Maintenance backlog for improving integrated planning

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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).

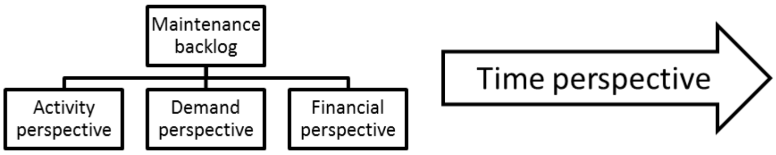


Figure 1 – Measurement of Maintenance backlog as a leading KPI can reduce the value of Profit Loss Indicator as a lagging KPI.

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).

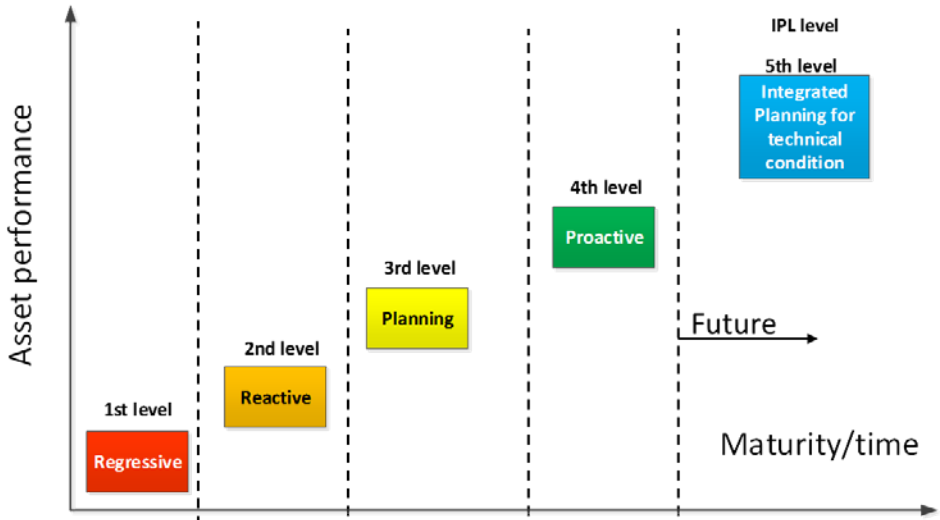
The above-mentioned challenges from both O&G and manufacturing industry have been approached by developing mathematical models and concepts. However, none of these offers KPIs as a tool for performing production planning alongside maintenance planning for a production system. KPI are the core of what 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 4^{th} 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.

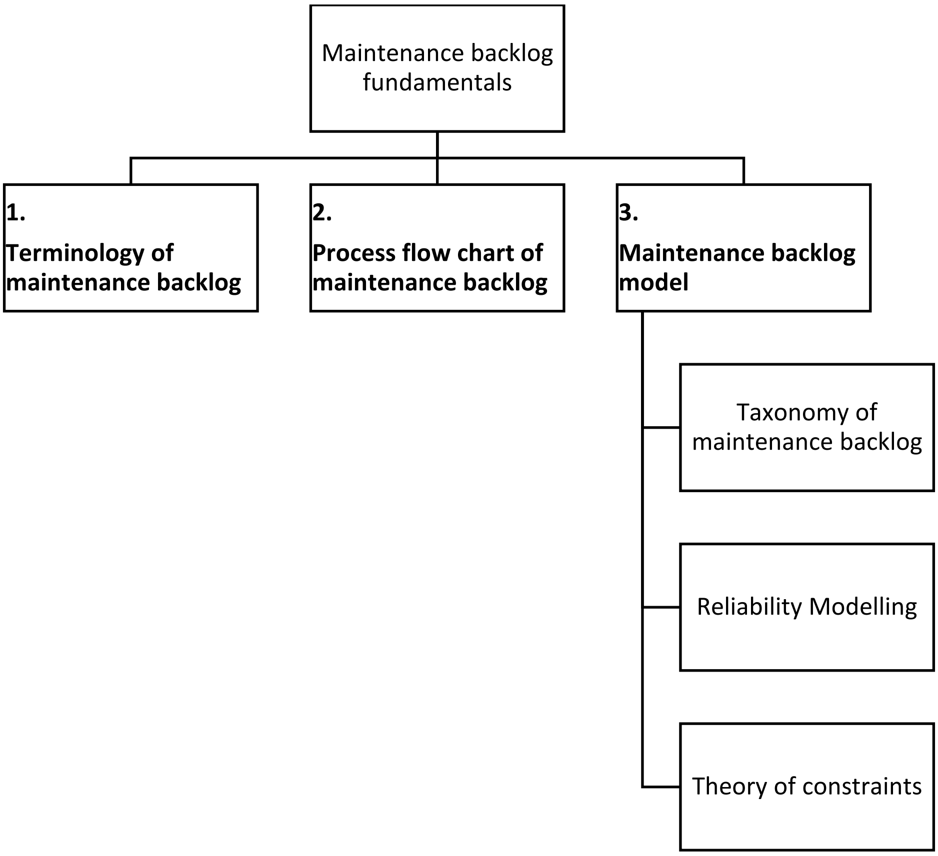


Figure 3 – Elements in maintenance backlog

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.

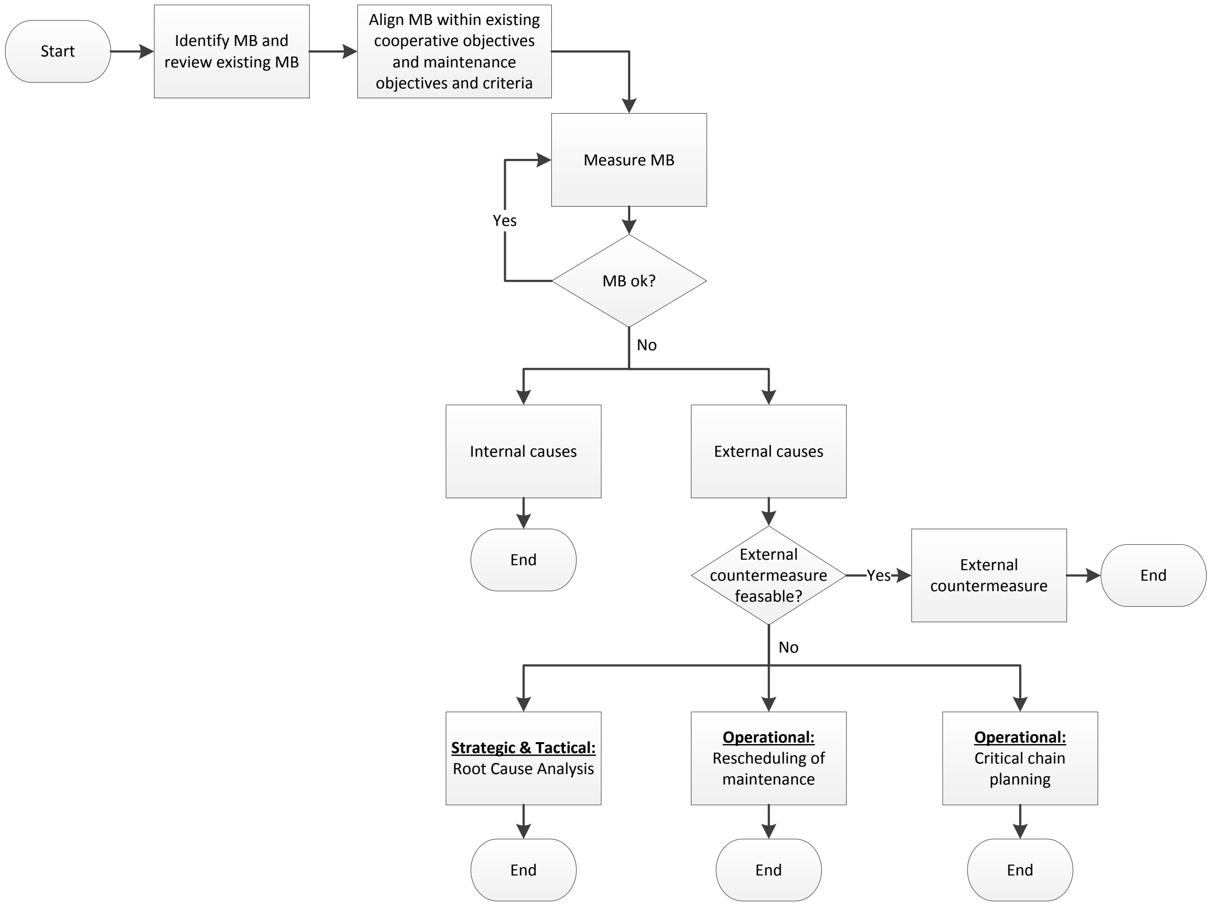


Figure 4 – Process flow chart of maintenance backlog

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.

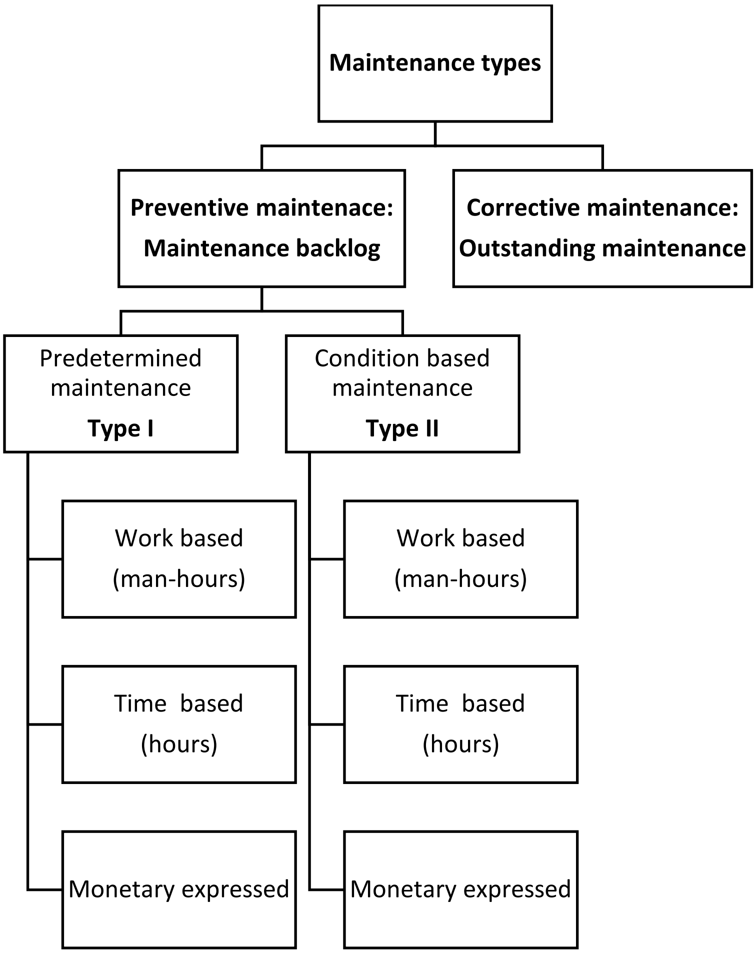


Figure 5 – Proposed taxonomy of maintenance backlog

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.

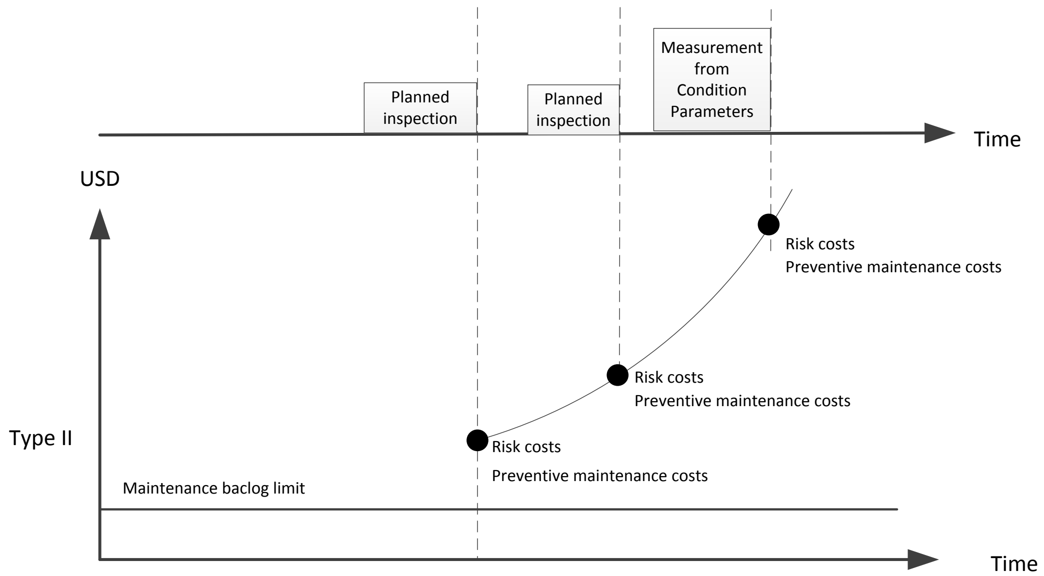


Figure 6 – Illustration of Type II maintenance backlog.

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.

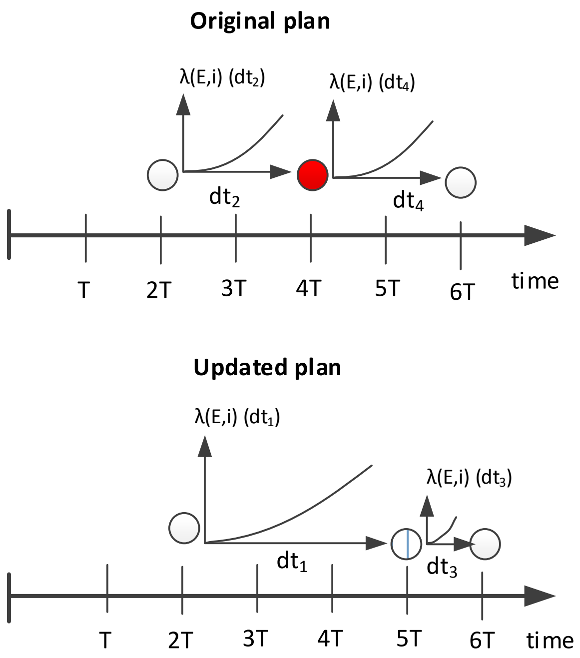


Figure 7 – Failure rate modelling with maintenance backlog (Rødseth, 2014)

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

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

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.

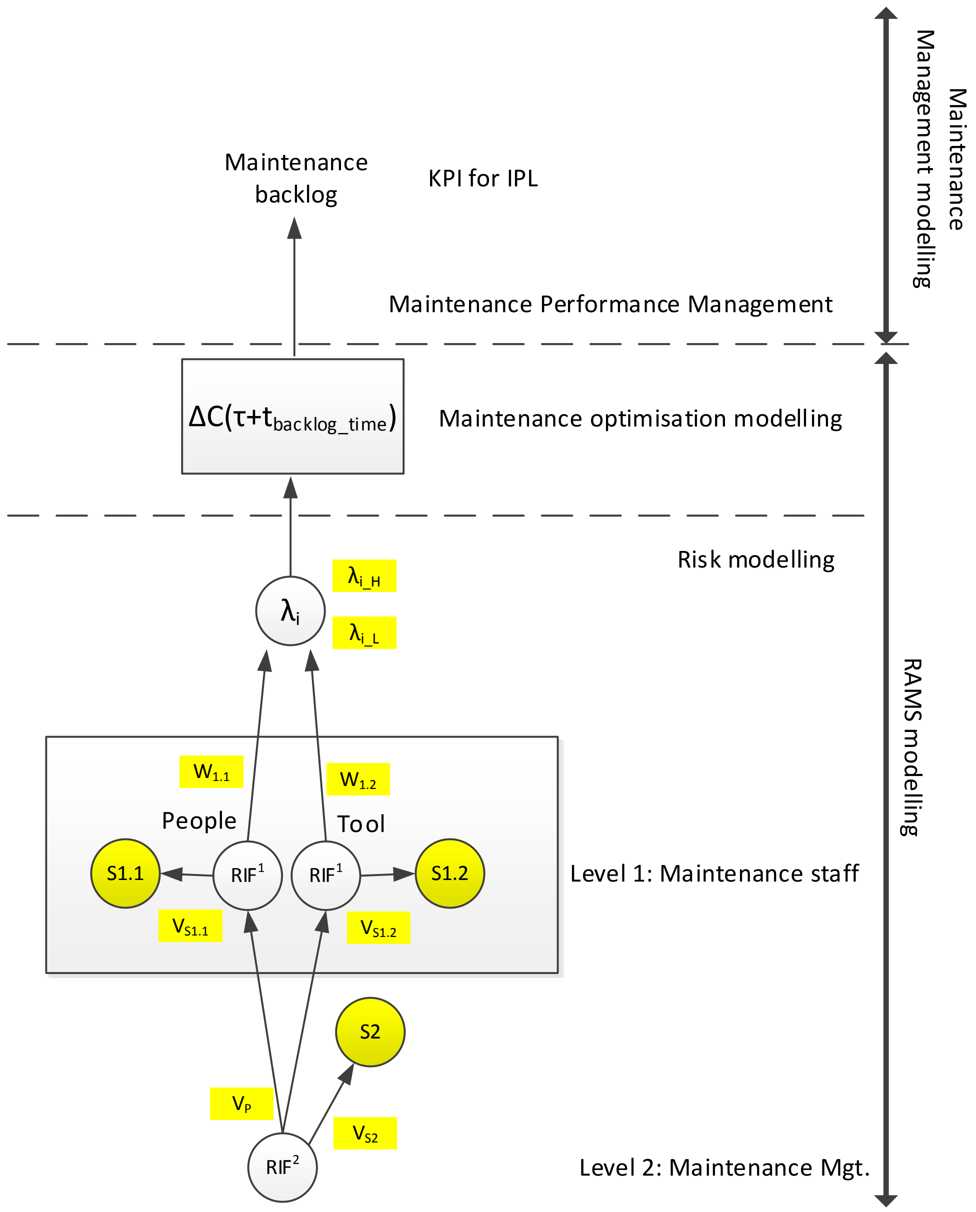


Figure 8 – Schematic modelling of maintenance backlog

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:

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

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

   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:

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

   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:

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

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

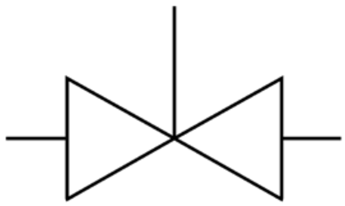
In O&G industry barriers and barrier management is regarded as important for major accident prevention. A set of principles for barrier management in the petroleum industry has been published (PSA, 2013). Furthermore, a report has also been published to increase the understanding of barrier management 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: $MB = t_1 - \tau$ where t_1 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: $MB\% = (t_1 - \tau)/(\tau_{limit} - \tau)$. When t_1 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.

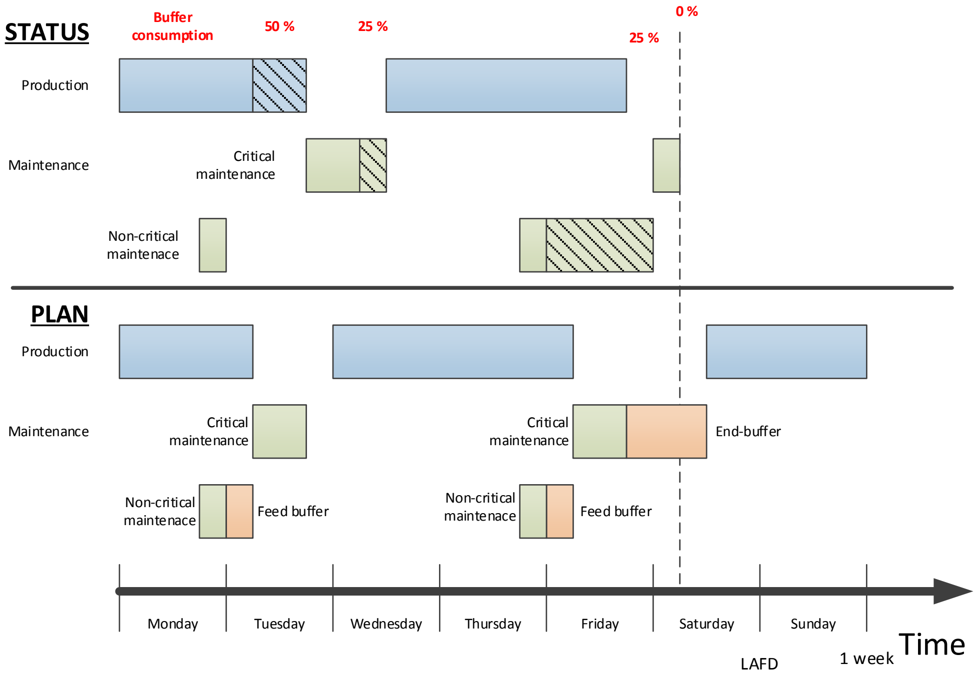


Figure 9 – Example of critical chain scheduling for IPL presenting both the plan and the status.

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.

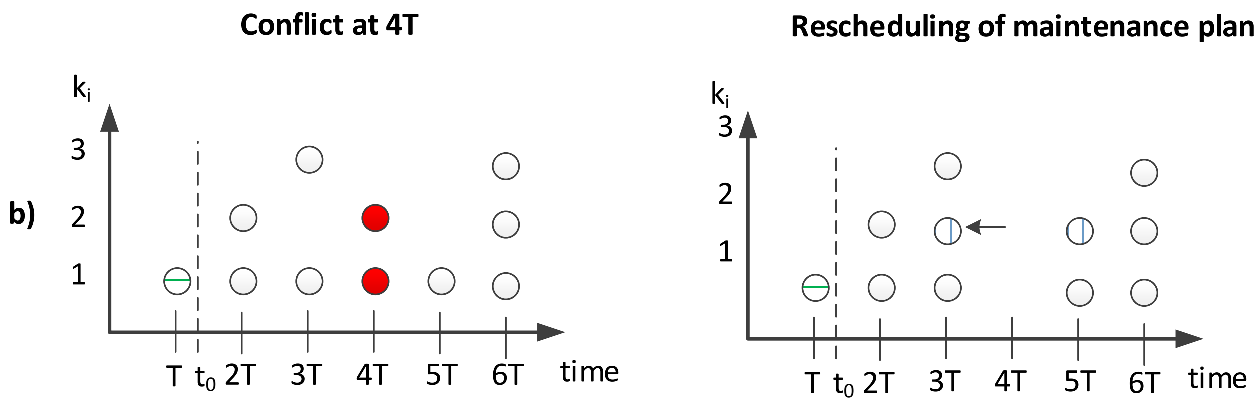


Figure 10 – Four rescheduling options for maintenance backlog at 4T adapted from (Rødseth, 2014).

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.

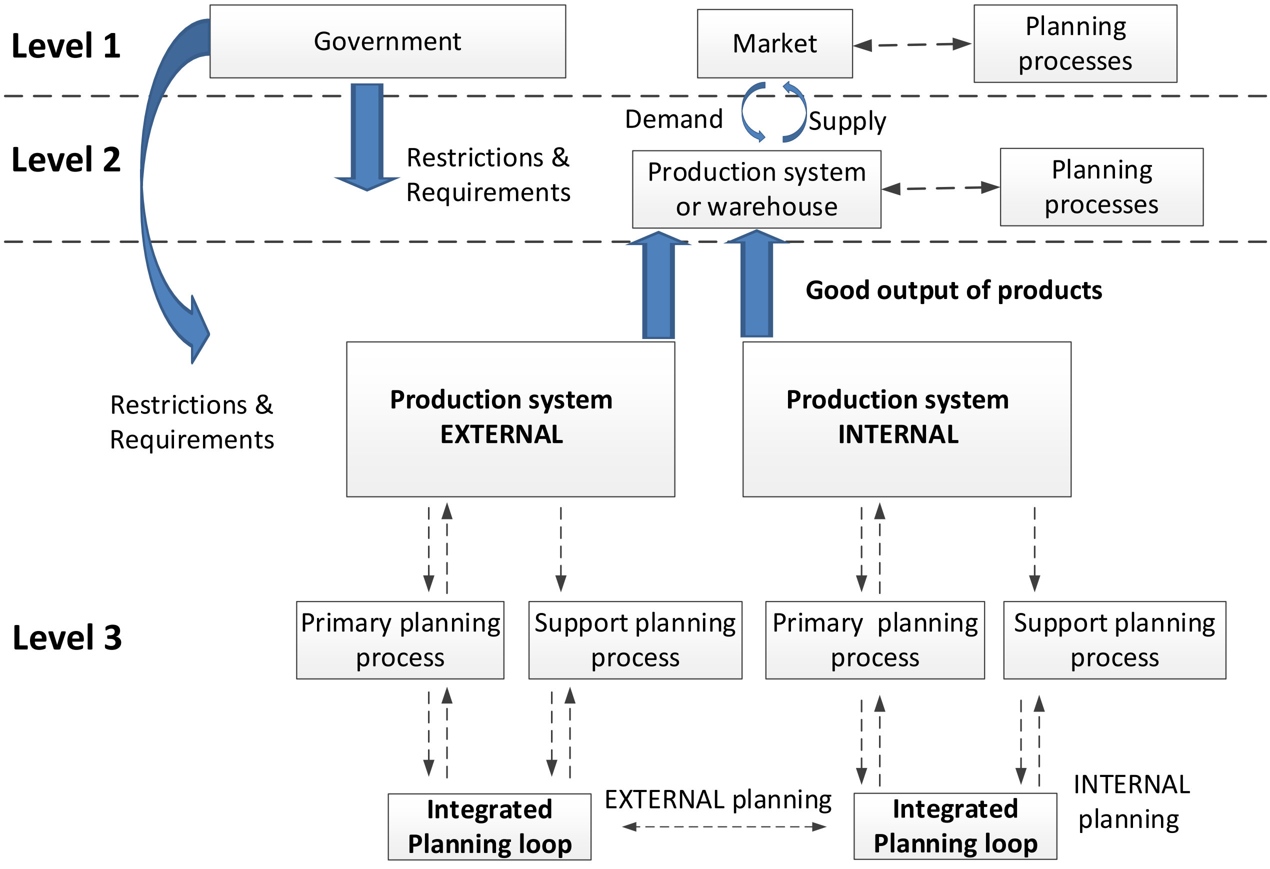


Figure 11 – IPL framework adapted from (Rødseth and Schjølberg, 2014b).

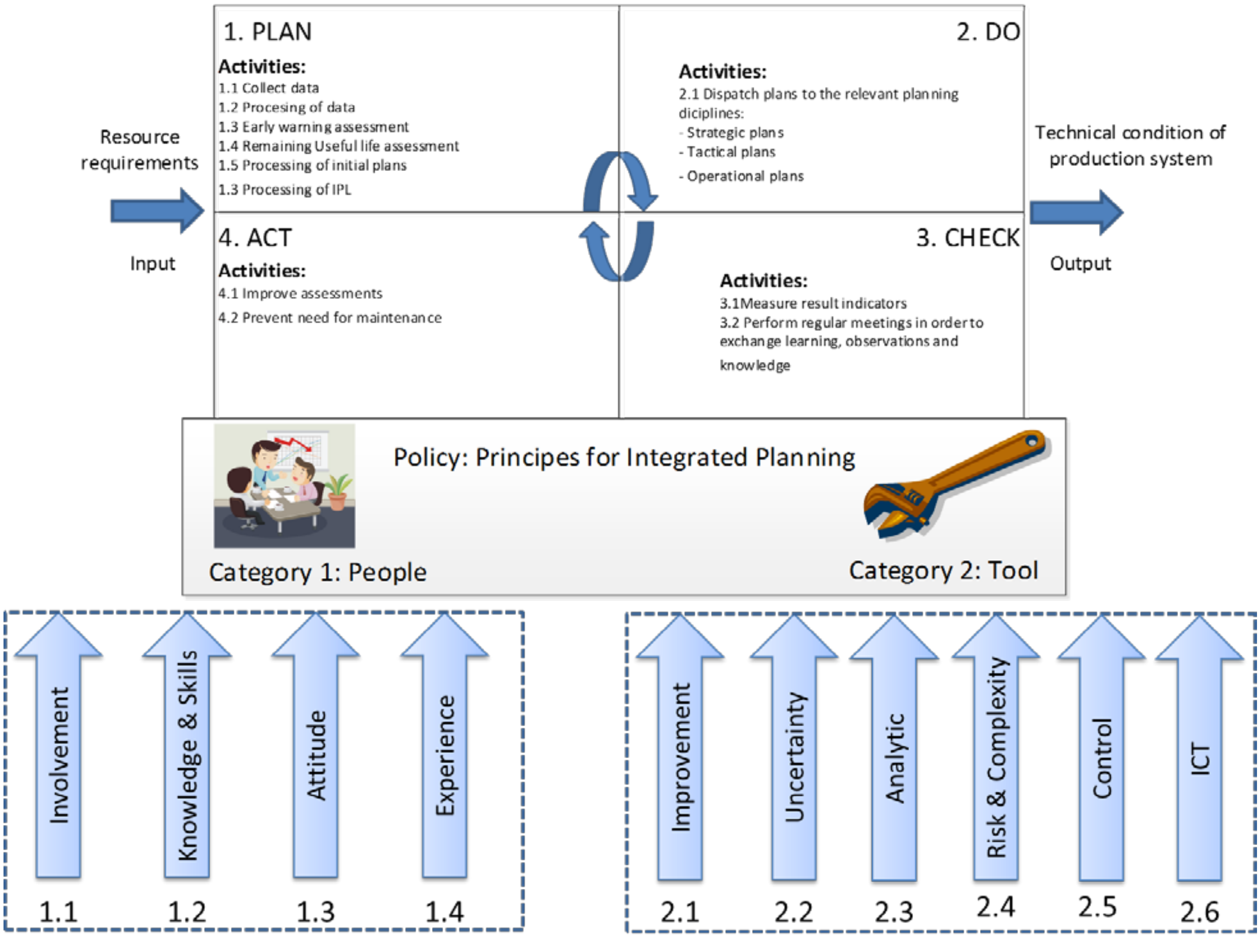


Figure 12 – IPL loop and principles for IPL adapted from (Rødseth and Schjølberg, 2014b).

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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