenge with SMP is the lack of linkage between maintenance as a support function and corporate objectives. As a remedy, a proposed measuring system for sustainable maintenance performance has been established [13]. Although the levels corporate, tactical and functional levels were established, it is need for further development of suitable Key Performance Indicators (KPIs).

A promising KPI that measure the status of the green aspect in manufacturing is the Profit Loss Indicator (PLI) [14]. By measuring the unintended time losses and waste in manufacturing, this KPI should represent to what degree the manufacturing is sustainable. PLI calculation has been tested before in manufacturing industry [15]. In order to justify these savings, it is crucial that PLI can be documented and traced where the potential of the savings are.

The aim in this article is to develop a structured approach for data-driven predictive maintenance that is aligned with the concept of PLI.

This article is organized as follows: In Section 2 data-driven predictive maintenance is introduced. Further in Section 3, the PLI indicator is introduced. In Section 4 the case study is described with results from PLI calculations. Further in Section 5 an structured approach for data-driven predictive maintenance is developed and discussed. Finally in Section 6, future aspects are discussed with concluding remarks.

II. DATA-DRIVEN PREDICTIVE MAINTENANCE

Condition-based maintenance (CBM) is a maintenance strategy that can improve the availability and avoid unnecessary maintenance actions [16]. This maintenance strategy can employ prognostics approach in the maintenance decision where RUL is estimated. A proposed taxonomy for predictive maintenance is shown in Figure 2 adapted from[16]. This taxonomy should be aligned with the maintenance terminology standard NS-EN 13306 [17]. In this standard predictive maintenance is a type of condition-based maintenance.

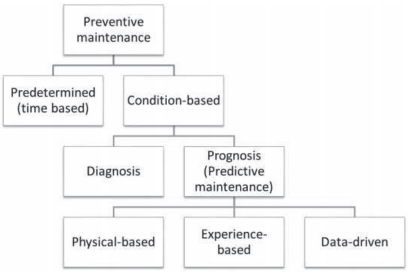

Fig. 2. Taxonomy for predictive maintenance adapted from [16].

From the process industry, it has been performed a literature review of how sensors should comprise capabilities for computational learning and accurate process data and insight in process knowledge [18]. Figure 3, which is based on the investigation from Kadlec [18], shows examples of which topics that would be dealt with both from the process industry perspective and the computational learning perspective.

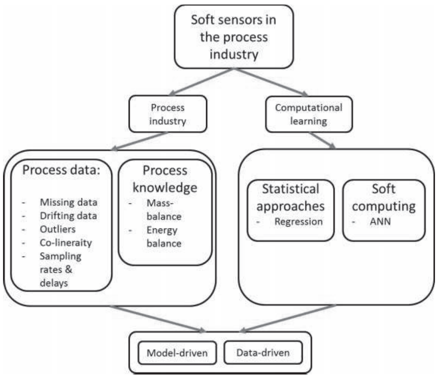

Fig. 3. Topics covered for developing both a model-driven and data-driven structure modified from [18].

From process industry, both process data and process knowledge must be further investigated. Process knowledge is also specified into several expertise of science such as mass balance and energy balance. The insight in these physical processes will be important to predict the technical condition of the equipment.

For process data, several phenomena must be identified and minimized. The missing data can be represented with a variable with constant value 0. The cause of missing data could be failure of a hardware sensor. Data outliers are sensor values that deviates from a meaningful value. The taxonomy for data outliers is obvious outliers and non-obvious outliers. The obvious outliners are those values violates physical constrains. An example could be a negative measurement from a pressure sensor. A non-obvious outlier is not so easy to detect. These values do not violate any limitation but still do not reflect the correct variable state. Drifting data is another problem that occurs for process data. The causes for drifting process data can be categorized into two types:

- *Changes of the process*. The process undergoes a deterioration process and will have drifting data. An example could be decrease of flow from a pump due to abrasion during operation of the plant.
- *Changes from external conditions*. The external environment can change where for example the purity of raw material has decreased. This can also change the process state.

A common remedy for drifting process data is to apply a moving window technique. This technique will then update the model on periodical basis where only the most recent data is used. The data co-linearity is another problem in process data due to for example redundancy. In this case, two neighbouring temperature sensors will deliver strongly correlated measurements. This situation can cause an unnecessarily increase of complexity in the model where more data than the necessary required data is provided. The last problem of process data is sampling rates and measurement delays. Based on a procedure, measurement of some variables can be measured in a different point in time than others. This can cause a problem of synchronization when state of the process is evaluated. The measurement delays occurs when there is a process-related delay. An example could be the dwell period within a reactor. An approach to compensate this situation is to synchronize the variables. However, this synchronisation would require extensive process knowledge.

The data driven methods in Figure 3 can be both soft computing with artificial intelligence and use of statistical methods such as regression analysis. As an example of artificial intelligence could be application of Artificial Neural Network (ANN) that has been successfully applied for aerospace structures [19] and Wind Energy Conversion System [20].

III. PLI IN MANUFACTURING

PLI has been developed as a tool for Integrated Planning (IPL) between the maintenance manager and the production manager. The first step for developing this KPI was to evaluate Overall Equipment Effectiveness (OEE) with following question [21]: How much money is lost since we still have a hidden factory in terms of six big losses? Data from the smelting industry supported that the monetary form of OEE would be substantial. The next step in the smelting industry was to calculate the PLI value based on OEE. For example, minor stoppages, which reduces the OEE value, resulted in a loss of delivered volume to the customer measured in ton. By calculating this loss with the sale price in $/ton results in a PLI value for the minor stoppages in the smelting industry. Further research with case study from the saw mill industry lead to a model with representation of a PLI cube as shown in Figure 4 [14].

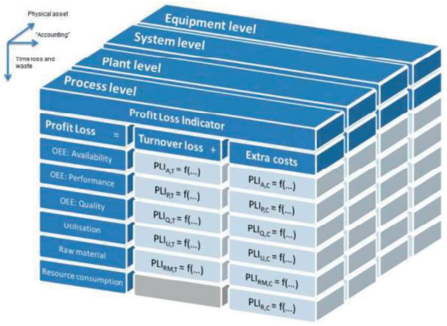

Fig. 4. PLI cube [14].

This cube represents all the variables that must be accounted for when calculating PLI. It has also been performed PLI calculation for the O&G industry [22] and also for qualitatively evaluation in the smelting industry and manufacturing industry [15].

The PLI indicator can measure several aspects of sustainability. The comparison between OEE and the waste categories from Toyota has also been performed [14]. In this comparison, following OEE elements is related to waste:

- Performance loss: Minor stoppage losses related to waiting.
- Quality loss: Defects and rework related to incorrect processing.

In addition, the environmental aspect is also covered through raw material and resource consumption in the PLI cube.

IV. CASE STUDY DESCRIPTION AND RESULTS

The purpose of the case study is to demonstrate the PLI model which is an essential step in developing a predictive maintenance concept. The specific case is a malfunction of an oil cooler in a machine center. This malfunction was first observed through a scrappage of the product in production and which also led to an unplanned downtime. The malfunction of the oil cooler led to instability of the production process and damaged part (scrappage). Before the malfunction of the oil cooler the temperature value increased significantly. After the scrappage of product, a quality audit meeting was performed to evaluate the cause and consequence of the scrappage. When the unplanned downtime occurred, maintenance personnel first inspected the machine and found out the cause of the downtime which was malfunction of the oil cooler. Then they took out the oil cooler from the machine and changed it with a new oil cooler. Due to anonymity, the specific time window for the unplanned downtime is not accurate. However, a realistic time window for such a downtime with 6 days is used instead.

The PLI results is shown in Table 1. The related PLI elements can be traced to both availability loss due to the unplanned downtime and the scrappage of damage part as a quality loss. Most PLI elements applied in for calculation is extra expenditures in terms of quality audit meeting and maintenance costs. The turnover loss in PLI is found from the loss of internal machine revenue which is an expected revenue for operating the machine.

TABLE I. PLI RESULT FROM CASE STUDY

Situation	***Type of PLI***	***PLI value***
Damaged part (scrappage)	*Quality:* Extra cost	120 000 NOK
Quality audit meeting	*Quality:* Extra cost	3 500 NOK
Maintenance labour costs	*Availability:* Extra costs	21 570 NOK
New oil cooler	*Availability:* Extra costs	47 480 NOK
Loss of internal machine revenue	*Availability:* Turnover loss	129 600 NOK
	Sum	**322 150 NOK**

The events occurring during the PLI events is further shown in Figure 5. As shown in the figure, the loss of internal revenue from machine will start immediately after failure of the machine is detected through damaged part (scrappage). In addition, it is a sequential activities of quality audit meeting and maintenance activities. During the maintenance activity, there is also a replacement of the oil cooler which contribute significantly to the maintenance costs and increased PLI.

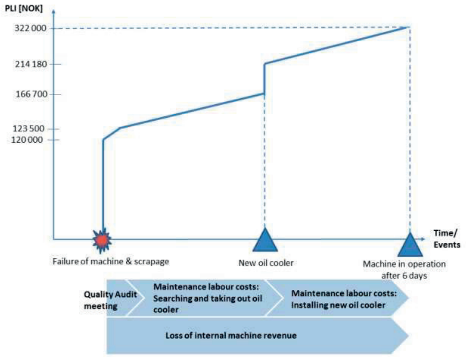

Fig. 5. PLI event of unplanned downtime.

V. AN STRUCTURED APPROACH FOR DATA-DRIVEN PREDICTIVE MAINTENANCE

Based on the insight of predictive maintenance and the PLI model, a structured approach for data driven predictive maintenance is proposed in Figure 6. In step 1 a hybrid model is applied for estimating RUL of the relevant component. In the case study, a first approach for building the hybrid model would be to use expert judgement. In this model, expert judgement would establish the threshold values from temperature curves of the oil cooler. Furthermore, this model could be built with physical models from thermodynamics and also data driven approach with use of e.g. ANN. In addition, the RUL estimate will not be a deterministic value but will instead be a stochastic variable due to uncertainty. A suitable approach for tackling this uncertainty would be to use three types of estimated values; worst case of RUL, most likely case of RUL and best case of RUL.

Further, in step 2 the estimated value of PLI is calculated for the unplanned event. Based on history data, PLI calculations such as shown in Table 1 would support an estimated PLI value. It is also possible to adjust this value when new information is available. For example, if it is expected that improved repair routines have been successfully implemented in the organisation, the expected maintenance labour costs could be reduced.

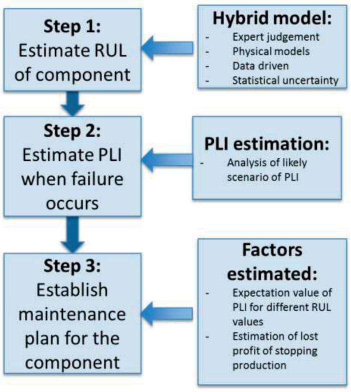

Fig. 6. Structured approach for data driven predictive maintenance

Further in step 3, the maintenance plan is established. Based on the different scenarios for RUL estimates (worst case, most likely and best case) and the estimated PLI, it is possible to propose different maintenance intervals and the expected PLI for each interval. These PLI values can then be further evaluated against production plans. From production plans it should be specified what would be the lost profit when the machine has planned downtime for maintenance. If this value is less than the PLI for unplanned downtime, the planned maintenance schedule should be performed. This would then also be an approach for IPL between production plans and maintenance plans.

VI. FUTURE ASPECTS OF PLI AND CONCLUDING REMARKS

This paper has demonstrated how PLI is calculated which will be a step in data-driven predictive maintenance. If RUL is estimated and taken into account for maintenance plan, this can in future reduce the PLI values for unplanned downtime. Reduction of this type of PLI value will also increase the sustainability aspect in green maintenance. For example, the environmental aspect will improve through e.g. reduction of scrappage which is considered as waste and associated disposal.

An important aspect which must be tackled in future is to enable accounting of the PLI in real-time. A challenge today is that due to both lack of technology and organizational factors, there can be delays for accounting the PLI value.

It is concluded that the structured approach for predictive maintenance should be investigated and developed further in detail. In particular it is of interest to demonstrate it for IPL.

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