RiskBIM - Risikostyring i BIM-drevne offentlige samferdselsprosjekter

BIM and Digital Twins

Application in maintenance and operation

Jørn Vatn

2022

Preface

This report summarizes the main contributions from NTNU in the RiskBIM project (Risk management in BIM-driven projects within the transport sector). The project is financed by the Norwegian Research Council under project number 295927. The project period has been from 2019 to 2022.

Bane NOR has been the project owner and the steering committee has been headed by Thomas Welte from Bane NOR. IFE has been project leader for the project. Initially André Alexandersen Hauge acted as project leader before Morten Gustavsen took over the leadership.

On behalf of NTNU I would like to thank Thomas, André and Morten for their excellent governing of the project. Also thanks to all the other project members from:

- IFE
- Bane NOR
- SVV
- COWI
- Multiconsult

Trondheim, 2022-10-25
Jørn Vatn

Contents

1 Introduction **2**

1.1 Background 2

1.2 Objective 3

2 Short description of concepts and terms **4**

2.1 Building information modelling (BIM) 4

2.2 Plant hierarchy / object structure 5

2.3 Failure reporting, analysis, and corrective action system 6

2.4 GIS- and surrounding models 6

2.5 Digital twin 6

3 Digital twin labelling **9**

3.1 Introduction 9

3.2 Operations DT 10

3.3 Condition DT 10

3.4 Risk DT 11

3.5 Environment DT 11

3.6 Maintenance cost DT 12

4 Bridge degradation model **13**

4.1 Degradation and maintenance model 13

4.2 Cost model 14

4.2.1 The DT model for degradation and repairs 15

4.2.2 The DT model for the traffic situation 15

4.2.3 Combining the DT's 16

4.2.4 White-box vs gray-box models 16

5 Railway drainage example **17**

5.1 Introduction 17

5.2 Model A 17

5.3 Model B . . . 19
5.4 Model C . . . 19

6 Railway turnout example **22**
6.1 Introduction . . . 22
6.2 Health indicator . . . 22
6.3 Prediction model . . . 23
6.4 Cost modelling . . . 24

7 Components of digital solutions for maintenance and operation **26**
7.1 The contition DT . . . 26
7.1.1 Information content . . . 26
7.1.2 Statistical inference . . . 27
7.1.3 Prediciton, forecasts and what-if inquireis . . . 27
7.1.4 Operations DT . . . 28
7.1.5 Risk DT . . . 29

8 Summary and conclusion **31**

Bibliography **32**

Chapter 1

Introduction

1.1 Background

The RiskBIM project is focusing on how Building information modelling (BIM) could be used to support risk assessment in various phases of road and rail projects. Broadly speaking a BIM would represent a digital representation of what will be or is being built. When a BIM interacts with the actual physical system terms as cyber physical systems and digital twins have been introduced. The terms being used are overlapping, and the interpretation of the terms are often not very precise, at least when it comes to how industry can benefit from the "promises" from the new concepts being introduced in these days of digitalization.

In the RiskBIM project we have investigated the use of BIM both when it comes to the engineering and building phase, but also when it comes to the maintenance and operation phase. In the following we mainly focus on the maintenance and operation phase of a road or railway system. Although the risk, and in particular HSE risk is the focus in RiskBIM, it appears that inspection and maintenance of the infrastructure is fundamental when it comes to ensure safe operation and avoid accidents. Therefore the case studies that have been conducted and which are reported in this report take inspection and maintenance as a starting point.

As already mentioned the terms being used are not always consistent. At the start-up of the project the objective was to be rather explicit on the use of BIM in the operation and maintenance phase of a system, but it appears that the BIM concept have shortcomings related to several factors, and the most important ones are maybe:

- Since BIM would only be available for a very small subset of the systems within the total asset of the road and railroad owners, it is not possible to develop a consistent system for operation and maintenance that really can rely on BIM

- BIM has severe limitations with respect to support real-time maintenance and operation

The report discusses these factors, and in order to bring new concepts and ideas we therefore take a wider perspective than pure BIM.

1.2 Objective

The first objective of this report is to clarify important aspects of BIM and what BIM can and cannot do wrt to support maintenance and operation with respect to risk. Then the next objective would be to give more general discussion on “digital” representations relevant for maintenance and operation. To cope with this we introduce the more general idea of digital twins and their capabilities. Finally we report on main findings from case studies. These case studies are master thesis projects and research papers from a PhD project.

The DNV-RP-A204 (2021) Qualification and assurance of digital twins - Recommended practice, proposes to introduce evolution stages for digital twins. In order to present a “real-time” risk picture and evaluate how operation and maintenance influence the risk it is important to be able to predict future development of the risk picture. Therefore we discuss the evaluation stages with respect to what we need, and in particular special focus is made on the predictive properties of a digital twin, and how the various digital twins interact.

Chapter 2

Short description of concepts and terms

2.1 Building information modelling (BIM)

Building information modelling (BIM) is a process supported by various tools, technologies and contracts involving the generation and management of digital representations of physical and functional characteristics of places. Building information models (BIMs) are computer files (often but not always in proprietary formats and containing proprietary data) which can be extracted, exchanged or networked to support decision-making regarding a built asset. BIM software is used by individuals, businesses and government agencies who plan, design, construct, operate and maintain buildings and diverse physical infrastructures, such as water, refuse, electricity, gas, communication utilities, roads, railways, bridges, ports and tunnels. The concept of BIM has been in development since the 1970s, but it only became an agreed term in the early 2000s. Development of standards and adoption of BIM has progressed at different speeds in different countries; standards developed in the United Kingdom from 2007 onwards have formed the basis of international standard ISO 19650, launched in January 2019. ISO19650 (2019) defines BIM as:

Use of a shared digital representation of a built asset to facilitate design, construction and operation processes to form a reliable basis for decisions.

Traditional building design was largely reliant upon two-dimensional technical drawings (plans, elevations, sections, etc). Building information modelling extends the three primary spatial dimensions (width, height and depth), incorporating information about time (so-called 4D BIM), cost (5D BIM), asset management, sustainability, etc. BIM therefore covers more than just geometry.

As some BIM software developers have created proprietary data structures in their software, data and files created by one vendor's applications may not work in other vendor solutions. To achieve interoperability between applications, neutral, non-proprietary or open standards for sharing BIM data among different software applications have been developed. Poor software interoperability has long been regarded as an obstacle to industry efficiency in general and to BIM adoption in particular. BIM is often associated with Industry Foundation Classes (IFCs) and aecXML – data structures for representing information – developed by buildingSMART. IFC is recognised by the ISO and has been an official international standard since 2013 (ISO16739-I, 2018).

Dynamic information about the building, such as sensor measurements and control signals from the building systems, can also be incorporated within BIM software to support analysis of building operation and maintenance. A reference is Liu and Akinci (2009).

There have been attempts at creating information models for older, pre-existing facilities. Approaches include referencing key metrics such as the Facility Condition Index (FCI), or using 3D laser-scanning surveys and photogrammetry techniques (both separately or in combination) to capture accurate measurements of the asset that can be used as the basis for a model. Trying to model a building constructed in, say 1927, requires numerous assumptions about design standards, building codes, construction methods, materials, etc., and is, therefore, more complex than building a model during design.

The optimistic perspective is that standardization work will ensure that all BIM software always work on portable data, that existing infrastructure easily can be scanned and documented in the same manner as new systems, and that sensor information and other documentation principles ensure that we always have a real-time representation of the system.

The negative perspective is that standardization will not work, BIM software uses proprietary data structures, it will be too costly to scan existing systems, and representation of sensor information is too complex to ensure real dynamic understanding of the asset. It has also been found that a typical BIM software will not enable a time resolution higher than days or weeks, making real-time dynamic updates impossible.

2.2 Plant hierarchy / object structure

A consistent plant hierarchy is essential for a computerized maintenance management system (CMMS). Reliability centred maintenance (RCM) is a technique to establish a preventive maintenance program for a system or a plant. In RCM it is essential to understand systems, subsystems, components, parts and maintainable items. A proper structuring is required to determine the appropriate maintenance tasks for the maintainable items, and implement these maintenance tasks into the CMMS.

For the railway, railML (Railway Markup Language) is an open, XML based data exchange format for data interoperability of railway applications. Similarly there exist a RoadXML. Ideally, the CMMS should be compatible with railML and RoadXML. To be efficient, also any BIM implementation should be compatible with these formats.

2.3 Failure reporting, analysis, and corrective action system

A failure reporting, analysis, and corrective action system (FRACAS) is a system implemented by software that provides a process for reporting failures, classifying failures, analysing failures, and planning corrective actions in response to those failures. It is typically used in an industrial environment to collect data, record and analyse system failures. A FRACAS system may attempt to manage multiple failure reports and produces a history of failure and corrective actions. FRACAS records the problems related to a product or process and their associated root causes and failure analyses to assist in identifying and implementing corrective actions.

An important part of the FRACAS will be implemented by the CMMS. I.e., all failures reported during maintenance will be recorded in the CMMS. Incidents and near-misses are typically reported in an incident reporting system, e.g., Synergi Life (DNV, 2022).

In order to update risk and maintenance models it is important that the FRACAS is aligned with the the risk and maintenance analyses conducted. Often there is a mismatch between e.g., RCM analysis and the FRACAS when it comes to structuring failure modes, failure causes and maintainable items.

2.4 GIS- and surrounding models

The plant hierarchy (object structure) captures the physical asset of the transportation infrastructure. The BIM will give additional detailed information on the built asset, but these system will not necessarily document the soundings important for the transportation infrastructure. Important risk factors are found outside the natural boundaries for the BIM, for example the risk of avalanches and flooding. GIS models can capture more aspects of the surrounding than a typical BIM. Such models can together with weather forecast models be used to model the risk picture. A GIS model usually only captures the geometry of the surroundings, but to get a more comprehensive picture also information regarding soil, vegetation etc. is required.

2.5 Digital twin

A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors for example a physical system, historical and future maintenance activities, or an operational plan. Data from multiple digital twins can be aggregated for a composite view. The notion of a digital representation of real-world entities or systems is not new. Its heritage goes back to computer-aided design representations of physical assets or profiles of individual customers. The difference in the latest iteration of digital twins, adopted from Gartner (2019), is:

1. The robustness of the models with a focus on how they support specific business outcomes such that high reliability and efficient maintenance

2. Digital twins' link to the real world, potentially in real-time for monitoring, and control

3. The application of advanced big data analytics and AI/ML to drive new business opportunities

4. The ability to interact with them and evaluate "what-if" scenarios

Experience shows that there is no common definition of the term digital twin, and the aspects to implement in the various companies digital twin varies.

In the recommended practice on qualification and assurance of digital twins (DNV-RP-A204, 2021) it is proposed to define a "ladder" for the evolutional stages of a functional element of a digital twin as depicted in Figure 2.1.

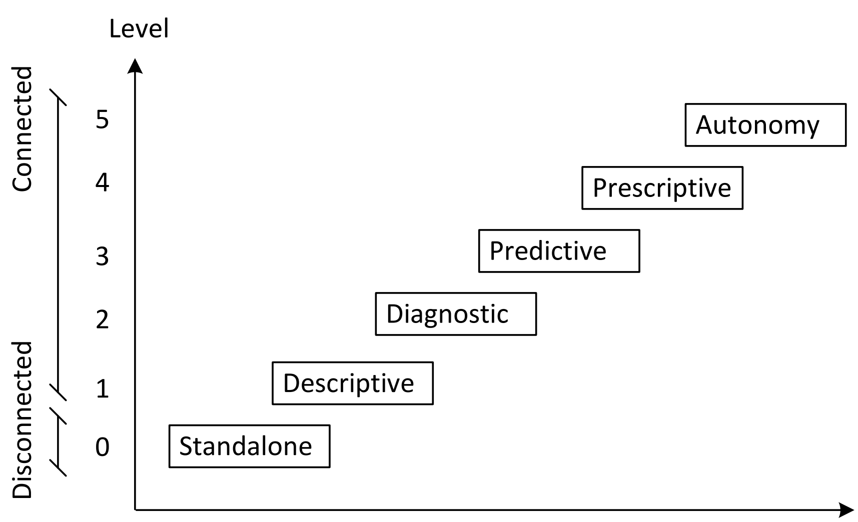

Figure 2.1: Evolution stages or capabilities of a functional element of a digital twin (DNV-RP-A204)

During the RiskBIM project it has become clear that in current BIM implementations the highest evolutions stage is the descriptive stage.

An ambition when it comes to bring the BIM valuable for the maintenance and operation phase, is also to reach higher stages in Figure 2.1.

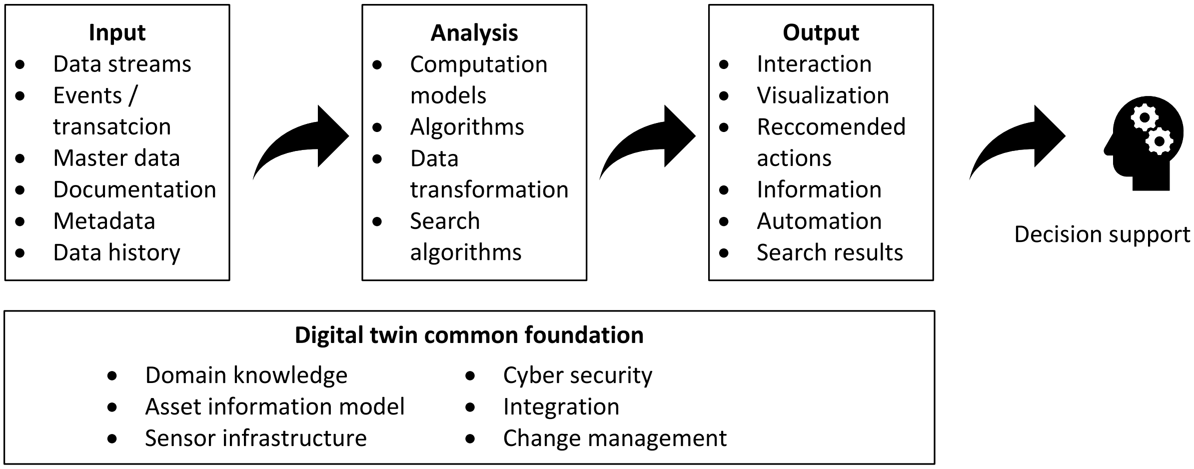

Figure 2.2: Elements of a digital twin (DNV-RP-A204)

DNV-RP-A204 also presents a generic model for the elements of a digital twin. Figure 2.2 indicates a process from input through analysis to output. It should be noted that the aim of RiskBIM is also to demonstrate such processes in all the pilots, but it should be emphasized that so far the analysis part is only demonstrated by direct human analysis, and not any model-based formal analysis.

To build up the input blocks in Figure 2 we need to integrate the BIM, the CMMS, the FRACAS and the GIS models discussed above in order to implement the analysis block if this is to be seen as part of a digital twin, i.e., a model based approach.

If the ambition also is on the diagnostic and predictive evolution stages the output block needs to be formally linked to the analysis block where input is analysed in (near) real-time.

Finally, the prescriptive and autonomy evolution stages relates to decision support in Figure 2.2, where "support" at the ultimate stage means e.g., automatic generation of maintenance work orders, automatic shutting down of road sections or railway lines in case of bad weather, increased degradation levels etc.

Chapter 3

Digital twin labelling

3.1 Introduction

According to DNV-RP-A204 (2021) a digital twin is defined as a *Virtual representation of a system or asset that calculates system states and makes system information available, through integrated models and data, with the purpose of providing decision support over its lifecycle.* In order to be more explicit regarding functionality of the digital twin we propose to label the digital twins according to the various application domains. The following labelling categories are proposed:

- The *Operations* DT: This DT contains operational plans, cost related to lost production, opportunity windows for maintenance etc
- The *Condition* DT: This DT contains information regarding the condition of the "hardware". In principle this DT contains both current condition, and historical data
- The *Risk* DT: This DT contains the risk picture
- The *Environment* DT: This DT contains information regarding the environment, such as temperature, precipitation, wind etc.
- The *Maintenance cost* DT: This DT contains the relevant mathematical models used for optimizing maintenance, interacting with the Operations DT

We will not elaborate on technical issues, i.e., how these DT are sharing data, how we can conduct "what-if" queries etc. In Chapter 7 we discuss in more detailed requirements for the various DT categories in light of our case studies.

3.2 Operations DT

For a railway system the operations DT typically contains the time table, and any planned deviations from the plan. For example freight trains are not necessarily scheduled in advanced. For train operations it is also important to have a model describing how failures and planned maintenance work on the track will affect the throughput, i.e., cancellations, delays etc. For road segments there will not be any time table, but important information would be daily traffic (ÅDT) split to a required level, i.e., by months and working days vs weekends.

In order to respond to *short term* what-if queries, it is required to have a model-based foundation and/or data driven based foundation if we have sufficient data for training purposes.

Long term what-if queries would typically be expected changes in traffic volume.

3.3 Condition DT

The condition DT contains information regarding the condition (health) of the infrastructure assets. Part of such information is contained in a computerized maintenance management system (CMMS). Information from online and offline condition monitoring systems are usually not transferred directly to the CMMS, thus the condition DT also include information from condition monitoring system as well as SCADA systems. Thus, the basic information contiained in a DT is:

- The plant hierarchy with the relevant objects
- Information regarding events for each object, in particular preventive maintenance and corrective maintenance tasks
- Condition information from condition monitoring systems, both off-line and on-line systems
- Infromation from the SCADA system

In this context we include both the information about the asset, e.g., a plant hierarch with the relevant objects (physical items) and the information from condition monitoring systems, and any event information related to objects.

Although measurements from condition monitoring systems may be available there is still a challenge for the condition DT to respond on:

- Early warnings or anomaly detection
- Diagnostics, i.e., clarify which part is degraded, what is the degradation mechanism etc, see Figure 2.1

- Prognostics, i.e., how will degradation evolve over time, and when will the item not be able to perform it's required function any more, also see Figure 2.1 for *prediction*.

Typical approaches for handling these challenges are signal processing, first principle approaches (white box), probabilistic modelling and signal processing (grey box) and machine learning (black box).

3.4 Risk DT

In the RiskBIM project the main focus is on risk, and in particular HSE risk. For the operation and maintenance phase of a system the (static) risk models could be categorized into:

- Qualitative and semi-quantitative models and techniques like bow-tie, FMECA, HAZOP, Task Analysis and preliminary hazard analysis (PHA)
- Quantitative system risk and reliability models like fault tree analysis, event tree analysis and Markov analysis
- Structural reliability models including assessment of loads and strengths

In order to make what-if inquiries to the risk DT it is important to explicit link the risk models to

- The items and elements in the condition DT
- The environment DT
- Other factors that have an influence, and are expected to change over time, e.g., changes in maintenance resources

The railway drainage example in Chapter 5 demonstrates aspects relevant for the risk DT.

The railway tunnel example in RiskBIM pilot study 3 demonstrates the use of bow-tie in the engineering phase of a railway project, and how the bow-tie model acts as a template to speed up the risk identification process, see Lillehammer et al. (2022) .

3.5 Environment DT

The environment DT shall contain all aspects of the environment, this means for example in a real-time perspective current temperature, precipitation and wind are important. But these dimensions can only partly cover the environmental impact on the infrastructure. For example the impact of precipitation on the infrastructure in terms of risk of insufficient drainage capacity depends on existing water saturation of the soil, snow melting in surrounding areas etc. To establish relevant and useful environment DTs is therefore very demanding.

In Chapter 5 we present a risk model that takes environment partly into account. We then discuss challenges in the DT representation.

3.6 Maintenance cost DT

The maintenance DT contains information regarding planned and executed maintenance, as well as logistics, personnel plans, how maintenance is organized etc. Cost models are required in order to what-if inquires for example related to changing time and amount of maintenance.

Chapter 4

Bridge degradation model

The degradation model has been developed by Tianqi Sun, see Sun and Vatn (2021, 2022a,b). The work is part of the Smarter Maintenance project, see NTNU (2020).

4.1 Degradation and maintenance model

For an infrastructure object such as a bridge, a degradation model has been developed. In this presentation a bridge is considered as a single-unit system, with four independent condition states. Each state represents a damage level of the bridge, where state 1 represents the best and state 4 represents the worst. Figure 4.1 illustrates the deterioration process where the λ's depicts the transition rates from one state to another.

$$1 \xrightarrow{\lambda_1} 2 \xrightarrow{\lambda_2} 3 \xrightarrow{\lambda_3} 4 \xrightarrow{\lambda_4} F$$

Figure 4.1: States and degradation rates

State F is a state representing a hazardous state from a safety point of view, e.g., a bridge collapse.

Today the system condition (state) can only be revealed by inspections. The current maintenance regime identifies maintenance tasks, MT, that shall be scheduled when a transition into a more degraded state has been observed. Depending on the system condition revealed, i.e., the state in Figure 4.1, a time frame for the execution of the identified maintenance task is set. The frequency of inspections in the Norwegian Road Administration is currently not reflecting the state.

In the current research a model has been developed which allows for a dynamic inspection regime, where inspection intervals depend on the observed condition.

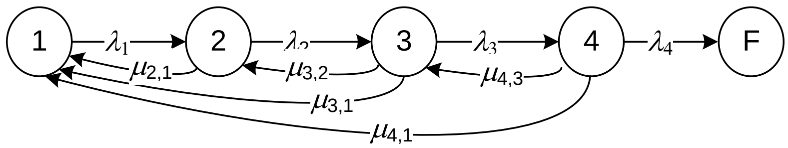

Figure 4.2: Model for hard maintenance

Figure 4.2 shows the model where hard maintenance is included. The repair rates, i.e., the μ's depict an improvement, and as indicated improvements are not always perfect. Since the degradation from one state to another only is revealed by an inspection, a repair will not start immediately after the degradation has taken place.

It is assumed that the system follows the long inspection regime when in state 1 or 2, the medium inspection regime when in state 3 and the short inspection regime when in state 4.

In the current model all inspections are assumed to be perfect and can reveal the true system condition.

When the system is found at a deteriorated state (all states except state 1), corresponding repairs will be scheduled immediately, but as Figure 4.2 shows repairs are not always perfect, either because the local conditions, i.e., the traffic conditions etc., or due to challenges in the maintenance.

4.2 Cost model

The cost model introduces two set of cost elements:

- Operator costs
- User cost

The operator cost is the cost associated with inspections and repairs, whereas the user cost is delay time cost, and cost related to increased travelling distance, i.e., when an alternative route is required.

The traffic model implemented is a rather simple model based on standard models found in literature. In principle it is possible to assign user cost to all states, but typically user cost are only relevant for state 4, where permanent speed restrictions and or limitation on passages could be implemented.

During repair, there will always be user cost to considered, but these costs obvious depend on the repair action, and the duration of the repair action.

In Figure 4.2 the repair rates (μ's) represent the total time, i.e., planning, logistic delay, active repair etc., hence the user cost is only charged for a small part of the "repair time".

The user cost model takes into account the possibility for re-routing, hence a network model is required. Currently a very simple "distribution model" is implemented for how the various vehicles choose between the original route, and the alternative route in situations with maintenance, or when the system is in state 4.

The traffic model in Figure 4.2 should be considered as a "stand-alone" digital twin.

4.2.1 The DT model for degradation and repairs

The model in Figure 4.2 should be considered as a "stand-alone" *condition* DT model according to the DNV-RP-A204 (2021) classification. There are various ways to increase the evolutionary stage:

- Traffic data such as number of vehicles passed, and weights of these. Such information could typically be obtained by surveillance cameras and advanced image recognition algorithms.
- Data from sensors, such sensors are installed on e.g., the Stavå-bridge
- Information from computerized maintenance management systems, where the status on planned and executed maintenance actions could be obtained

This means that in the development of the DT, it should be possible to get a "real-time" DT, and not only a static model as shown in Figure 4.2. This is important because the "traffic model" would need to know the status for "other infrastructure elements".

4.2.2 The DT model for the traffic situation

The current traffic model is to be considered as a "stand-alone" *operations* DT model according to the DNV-RP-A204 (2021) classification. To perform short term maintenance planning it is required to know the traffic situation. The user cost associated with e.g., closing the bridge for maintenance during the night, depend on rerouting possibilities, and the current traffic situation.

Since the current traffic model is a static stand-alone model, it needs to be developed, having sufficient resolution for the decisions to be made. For example number of vehicles passing hour by hours for the planning horizon, such that the maintenance model can take into account when to start a repair (i.e., which week), and how to proceed, i.e., which hours of the day should be used.

4.2.3 Combining the DT's

In the PhD research project initial work has been conducted to investigate how the two DT models could be integrated, but there is more work to make them operational (only conceptual for this theoretical work), and finally to merge the models in a real-time application.

4.2.4 White-box vs gray-box models

The models introduced above are often denoted grey-box models because the degradation is only partial described, this in contrast to so-called white-box models. The following characteristics are often used

- *White-box models*. These are models where the physical degradation of an item is described by the laws of physics, chemistry etc. For example a fatigue model for crack propagation.
- *Gray-box models*. These are models where degradation is modelled by probabilistic models. In the current work Markov state models have been used, but other common models are the Gamma, Wiener and Inverse Gauss processes. Typically the degradation increments are described by stochastic jumps. These processes may include covariates representing physical conditions, but the relation between the increments and the physical conditions and factors are usually established by regression methods rather than physical laws.
- *Black-box models*. The black-box models aim to make predictions regarding future degradation without specifying any model. These models are "trained" by large amount of data. Typicall models are machine learning methods like deep neural networks and Random forests.

In the master thesis by Lee (2022) the basic Markov model by Tianqi has been extended to also include a whitebox model. The aim in this work has been both to investigate how physical models can be used, and how synchronization of maintenance and operation. A prototype tool in Matlab has been established.

In the current work no machine learning models have been enveloped, but part of the Smarter Maintenance proejct (NTNU, 2020), several studies are conducted to test machine learning models relevant for road maintenance.

Chapter 5

Railway drainage example

5.1 Introduction

This example is based on a master degree project at NTNU conducted by Platou (2020). The project was preceded by a specialization project where one preliminary finding was that modelling capabilities within existing BIM software was too limited to realistically establish real-time models relevant for maintenance and operation. Therefore the main focus for the modelling was more conceptual where the idea is to develop a degradation model for the drainage system for the railroad, and link this model to the weather in order to investigate opportunities for real time decision support.

Three models were developed, i.e., model A, B and C where more and more functionality was introduced. In the following the core elements of the models are presented, and discussed in relation to the DNV-RP-A204 (2021) maturity levels and types of digital twins.

5.2 Model A

Model A only treat the condition on the drainage system. A discrete state variable is introduced, and Table 5.1 shows the values used. With respect to the type of digital twins this model is then a condition DT. Note that it will be demanding to model such a state variable in a BIM system since the degradation is not explicitly related to e.g., a culvert as such.

The model is by the way it is implemented in the master project categorized as a stand-alone DT. However, it would be straight forward to implement the model as part of the CMMS where measurements form inspection could be used to determined the actual state, and by knowing the state, and the transition rates introduced in the model the model will have prediction capabilities according to Figure 2.1. The model by it self has no diagnostic capabilities nor any prescriptive capabilities.

Table 5.1: States for model A

State	Grade	Description
0	New	Culvert has dimensioned capacity
1	Moderate	Culvert has somewhat reduced capacity
2	Significant	Culvert has significant capacity challenges
3	Failure (Critical)	The culvert has very little or no functional ability
5	2.1	
6	2	Virtual states for maintenance decisions
7	3	

Figure 5.1 shows the states and transitions. The λ's are degradation transitions where the μ's are repair and restoration rates. The q values represent decision to related to repair and restoration, where these decisions only take place after each inspection of the culvert, hence the transition into such decision states are indicated by dashed liens. Note that the text in some nodes are given in Norwegian.

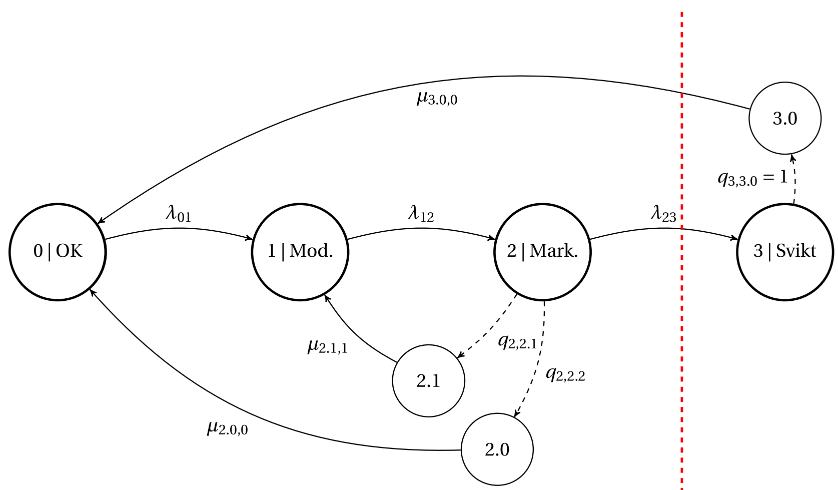

Figure 5.1: Model A with transitions

The repair strategies are as follows

- When state 3 (Failure) is revealed, a complete repair to a good as new state is performed
- When state 2 (Significant) is revealed, either a complete repair to state 0 is performed with probability $q_{2,2.2}$ or a minor repair to state 1 is performed with probability $q_{2,2.1}$
- When state 1 (Moderate) is revealed no action is taken

5.3 Model B

In Model B aspects of the environment DT is included, i.e., precipitation. Precipitation is discretized in tree levels. The definition of the levels would depend on local conditions like the catch area of precipitation, snow melting etc surroundings. Ideally real-time models should be applied to ensure the environment DT is matches the capacity challenges in the condition DT of e.g., a specific culvert. Table 5.2 shows the states used in model B. Note the use of the double indexing for precipitation, where the first index corresponds to the state (e.g., culvert state) and the second index is the precipitation level.

Table 5.2: States in model B

State	Grade	Description
0	New	Culvert has dimensioned capacity
1	Moderate	Culvert has somewhat reduced capacity
2	Significant	Culvert has significant capacity challenges
3	Failure (Critical)	The culvert has very little or no functional ability
$i1$	Precipitation level 1	12-hour accumulated precipitation
$i2$	Precipitation level 2	corresponding to local threshold values
$i3$	Precipitation level 3	– ” –
5	2.1	
6	2.0	Virtual states for maintenance decisions
7	3.0	

Figure 5.2 shows the corresponding Markov diagram. As for Model A virtual states are introduced to capture maintenance decisions based on results from periodical inspections.

Model B captures important aspects of the condition DT, the environment DT and the maintenance (cost) DT. However, since the operation and risk DT is not included, the model will as such not give sufficient decision support. Also, the Model B is a stand-alone model according to the maturity levels of Figure 2.1, and will in the same way as Model A have predictive capabilities if implemented as part of the CMMS and an online precipitation model, e.g., weather forecast models.

5.4 Model C

The final model is also introducing the preparedness strategies, i.e., to each combination of degradation and precipitation level a colour regime is introduced. The aim is to define the zones of preparedness level depending on the condition status. Current practice is to only include the precipitation level. Table 5.3 shows the states introduced. Also note that Model C introduced a more refine model for the states. This is because degradation of the physical asset, here the

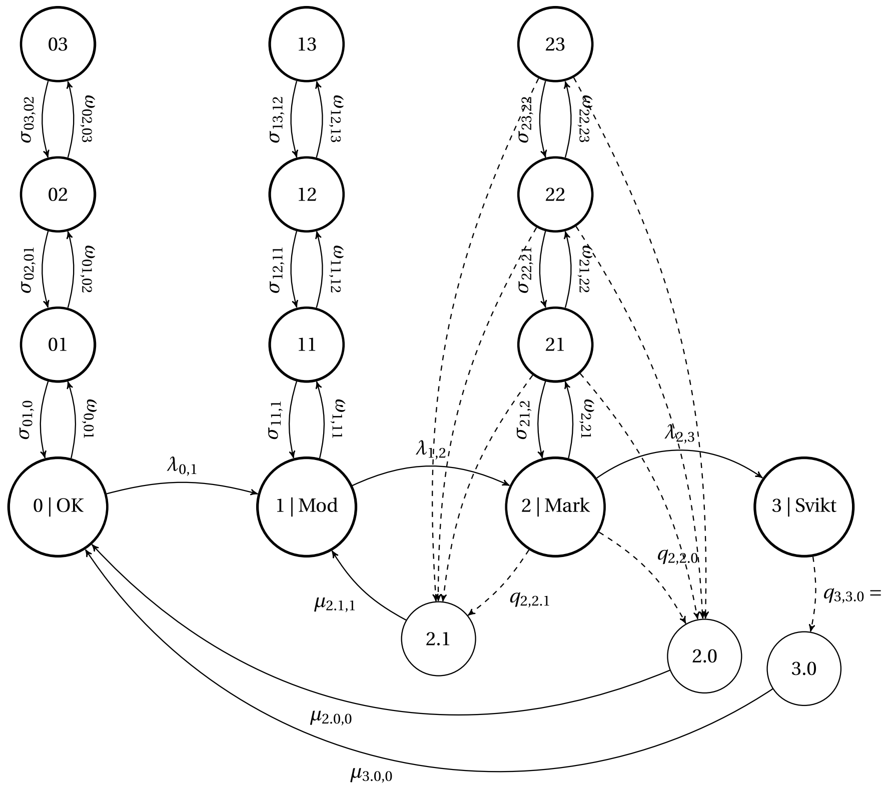

Figure 5.2: Model B

culvert, is assumed to be a continuous process. Using only 4 levels with exponentially sojourn times is not realistic, and by introducing the extra grading – and –– a more realistic model is obtained.

Figure 5.3 shows the final Model C. It should be noted that here we have only visualized the colour regime for some of the main "condition" states. The full model is presented in the master thesis. In the master thesis it is also discussed aspects of including the risk DT, i.e., focusing on derailment probabilities for the various states.

As for Models A and B, Model C in the master thesis project is a pure stand-alone model that has been investigated. The model has predictive capabilities, but it is required to connect to the real-time data streams in order to reach higher maturity levels according to Figure 2.1. How this can be done is not elaborated in the master thesis.

Table 5.3: Sates for model C

State	Grade	Zone	Description
0	OK		
1	OK-	Green	Culvert is in a generally acceptable condition
2	OK–		
3	Moderation		
4	Moderate-	Yellow	Culvert is in a state of reduced capacity
5	Moderate–		
6	Serious		
7	Serious-	Orange	Culvert has significant capacity challenges
8	Serious–		
9	Failure (Critical)	Red	Culvert has very little or no functional ability
$i1-3$	Precipitation level		1-3 12-hour precipitation corresponding to local threshold values
B$i1-3$	Emergency preparedness level		1-3 Emergency preparedness level to corresponding precipitation level

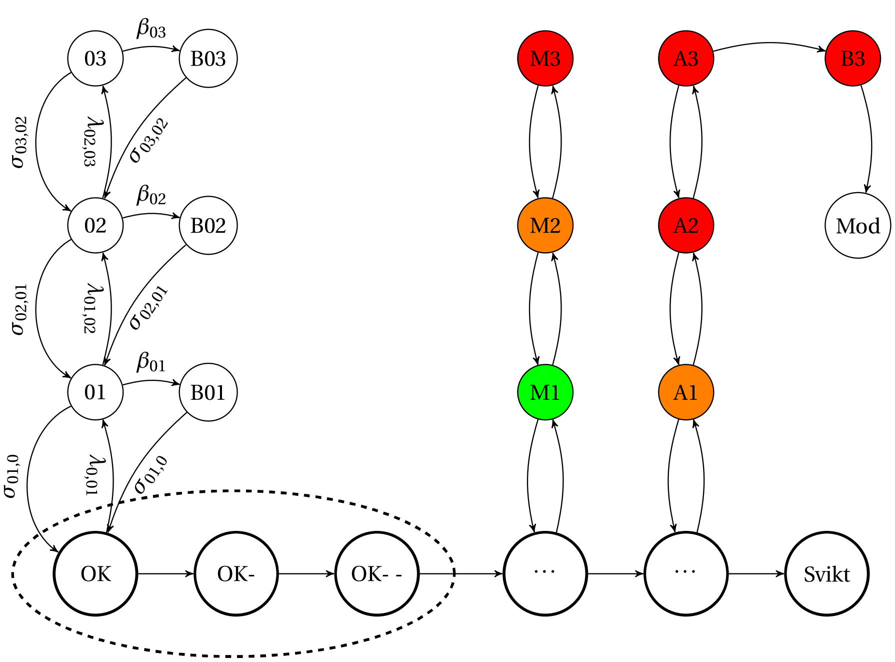

Figure 5.3: The dynamic of degradation in model C

Chapter 6

Railway turnout example

6.1 Introduction

This example is based on a an earlier work but is included in order to shed more light on the various categories of digital twins (Vatn, 2018). The turnouts (switches) in the railways are components that are expensive to inspect and maintain. In Norway Bane NOR has proposed to use turnout SCADA data as a health indicator and use this indicator to support maintenance decisions.

6.2 Health indicator

More specifically, the electrical effect during operation of the turnout is used as an indicator for the health of the turnout. Figure 6.1 shows a principal sketch of the effect during one switching cycle. The idea is to establish a signature curve, $s(t)$ based on "normal" operation of the turnaround engine. For numerical analysis we obtain s_i by discretization. Upon degradation of the engine and/or the mechanical parts of the turnout, it is expected that the demanded effect to operate the engine is increasing, i.e., the actual effect a_i. A natural health indicator to be used for anomaly detection is:

$$\mathrm{HI} = \sum (a_i - s_i)^2 \tag{6.1}$$

An alarm could then be raised when the health indicator HI exceeds a threshold value.

The objective of anomaly detection is to get some early warning regarding coming failures. Upon the detection of an early failure, the PF-interval model is used in this study to model degradation beyond the threshold value. The situation is as follows: A component is put into service at time $t = 0$. After a random time T_P the component enters a degraded state, i.e., when the health indicator exceeds the threshold value. This state is often referred to as a potential failure

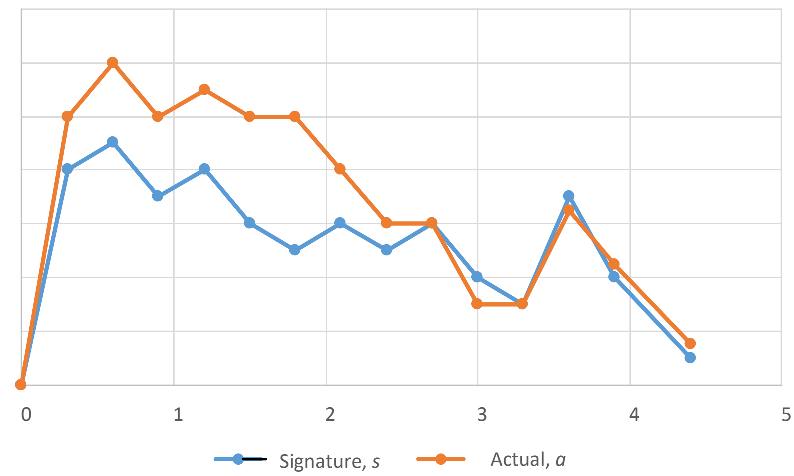

Figure 6.1:

(P). The component will fail (F) after another random time T_{PF} if no action is taken. Figure 6.2 illustrates the situation.

6.3 Prediction model

A Cox proportional failure rate function is used in this study as a basis for formulating the failure rate function, $z(t) = f(t)/R(t)$ for T_{PF} (t is running time *after* the potential failure has occurred), (Cox, 1972). T_{PF} is often referred to as the PF-interval, and the corresponding failure rate function is:

$$z(t|\mathbf{y},\overline{\mathbf{x}(t)}) = z_0(t)e^{\boldsymbol{\beta}_1\mathbf{y}}e^{\boldsymbol{\beta}_2\overline{\mathbf{x}(t)}} \tag{6.2}$$

where $z_0(t)$ is a baseline failure rate function, typically on the form $z_0(t) = \alpha\lambda^{\alpha}t^{\alpha-1}$ in the Weibull case. $\mathbf{y}$ is a vector of state variables at the point of time of the potential failure is observed, and $\overline{\mathbf{x}(t)}$ is the average load profile t time units ahead. $\boldsymbol{\beta}_y$ and $\boldsymbol{\beta}_x$ are regression coefficient vectors established by for example statistical analysis of data.

The failure rate function in eq. (6.2) is a classical model. In the study by Vatn (2018) the failure rate function was used as part of a *stand-alone* digital twin according to DNV-RP-A204 (2021) evolution stages. In order to reach a *connected predictive stage*, see Figure 2.1, for the condition digital twin it is required that $\mathbf{y}$ could be accessed from sensor readings and communicated via the "internet of things" and then processed according to relevant algorithms. In the railway example the health indicator given by eq. (6.1) is a starting point for $\mathbf{y}$ in eq. (6.2) .

Further $\overline{\mathbf{x}(t)}$ needs to be accessed in real time from enterprise resource planning (ERP) systems and other system for future production plans. In this example $\overline{\mathbf{x}(t)}$ would be part of the *operations* digital twin.

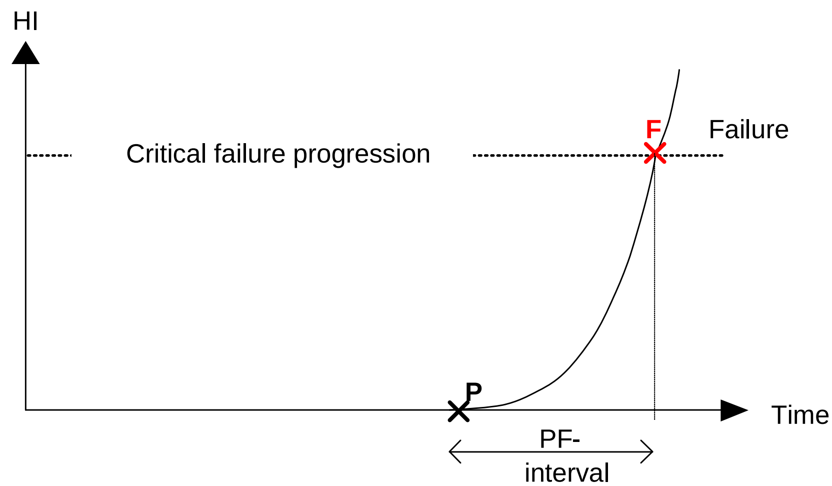

Figure 6.2: PF-Model

If eq. (6.2) is part of the *condition* digital twin we may now make inquires regarding the probability of failure if we wait for example t time units before the potential failure is fixed:

$$F(t|\mathbf{y},\overline{\mathbf{x}(t)}) = 1 - e^{-\int_0^t z(u|\mathbf{y},\overline{\mathbf{x}(u)})\,du} \tag{6.3}$$

where $\overline{\mathbf{x}(t)}$ is part of the *operations* digital twin and will for the railway example represent the number of operations of the turnout in the near future. In order to reduce the load on the turnout and hence the degradation rate it is possible to lock the turnout such that it cannot be operated until a maintenance action is executed. This will obviously give some negative consequences with respect to the circulation, i.e., delays are expected due to less flexibility with respect to crossings.

6.4 Cost modelling

The cost term related to reducing the number of operations of the turnout is denoted *relax cost*:

$$\text{Relax cost} = c_{\text{R}}(x) \tag{6.4}$$

where x represent e.g., the number of switch operations. For the railway example the relax cost depends on many factors, e.g., the point of time during the day when the locking of the turnout is implemented. A real-time model is thus required for the operations digital twin. Upon an early warning it is required to visit the cite where the turnout is located. The cost of this depends both on travelling cost and any implication on the circulation. The more emergent it is, i.e., a short lead time t, the more costly it would be to organize the call-out of maintenance personnel. Further if the early warning is indicated in the morning rush, many trains will be affected as it would be required to stop the traffic during an inspection of the turnout and a subsequent hard maintenance task. Therefore the preventive maintenance cost would also depend on the time of the call-out:

$$\text{Preventive maintenance cost} = c_{\text{PM}}(t) \tag{6.5}$$

where c_{PM} includes both the direct cost of the PM activity and the punctuality cost caused by closing the line during preventive maintenance. The total cost is thus both a function of the time of the maintenance, and the relax-strategy:

$$C(t,x) = c_{\text{PM}}(t) + c_{\text{U}} F(t|y,x) + c_{\text{R}}(x) \tag{6.6}$$

where c_{U} is the unavailability/punctuality cost if a failure occurs during the lead time t.

Table 6.1 summarizes content of the various digital twins in the turnout example: Decision

Table 6.1: Content of the various digital twins

Digital twin	Content
Condition	$y = \text{HI}$, $z(t\|y,x)$
Operations	c_{U}, $c_{\text{PM}}(t)$,
Maintenance cost	$c_{\text{PM}}(t)$

variables are t and x, i.e., when the line should be closed for execution of predictive maintenance and how many switching operations we allow during the delay time t respectively.

Chapter 7

Components of digital solutions for maintenance and operation

Chapter 3 of this report proposes to introduce the following digital twins:

- The *Operations* DT: This DT contains operational plans, cost related to lost production, opportunity windows for maintenance etc
- The *Condition* DT: This DT contains information regarding the condition of the “hardware”. In principle this DT contains both current condition, and historical data
- The *Risk* DT: This DT contains the risk picture
- The *Environment* DT: This DT contains information regarding the environment, such as temperature, precipitation, wind etc.
- The *Maintenance cost* DT: This DT contains the relevant mathematical models used for optimizing maintenance, interacting with the Operations DT

7.1 The contition DT

The condition DT is the most important digital twin, or source of information when planning and executing maintenance.

7.1.1 Information content

The condition DT contains information regarding the asset. The basic information is:

- Description of the asset structured in e.g., a plant hierarchy with relevant item description at the various levels in the plant hierarchy. The computerized maintenance management system (CMMS) holds this information.

- Preventive maintenance activities carried out on each item. The information comprises both what has been done at which dates, and any state information collected during the preventive maintenance. The basic information regarding preventive maintenance is stored in the CMMS, however raw data from inspection or condition monitoring activities is usually not stored into the CMMS system, but in dedicated information systems.

- Corrective maintenance activities carried out on each item. Failure mode, failure causes and failure mechanisms should be reported according to a predefined structure, typically established as part the reliability centred maintenance (RCM) exercises. The corrective maintenance reports are also saved in the CMMS.

- Condition monitoring and inspection information. The condition monitoring information as well as information from inspection could be rather comprehensive, e.g., vibration measurements, scans from ultrasonic inspections, or a report from a manual inspection. Only a limited (extracted) amount of the information is saved as part of the CMMS. The complete information from condition monitoring and inspection is then saved into dedicated information systems.

- Supervisory control and data acquisition (SCADA) system is a system containing data for efficient operation. For example information regarding pressure, temperature and flow could be used to optimize a production line. Information from the SCADA system will in many situations also give extra information regarding the condition of the asset, in particular if first principle models are available.

7.1.2 Statistical inference

Statistical inference is the activity to assess the historical performance of the asset. The activity could also be denote historical inquires. The most obvious question from a maintenance perspective would be to estimate the failure rates of the various items. Historical failure rates would be a starting point when the preventive maintenance program is to be establsihed, or re-established.

Statistical inference is basically an activitiy carried out in order to evaluate the historical performance of the system. However, use of e.g., regression models, could give a basis for prediction.

7.1.3 Prediciton, forecasts and what-if inquireis

Prediction and forecast are terms used to infer regarding the future performance of a system. Predictions and forecasts would be subset of what-if inquires, typically a “what-if-we-proceed-as-before" inquirey, would answer a prediction inquirey. Therfore, we only consider what-if inquireis in the following.

The most evident "if" with respect to maintenance would be

- What if we do more maintenance?
- What if we do less maintenance?
- What if we postpone maintenance until next opportunity?
- What if we reduce the load on an item, will it then survive until the next maintenance opportunity?

In Section 4.2.4 white, grey and black box models were discussed. In order to make what-if inquires we need one or more of these models.

It requires significant modelling work to set up the condition DT in such a way that it is possible to provide support for what-if inquires. To some extent, it is possible to utilize those mathematical models that were used as basis for the preventive maintenance program. For example Bane NOR has to some extent used the OptiRCM tool which provides a reasonable set of mathematical models that may be used as basis also for what-if inquires.

Relevance of BIM:

It is rather obvious that the BIM data models provides *limited information* that is relevant for the condition DT. Information from BIM that can be exported to the condition DT, for example through the CMMS, would be detailed object infomration such that the plant hierachy is feed with as much as possible of relevant data from the constructuion phase of a project.

7.1.4 Operations DT

The Operations DT contains operational plans, cost related to lost production, opportunity windows for maintenance etc. There is no easy way we can define the content and functionality of the operations DT. For railway applications the time-table is obvious an important element of the operations DT. If the time-table is available, it is possible to schedule maintenance in a way such that delays are minimized, or at least considered as part of the planning. The operations DT should also be able to "optimize itself" in terms of a time-table that is efficient for the end user and also enables reasonable "white slots" for maintenance. This is outside the scope of this discussion.

For road usage there is no "time-table", but historical data regarding volumes of trafic is to some extent available. Also, models that can predict re-routing and congestions for a given restriction due to maintenance work exist. Such models would be important elements of the operations DT.

Relevance of BIM

It is hard to anticipate any BIM data can be relevant for the operations DT.

7.1.5 Risk DT

The risk DT contains the risk picture. For operations and maintenance the risk picture is the risk related to the operational phase of the road or railway, including periods of maintenance and renewal.

When it comes to risk caused by maintenance and renewal the perspective is very similar to the construction phase. The BIM is considered as an important tool for planning of maintenance and renewal activities. It can be foreseen that in particular the BIM functionality with respect to visualization of layout, geometry and hazards will be valuable to ensure safe execution of maintenance and renewal activities.

With respect to "operational risk", e.g., risk of using the road and railroad for transportation, the BIM is not considered of particular value. To shed light on the functionality of a risk DT it is recommended to distinguished between:

1. Risk related to missing, inefficient or inadequate safety barriers
2. Risk related to degradation of components or systems

The first situation is characterizing e.g., the Åsta-accident in 2000 where automatic train protection (ATP) were not installed despite the the decision to implement ATP several decades earlier. Although we do not know the cause behind the collapse of the bridge at Tretten in 2022, it is very likely that degradation and subsequent loss of integrity of the structure was the direct cause behind that event.

With this categorization we may also denote the first one in terms of "as built risk", and the second one as "degradation risk".

For a railway system the BIM would not be very relevant for "as built risk". To some extent it is possible to imagine that the BIM and it's visualization could spot challenges related to e.g., level crossings where a "bird perspective" could spot some challenges not revealed in the engineering and approval phase of the railway system, for example if we consider "transparent conditions" as a safety barrier for the level crossing, i.e., seen from the vehicles point of view. But for example for the signalling system the BIM is not anticipated to give any value wrt to "as built risk".

For a road system BIM could play a more important role to spot hazards that might become challenging in the operational phase of the road system, for example part of the road where "lack of transparent conditions for overtaking", "areas exposed to extreme wind conditions" etc. However, it is still unclear to what extent BIM would give additional information compared to what the road planners had available in the engineering phase of the road project.

When it comes to the "degradation risk" this risk is related to the degradation of the road and railroad components and systems. An example is as mentioned above, the load-bearing constructions of a bridge. Deterioration of these could lead to the bridge collapse. Another example is the drainage system of a road or railroad. Degradation of the drainage capacity is compromising an important "as built" safety barrier.

The risk DT therefore should contain a listing of all safety barriers, and links to the corresponding "objects" in the condition DT. Ideally, the risk DT can then update the risk picture based on the condition of the asset, i.e., respond to the the degradation in terms of an updated (real-time) risk picture.

Chapter 8

Summary and conclusion

The starting point for the Risk BIM project with respect to maintenance and operations was to investigate if BIM models could support decisions and work processes. Two important challenges were identified:

1. BIM models will only be established for new infrastructure, hence the value of this information for maintenance and operation of the entire infrastructure network will be limited

2. The resolution in existing BIM computerized tools are limited with respect to model and represent time

In the project we therefore proceed with digital tools in more general. The concept of digital twins was introduced, and in particular the evolution stages proposed in DNV-RP-A204 (2021) are considered valuable to characterize the digital models demonstrated in this study, and what it will take to reach higher stages in the evolution ladder proposed. A primary objective for maintenance and operation is to reach the predictive stage.

To be more explicit on the content of a digital twin it was proposed to categorize digital twins into:

- *Operations* DT
- *Condition* DT
- *Risk* DT
- *Environment* DT
- *Maintenance cost* DT

Highlights from three case studies are presented in the context of digital twins. Mathematical models for supporting decisions on maintenance and operation are developed and we discuss maturity levels according to the evolution stages proposed in DNV-RP-A204 (2021).

After presenting the case studies we discuss content and requirements for the various categories of digital twins. For infrastructure managers like Bane NOR and SVV it is recommended to develop a map regarding the various type of information and which digital system that should contain the “master data”. This will basically correspond to the “descriptive” stage in the DNV-RP-A204 (2021) ladder.

Back to the the starting point of Risk BIM it will be important to identify which elements of the developed BIM models should go into which digital system.

To climb on the DNV-RP-A204 (2021) evolution ladder towards diagnostic and predictive digital twins this will require a systematic approach to white, grey and black box models. Some examples are given in this report, but significant and systematic work is required to really realize the potential of digital twins within the maintenance and operation area.

Bibliography

Cox, D. (1972). Regression models and life-tables. *Journal of the Royal Statistical Society, Series B.*, 34 (2):187–220.

DNV (2022). Synergi life. https://www.dnv.com/services/qhse-and-enterprise-risk-management-software-synergi-life-1240.

DNV-RP-A204 (2021). Qualification and assurance of digital twins - recommended practice. Standard, DNV, Høvik, NO.

Gartner (2019). Top 10 strategic technology trends for 2019. https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019.

ISO16739-I (2018). Industry foundation classes (ifc) for data sharing in the construction and facility management industries - part 1: Data schema. Standard, International Organization for Standardization, Geneva, CH.

ISO19650 (2019). Building information modelling (bim). Standard, International Organization for Standardization, Geneva, CH.

Lee, J. (2022). Digtal twins for synchronisation of production andmaintenance. Master's thesis, Norwegian University of Science and Technology.

Lillehammer, G., Gustavsen, M., and van Loopik, G. (2022). Semi-automated generatedbowtie diagrams for optimizing safety analysis in the railway infrastructure. In Leva, M. C., Patelli, E., Podofillini, L., and Wilson, S., editors, *Proceedings of the 32nd European Safety and Reliability Conference*.

Liu, X. and Akinci, B. (2009). Requirements and evaluation of standards for integration of sensor data with building information modelst. In *Caldas, Carlos H.; O'Brien, William J. (eds.). Computing in Civil Engineering*, page 95–104.

NTNU (2020). Smarter maintenance. https://www.ntnu.edu/smartermaintenance.

Platou, J. F. S. (2020). Stokastisk tilstandsmodellering av stikkrenner i jernbanen ved bruk av multi-fase markovmodeller. Master's thesis, Norwegian University of Science and Technology.

Sun, T. and Vatn, J. (2021). Modelling of condition-based inspections and deterministic maintenance delays for bridge management. In *Proceedings of the 31st European Safety and Reliability Conference(ESREL)*, pages 703–710.

Sun, T. and Vatn, J. (2022a). A markov-base bridge maintenance optimization model considering user costs. In *Proceedings of the 32nd European Safety and Reliability Conference(ESREL)*.

Sun, T. and Vatn, J. (2022b). A phase-type maintenance model considering condition-based inspections and maintenance delays. *Submitted for publication in Reliability engineering and system safety*.

Vatn, J. (2018). Industry 4.0 and real-time synchronization of operation and maintenance. In *Proceedings of the 32nd European Safety and Reliability Conference(ESREL)*, pages 681–686.