Framework for implementing track deterioration analytics into railway asset management

Mikko Sauni, Heikki Luomala, Pauli Kolisoja and Kalle Vaismaa
Research Centre Terra, Tampere University, Tampere, Finland

Abstract

Purpose – Recent research outputs can be difficult to implement into ongoing safety critical processes. Hence, research is well beyond current practices in railway asset management. This paper demonstrates the process of creating tangible change within a railway asset management organization by introducing a framework for advancing track geometry deterioration analyses (TGDA) in practice.

Design/methodology/approach – The research was conducted in three parts: (1) maturity models were reviewed and adapted as the basis for the framework, (2) the initial maturity level was investigated by conducting semi-structured expert interviews, and (3) a framework for development was created in cooperation with stakeholders during three workshops. The methodology and findings were tested and applied in the Finnish state rail network asset management.

Findings – The main output of this study is the framework for advancing TGDA in railway asset management. The novel framework provides structure for controlled incremental development, which is essential when altering a safety critical process.

Practical implications – The research process was successfully applied in Finland. Following the steps presented in this article, any organization can apply the framework to plan their development schemes for railway asset management.

Originality/value – Full-scale implementation of novel models and methods is often overlooked, which prevents practical asset management from obtaining tangible benefits from research. This research provides an innovative approach in narrowing the overlooked research gap and brings research results within the reach of practitioners.

Keywords Asset management, Railway, Track geometry, Deterioration, Framework, Maturity model

Paper type Research paper

1. Introduction

The majority of rail infrastructure funding in the EU gets spent on maintenance and renewals (M&R) (Commission, 2021). This is because railway tracks endure strenuous loading and harsh weather conditions in daily operations, resulting in structural deterioration. Furthermore, as railways are safety critical infrastructure with regard to, for instance, high-speed passenger traffic and hazardous cargo, their safety needs to be closely monitored. The primary means of monitoring the condition and safety of railway tracks include conducting track geometry measurements using a specific track recording car. The track recoding car measures the relative position of the rails, thus providing detailed information on the condition of the tracks and the safety of operations. Recently, track recording car measurements have become a source of

increasing research interest. The literature reviews by Higgins and Liu (2018) and Soleimanmeigouni et al. (2018b) present the growing amount of research published on the topic. One driving force for the interest in track recording car measurements is the advances in data analytics. Novel data analytics method and software are incorporated across all industries, railways being no exception. The data from track recording cars are usually time series data from several years with high accuracy and decent measurement alignment, making the data attractive for further analysis. Track recording car data analyses have been used, for instance, to analyse the effectiveness of maintenance (Soleimanmeigouni et al., 2018a), predict unplanned maintenance needs (Andrade and Teixeira, 2014) and investigate root causes of problematic track deterioration behaviour (Sauni et al., 2020). All this information is vital to successful asset management, for example, in selecting the timing and means of M&R.

However, it is exactly here, in the implementation of research results into practical asset management, where the development lags. In some organisations, practical asset management revolves more around the personnel's expertise and experience rather than on a systemic process. Systemic refers to a documented data-based process in this context. The problem is that if practical asset management does not utilize track geometry deterioration modelling, the maintenance actions may be timed poorly or have little impact, which will lead to repetitive and inefficient M&R. Therefore, it is important to investigate the maturity of current practices on track geometry deterioration analyses (TGDA) and form a framework tailored for advancing them. With a controlled process and a documented framework for advancing TGDA, M&R can be allocated more efficiently in the future. This type of controlled process development is made possible by applying maturity models (Albliwi et al., 2014; Helgesson et al., 2012). However, there are no currently available maturity models for TGDA process improvement, and the available generic maturity models are typically too general for this specific task, as they are created for organization-wide development.

The aim of this study was, therefore, to create a framework for implementing TGDA development in railway asset management. The study was divided into three goals:

(1) Adapt a maturity model for advancing TGDA

(2) Investigate railway asset managers' maturity level in TGDA

(3) Provide a tangible framework with which railway asset managers can advance their maturity in TGDA

Consequently, the study was conducted in three parts (Figure 1). First, a generic maturity model for track geometry management was developed according to literature on asset management maturity models. Following this, semi-structured interviews of track asset management professionals were conducted to define the current maturity level. Finally, workshops were held with track maintenance and asset management professionals to create concrete steps for incrementally advancing the maturity of track geometry management. The study was done in the context of Finnish railway asset management, and Finland was used as a case example of implementation in parts 2 and 3 of this study. The main contribution of this paper is the framework for advancing the maturity level of TGDA in railway asset management. This study also provides a means for determining the maturity level of TGDA in a railway asset management organization. The rest of this paper is organized as follows. First, the background of Finnish rail network ownership and management is elaborated to bring context to the case examples. Also, the background on TGDA is elaborated. Second, the three-part process is presented. Finally, findings and conclusion are provided.

Figure 1.
Research methodology
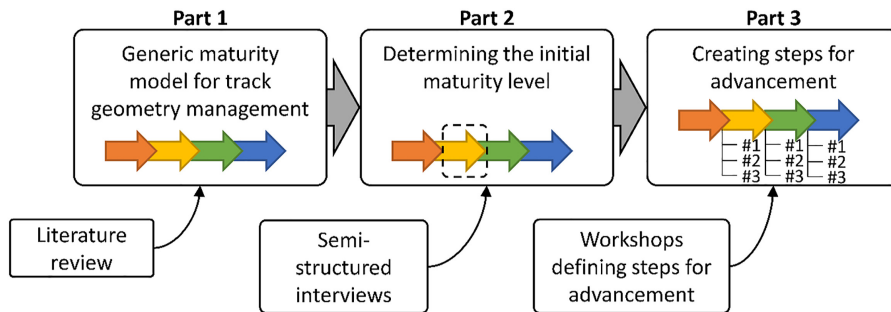
2. Background

2.1 Finnish rail network ownership and management

The reader must consider that this study was done in the context of Finnish rail network ownership and management. Even though the framework created in this study is meant to be generic, the underlying organizational arrangements inevitably affect the way the framework is used. Therefore, this section is dedicated to elaborating the basic structure of Finnish rail network ownership and management.

The state-owned rail network in Finland is around 6,000 km long. The track network is mostly single track, and around half the length of the network is electrified. The maximum axle weight is primarily 22.5 tonnes; however, some lines have 20 or 25 tonne maximum axle weights. The maximum speed for passenger trains is 220 and 120 km/h for cargo trains, but most of the network is limited to slower speeds than the maximum. The division of responsibilities for managing the Finnish state-owned rail network is presented in Figure 2. Management of the state-owned rail network is run by the Finnish Transport Infrastructure Agency (FTIA) or Väylävirasto in Finnish. The FTIA is steered by the Ministry of transport and communications (LVM), which is a branch of the Finnish government. The permits to run the rail network are controlled by the Finnish Transport and Communications Agency, Traficom. The FTIA's role is to be the infrastructure owner and organize transportation on the network in accordance with LVM steering while satisfying Traficom's requirements.

The FTIA outsources its daily track management and M&R to private companies. The FTIA sets the guidelines on which the operations are based. The FTIA also tenders and supervises the contracts for track management, track maintenance and track geometry measurements. Track managers are private consultant companies who are responsible for managing and supervising daily M&R. Daily M&R is conducted by private rail construction and maintenance companies. Track geometry measurements are conducted by a private company. Periodical measurements are performed using one track recording car for the whole network. A new contract for the track recording car was tendered in 2016, and in 2021, the new track recording car started commercial operation. Therefore, analysing the track geometry measurement results is very topical in Finland, as new policies and practices are being formed.

2.2 Track geometry deterioration analysis

Track geometry describes the position and location of the rails. Track geometry can be measured using either absolute or relative measurements. Absolute measurements are generally performed using a total station or a GPS measurement device to provide coordinates for the rails in a specified coordinate system. Relative measurements, on the other hand, provide measurement data about deviations from an ideal geometry, thus describing
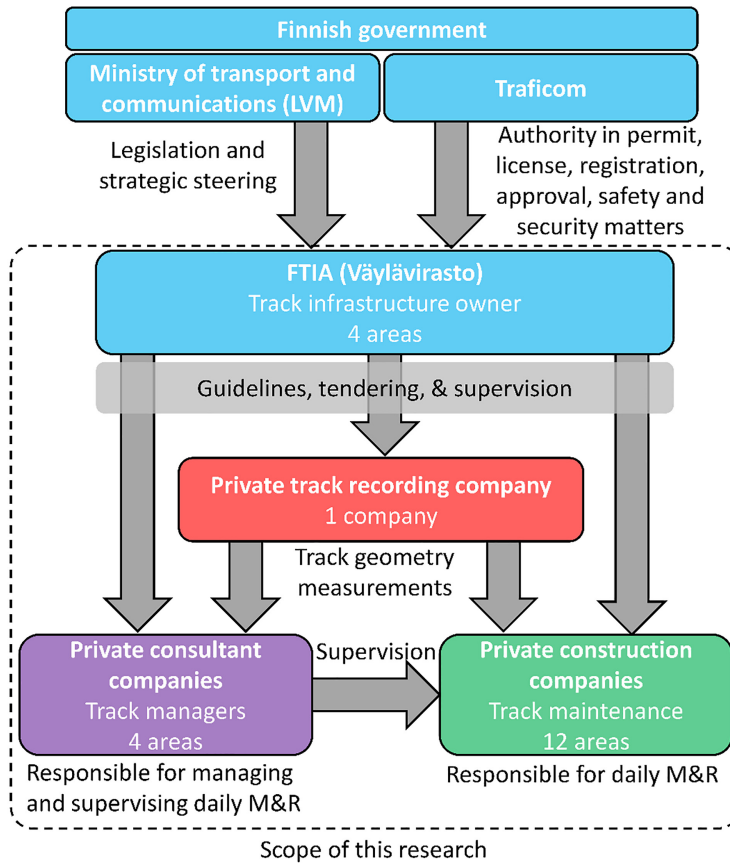
Figure 2.
Division of
responsibilities in
Finnish rail network
ownership and
management

the smoothness of the track geometry. Relative measurements are usually performed using a track recording car. Relative track geometry measurements are predominantly used for statistical TGDA because they are conducted recurrently, continuously, and they offer information about the quality of the structures rather than positioning information. Therefore, analyses based only on relative track geometry measurements are discussed from hereon. It is also worth mentioning that instead of using track geometry measurements, track geometry deterioration could also be approached with mechanistic models. However, their use is not regarded in this study, as they are better suited for individual structure resilience analyses rather than complete sections of track with varying structure types (Elkhoury *et al.*, 2018).

The basic use cases for (relative) track geometry measurements are the inspection of safety and quality of the tracks. If the measurements reveal deviations exceeding a safety threshold, traffic is restricted and immediate maintenance actions are taken (Figure 3a). If the measurements reveal only poor quality, but the safety limits are not exceeded, maintenance is planned to be conducted soon, but not immediately. The limit values for safety and maintenance limits are presented in the international standard series EN-13848, and they are usually specified further in national guidelines.

More advanced use of the track geometry measurements includes collecting data from several measurements and forming time series data. Typically, the standard deviation (SD) of
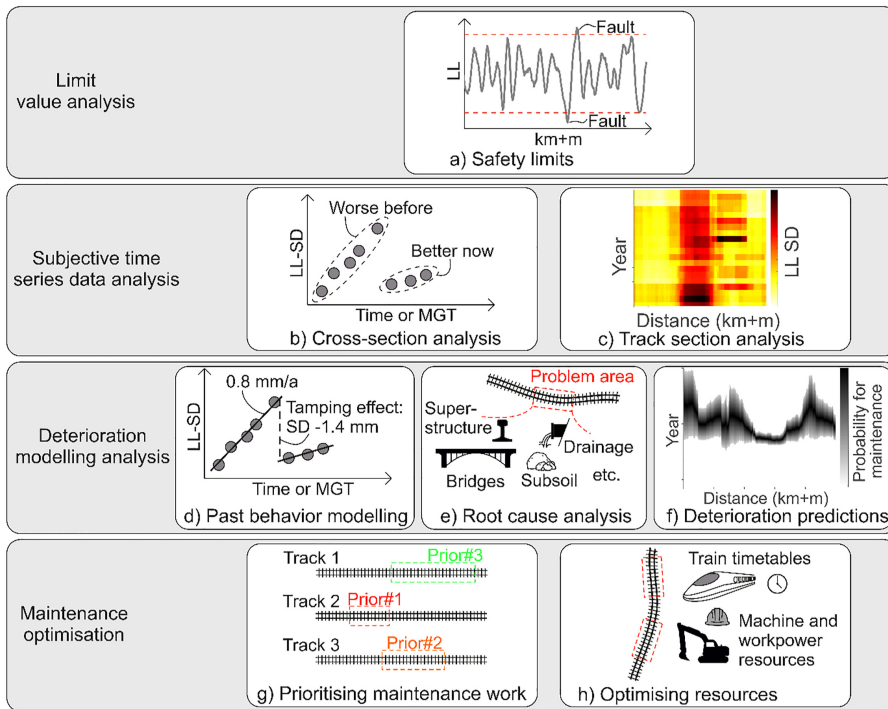
the vertical track geometry measurement signal, or in different terminology, the longitudinal level (LL) is used in the time series data analyses (Higgins and Liu, 2018). The SD provides a smooth parameter, which is easy to interpret and align amongst different measurements. The LL SD values can be plotted and examined manually, and interesting trends can be observed with suitable tools, for example, individual cross section measurement histories or heatmaps (Figure 3b and c). However, for more detailed analyses, track geometry behaviour is modelled using some mathematical idealization. The basic modelling methods include linear, exponential and logarithmic models (Neuhold *et al.*, 2020). In these approaches, the maintenance intervals need to be defined first, either from the maintenance history or by evaluating decreases in the LL SD (Sauni *et al.*, 2022). Additionally, some more complex models, such as stochastic and probabilistic models, have also been used to model the behaviour of track geometry (Elkhoury *et al.*, 2018; Higgins and Liu, 2018). Regardless of the model used, the result of track geometry deterioration modelling is generally a numerical description of the track geometry deterioration behaviour. The numerical values representing the behaviour can be used to compare the track geometry deterioration rate of different areas and time periods, or to evaluate past maintenance effectiveness (Figure 3d). This information can be combined with other asset data to investigate the root causes for track geometry issues (Figure 3e) (Sauni *et al.*, 2022). Track geometry deterioration modelling can be used to predict future behaviour based on the track geometry deterioration history (Figure 3f) (Sauni *et al.*, 2022). The predictions can be used to prioritize maintenance and optimise resources before safety limits are exceeded (Figure 3g and h). Prioritizing maintenance based on track geometry deterioration modelling is necessary, as there are usually more repair needs than there are available funding. After the maintenance needs have

been prioritized, maintenance resources (track work machines and timetables) can be optimized. Maintenance prioritization and resource optimization can be combined in some organizations, if the maintenance is conducted by the track owner, see for example (Bressi *et al.*, 2021). Otherwise, if a company, responsible only for track maintenance but not track ownership, performs the prioritization and resource optimization, they can emphasize resource optimization to ease their work schedule, instead of focusing on which segments of the track require the most immediate attention. All the analyses mentioned above are summarized in Figure 3.

2.3 Maturity models

Maturity models provide a good basis for controlled incremental development, as their background is in managing large software projects (Paulk *et al.*, 1993). The capability maturity model (CMM) can be considered one of the original maturity models, from which many variants have been developed, each with their own characteristics (Albliwi *et al.*, 2014; CMMI Product Team, 2010; Helgesson *et al.*, 2012; Paulk *et al.*, 1993; Poeppelbuss *et al.*, 2011). These maturity models have been used, for instance, in setting future goals for development with high success (Herbsleb and Goldenson, 1995).

Nonetheless, the models are not without criticism. One major critique is that the readymade models, such as the CMM (Paulk *et al.*, 1993), do not cover every aspect of an organization (Albliwi *et al.*, 2014). Furthermore, Poeppelbuss *et al.* (2011) present three general challenges associated with using maturity models: (1) vastness of theoretical research, (2) empirical assessment of maturity levels and (3) the lack of one linear sequence for development in practice.

In this study, the comprehensiveness of maturity models is not as important as their adaptability in defining the maturity levels within these models. This is due to the research focusing on a clearly defined process, TGDA, rather than a whole organization. As for the general challenges associated with maturity models, this study applies only the principles of past maturity models, which eliminates the need for a readymade model (challenge 1). The assessment of maturity levels was based on the interviews and workshops held with relevant stakeholders which provided a comprehensive assessment (challenge 2). Finally, the end results, a framework for TGDA development, will be based on a maturity model, but the process will not be strictly linear (challenge 3). Rather, the process will describe the order of the steps required for advancing TGDA.

The process of creating a maturity model has been reported in previous studies (de Bruin *et al.*, 2005; Maier *et al.*, 2012). This includes, at least, phases for planning, developing, evaluating and maintaining the model (Maier *et al.*, 2012). Planning and developing a maturity model require vast domain knowledge that must be obtained from industry experts, by conducting surveys, interviews and workshops (Maier *et al.*, 2012). Model evaluation can be done in different ways: evaluation by the model authors, evaluation involving the industry experts and evaluation through practical case-use (Helgesson *et al.*, 2012). The created model must also be maintained by re-evaluating the current maturity level and revising goals.

Similar to the current study, the supporting ideals of maturity models have been applied to different applications in previous research, for example, building information models (Eadie *et al.*, 2015) and railway cybersecurity (Kour *et al.*, 2019). Maturity models have even been integrated into railway operations in the International union of railways (UIC) application guide for asset management (UIC, 2016). However, the maturity model reported by the UIC covers the overall maturity of an entire asset management organization which is too general a starting point for specific process development, such as TGDA. Therefore, this study applied and modified the established maturity model as the basis for TGDA development, as is reported in section 3 of this paper, to fill this gap in research.

The principal justification for using a maturity model as the basis for TGDA development was the possibility of assessing current maturity and setting intermediate goals for tracking development. These strengths have been observed in previous research on the topic (Hirose *et al.*, 2020). Incremental evolution rather than sudden revolution is preferred also in this case because the development concerns an ongoing safety critical process, which cannot be disturbed. More specifically, track geometry measurements are used to determine whether it is safe to conduct rail traffic. If this process is seized, or the results interpretation is disturbed, this might result in unacceptable track irregularities going unnoticed, which can cause train derailments. Furthermore, incremental development helps to form logical progress for the development as the next maturity level should not be pursued until the conditions of the current maturity level are satisfied. This prevents, for example, implementing elaborate deterioration models before data production and pre-processing are in order. Finally, it should be noted that the primary objective of this research is not only to create a maturity model but also to develop the competence of an asset management organization. To achieve this result, maturity models are utilized as the vehicle for implementing development.

3. Research process

3.1 Part 1: adapting a generic maturity model for TGDA development

In this study, the maturity model from UIC (2016) was applied to track geometry deterioration management. The initial version of the TGDA specific maturity model was created by the authors of this paper based on the different types of TGDA (*cf.* Figure 3). The further development and evaluation of the model were performed with industry stakeholders in the workshops reported in part 3 of this research. A consensus over the contents of the maturity model and the respective framework was reached during the workshops.

The generic maturity model was modified into a four-level model with the following levels (Figure 4). The first level is ensuring traffic safety, as chaotic track geometry management is not an option for a responsible asset manager. Ensuring safety means periodically measuring track geometry to reveal locations with deviations exceeding safety thresholds and requiring immediate maintenance. The next level is monitoring track quality, which includes, for instance, collecting measurement time series data in a database. These data can be analysed subjectively to reveal areas with recurrent problems and progressive deterioration. The third level, track geometry management, includes connecting other asset management systems and data to track geometry measurement databases and modelling track geometry deterioration. With these advancements, for example, the root causes of track geometry anomalies can be investigated. The last level, optimizing track geometry, contains optimizing and prioritizing maintenance according to available maintenance resources, track repair time and track class, for instance. The excellent level was not considered because excellence can be defined as having fully optimized maintenance.
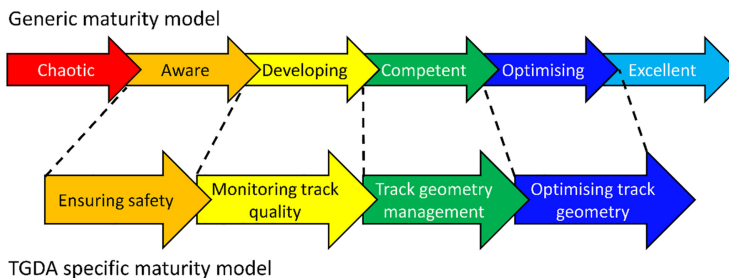

Figure 4.
A generic maturity model applied to TGDA

The TGDA specific maturity model was used as the basis for investigating the maturity level in Finland (part 2 of this study) and for determining a detailed framework for future development (part 3 of this study). Detailed contents for each level in the maturity model were researched in part 3 of this study.

3.2 Part 2: investigating the maturity level in TGDA
The aim of this part of the study was to find a suitable way of assessing the current maturity level in TGDA. The current maturity level must be investigated first because it is pertinent to create the framework based on actual needs from the industry, as the framework is to be implemented in practice. Thus, the current processes and development needs for TGDA must be investigated by interviewing experts in the field. In the case of Finland, the interviewees included experts from all private companies that had either track M&R or track management contracts with the FTIA and FTIA's own personnel. Most interviews were group interviews comprise experts from the same organization. The interviewees were a representative sample of Finnish railway asset management as all track management areas and organizations were represented. The interviewees included:

- 5 track maintenance experts from 3 track construction companies

- 12 asset management experts from 4 track asset management companies

- 5 track inspection and maintenance experts from the infrastructure owner

The interviewees were highly experienced with 18 years of experience from the railway sector on average.

The interviews were conducted as semi-structured interviews. The rationale behind choosing semi-structured interviews as the mode of surveying included:

- Low number of interviewees, $n = 22$

- Exploratory nature of the interviews

- Possibility of group interviews

The low number of interviewees was due to the limited number of people working closely with track geometry data in Finland. Furthermore, the interviews were exploratory as there was little written about current practices in Finland. Also, many participants wished to be interviewed in groups along with colleagues from their organization to allow for colleagues to supplement their answers. Semi-structured interviews allowed for taking all these into consideration while still having some control on the topics that were discussed in the interviews.

All interviews followed the same format. The interviews were segmented into three themes with relevant subquestions. The subquestions were used to generate discussion and to guide conversation if needed, but the participants were free to answer as they pleased, and follow-up questions not belonging to the standard form were presented as conversations diverged. The themes and questions were identical for every interviewee regardless of their position or organization. The basic structure of the interviews is presented in Table 1. The interviews were conducted, reported and analysed in Finnish, but the form and conclusions were translated into English for this paper.

The interview structure had a larger number of simpler questions introduced first to get the interviewees talking and relaxed about answering. Later in the interview, the questions were more open ended and there were fewer of them to allow the interviewee to answer in greater length, and possibly even wander off topic. The purpose of theme 1 and its subquestions was to investigate the current use of track geometry measurement results and

Theme	Sub questions
T1: Current use of track geometry measurement results	Q1: For what purpose do you use track geometry measurement results in your line of work, and what information do you require from them?
	Q2: Who handles track geometry measurement results in your organization, and are there differences between the use-cases of different personnel within your organization?
	Q3: Which guidelines do you follow in analysing track geometry measurement results, and what other guidance do you know of related to the topic?
	Q4: Are there deficiencies in the guidelines related to your use?
	Q5: What procedures, related to your work, are conducted/ordered in different circumstances according to track geometry measurement results?
	Q6: Do you use track geometry measurement results for some other purposes besides analysing the condition of the track, for example, contractual purposes or work planning?
T2: Procedures for analysing track geometry measurement results	Q7: Do you refine the track geometry measurement results (e.g., with statistics, models or key figures) in addition to the results provided to you?
	Q8: Do you know of some methods for refining the measurement results that would be suitable for your use but are not currently in use?
	Q9: What other sources of information do you use when analysing track geometry measurement results (e.g., plans, maps, photos and reports)?
	Q10: What other sources of information would you require to aid track geometry measurement result analysis, but they are not currently available?
T3: The potential of track geometry measurement result analysis	Q11: What could be achieved by analysing track geometry measurement results if current problems did not exist?
	Q12: What do you wish to be changed in the processes of analysing track geometry measurement results?
	Q13: What directions for future development do you know of, or would hope to see, regarding track geometry measurement analysis?

Table 1.
The structure of the
interviews

describe the general process of handling the data in the organization. This theme was especially important because the framework was to be built upon current practices, which were unknown beforehand. Theme 2 discussed the analysis of track geometry measurement results in a narrower focus. Special attention was paid to the further handling and refining of the results by the interviewees. The ways interviewee have had to work around and complement the current processes would tell a lot about what deficiencies current processes have. Questions 6, 7 and 9 had examples within them, which could be interpreted to be leading the interviewee on. However, this was a deliberate choice to have the examples presented with the questions, as an expert on the matter, that can consider the examples to be self-evident and not mention them otherwise. Theme 3 focused on getting the interviewee to reflect on what the limitations to the current analyses really are, what could be done to change them and what would be the effect.

3.3 Part 3: creating a framework based on the TGDA maturity model
Once the maturity model and current maturity level were investigated, it was time to create a framework for advancing TGDA development. The framework was designed in a set of three workshops. The topics of workshops were (1) knowledge areas, (2) development paths and (3) implementation plan. Knowledge areas refer to the categories which form the structure of the framework. Development paths refer to the tangible contents of maturity levels. The workshops were held with 2-month intervals in the winter of 2021–2022. The contents of each workshop regarding the framework are shown in Figure 5.

The goal of the first workshop was to determine the knowledge areas that will structure the framework. The workshop was held online on Teams, and the group work was done on
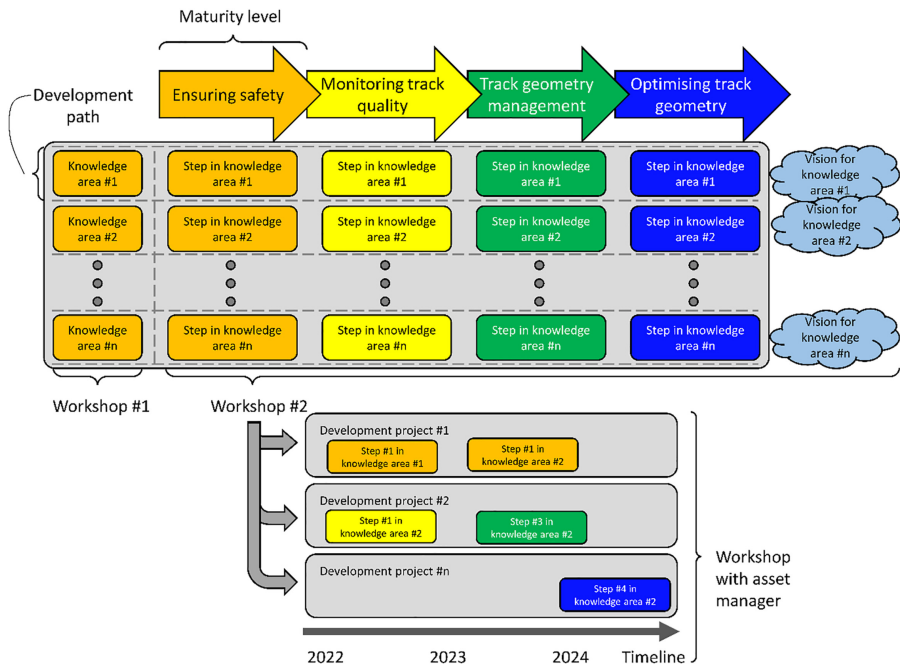
Figure 5.
The design of the
workshops

the whiteboard application Flinga, which could be operated freely by any participant. There were 23 participants and four organizers who were divided into groups of 3–4 people, each group with their own whiteboard. The participants were divided into groups based on their affiliation so that infrastructure owners, asset managers and maintenance personnel were mixed and represented as diversely as possible in different groups. The participants were first asked to come up with possible knowledge areas by answering a supporting question: "What areas or processes are affected by or connected to track geometry measurements in your line of work?" From here on, the participants created mind maps of the most essential knowledge areas and operations related to them. These mind maps were the result of the first workshop. The mind maps were later analysed using ATLAS.ti to identify the most frequently mentioned topics. Overall, 323 observations in 65 codes and 8 code groups were created. From these codes and code groups, six knowledge areas were created to be further developed in the second workshop.

The goal of the second workshop was to create development paths to the six knowledge areas obtained from the first workshop's results. The knowledge areas were presented to the participants along with preliminary visions for the future of said areas. The participants were divided into six groups, and each group was given one knowledge area. The first task was to challenge and supplement the given preliminary visions. After this, blank four-level maturity models, as described in part 1 of this study, were given, and participants were asked to fill in the models with concrete actions for each stage. Then, the groups were rotated twice so that they could comment and supplement the previous groups' work.

Before the third workshop, an implementation plan was developed in cooperation with the asset manager. The implementation plan included placing the steps from the framework on a timeline within a relevant process, whether it be a development project, contract or guideline. In this way, the contents of the framework could be implemented concretely as the next

development milestones for said processes. The third workshop concentrated on commenting and supplementing the framework and implementation plan. In addition to getting much valued feedback on the framework and implementation plan, the final workshop played a role in presenting the results and engaging different organisations in the forthcoming development.

4. Results and discussion

In part 1 of this study, a maturity model was adapted for incremental advancement of TGDA in railway asset management. The developed four-level maturity model functions as the basis, on which the framework was built in part 3 of this study. The new knowledge produced concerned the application of maturity models into a novel domain, TGDA in railway asset management. The purpose of this maturity model was only to create the structure for the developed framework, not to be tested and validated as a stand-alone maturity model, as is common with applied maturity models (Helgesson *et al.*, 2012). The validity of the maturity model and consensus over the contents of the model were verified during the industry stakeholder workshops.

The interviews, held in part 2 of this study, were successful in determining the current maturity of TGDA in Finland. The exploratory nature of the semi-structured interview provided a systematic way of collecting data while enabling leeway for the interviewees' answers. The interviews revealed different use-cases and user types, which helped in designing and supplementing the framework. This novel information was utilized in constructing the initial framework for part 3 of this study.

As a conclusion from the interviews, the maturity level of TGDA was primarily at the *monitoring track quality* level (Figure 6). In Figure 6, the observations in the green area indicate that the level is satisfied to that degree. The observations in the red area indicate that the level is not satisfied with regard to the comments. Figure 6 does not depict the maturity of

+For

- Periodical track geometry car measurements are conducted
- Limit values are set for different track classes

- Measurement reports are collected in a central database
- Individual faults are analysed and recurrent problems identified

- Individual attempts in assessing root causes of problems using asset data

- Individual attempts in assessing effectiveness of different tamping plans

Ensuring safety → Monitoring track quality → Track geometry management → Optimising track geometry

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- Time series data is not formed
- Track fault analysis is based solely on past experience

- No central system for connecting asset data to track geometry data
- Maintenance rarely proactive

- No prioritisation for maintenance work or optimisation for resources
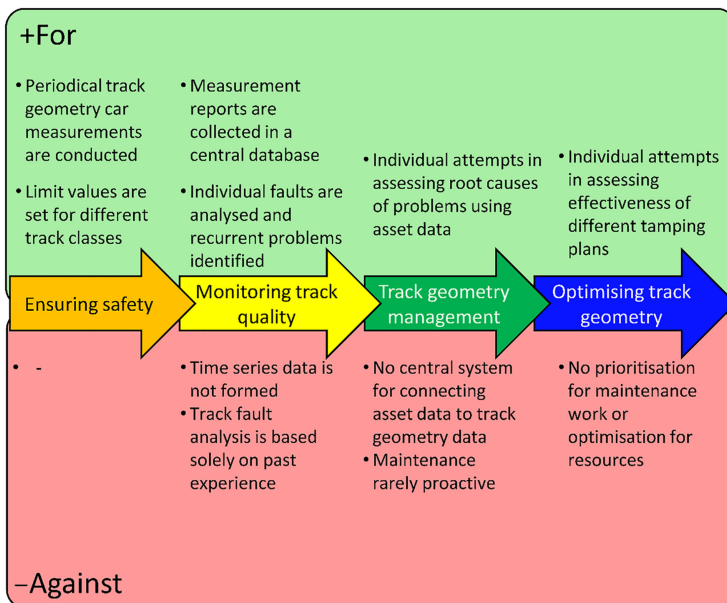
−Against

Figure 6.
The initial maturity level of TGDA in Finland

asset management throughout the asset management organization but only the maturity of the TGDA. There were some observations of more developed analyses made by individuals on their own. The individual more developed analyses included assessing what quality levels could be achieved with different tamping plans and connecting asset data to recurring problem areas. However, overall, current practices in the industry are more focused on the *monitoring track quality* maturity level. The focus in TGDA has been in identifying problem areas on track sections and to plan their remediation. For example, numerical track geometry measurement data are not shared, there are no methods in use for modelling track geometry deterioration, and asset data are not generally connected to track geometry measurement data.

The end-result of the workshops was the framework for advancing TGDA in Finland (Figure 7). The framework included six development paths: Measurement result analysis (1) referred to the process after measurement when visualizations and analytics are produced for the user. Data systems (2) covers the software needed to store data and create the analytics. Maintenance (3) refers to designing, conducting and supervising the maintenance actions included in the current maintenance contracts, whereas asset renewals (4) indicate repairs and investments not included in current maintenance contracts (e.g. large-scale track renewals). Knowledge (5) includes the ability to utilize the results as well as the required guidelines and training. Lastly, there are the contracts (6) needed to acquire the services required to achieve a certain maturity level. Each development path has a vision depicting the ultimate goal of said path and four maturity levels presenting incremental steps in progressing towards the vision. The maturity levels increase to the right. A maturity level contains all the requirements from previous levels, thus making the development cumulative. Before advancing to the next maturity level, all development paths should satisfy the current maturity level. In this way, the development is incremental and builds upon implemented practices, which is important in creating tangible progress during development. Also, as track geometry condition monitoring is a safety critical process, new features must be implemented one-by-one while making sure the current process is not disturbed.

The framework is a tool for advancing TGDA in railway asset management. The framework enables examining the development in the present and distant future at the same time, all the while maintaining focus on the correct order for the development. This is achieved by following the development paths in the framework. This was found very helpful when turning visions into actual development projects.

The workshops yielded valuable information to supplement the framework. If the framework was created using only available literature, many pragmatic aspects would have been overlooked. For example, the diversity of different TGDA user types and use cases would not have been uncovered without the workshops. Additionally, the workshops engaged the stakeholders in the development. As the framework was developed in the workshops with the stakeholders, the development was transparent, and the stakeholders had an influence on the framework. This is believed to reduce resistance to change and provide community support for the succeeding development projects. Similar observations regarding the benefits of workshops have been made in previous research (Ørngreen and Levinsen, 2017; Phaal *et al.*, 2007).

The limitations of this framework concern the influences of the Finnish railway operating environment on the study. The perspective in the framework was a buyer–supplier model, in which the infrastructure owner acts as the buyer who has the responsibility for implementing the development. Additionally, the participants were solely from Finland, limiting the different operating environment experiences obtained in the interviews and workshops. Nevertheless, the steps within the framework were designed to be universally applicable, but the global validation of the framework was left as a source of future research. It is also worth noting that the steps within the framework are not equal in effort. Therefore, the
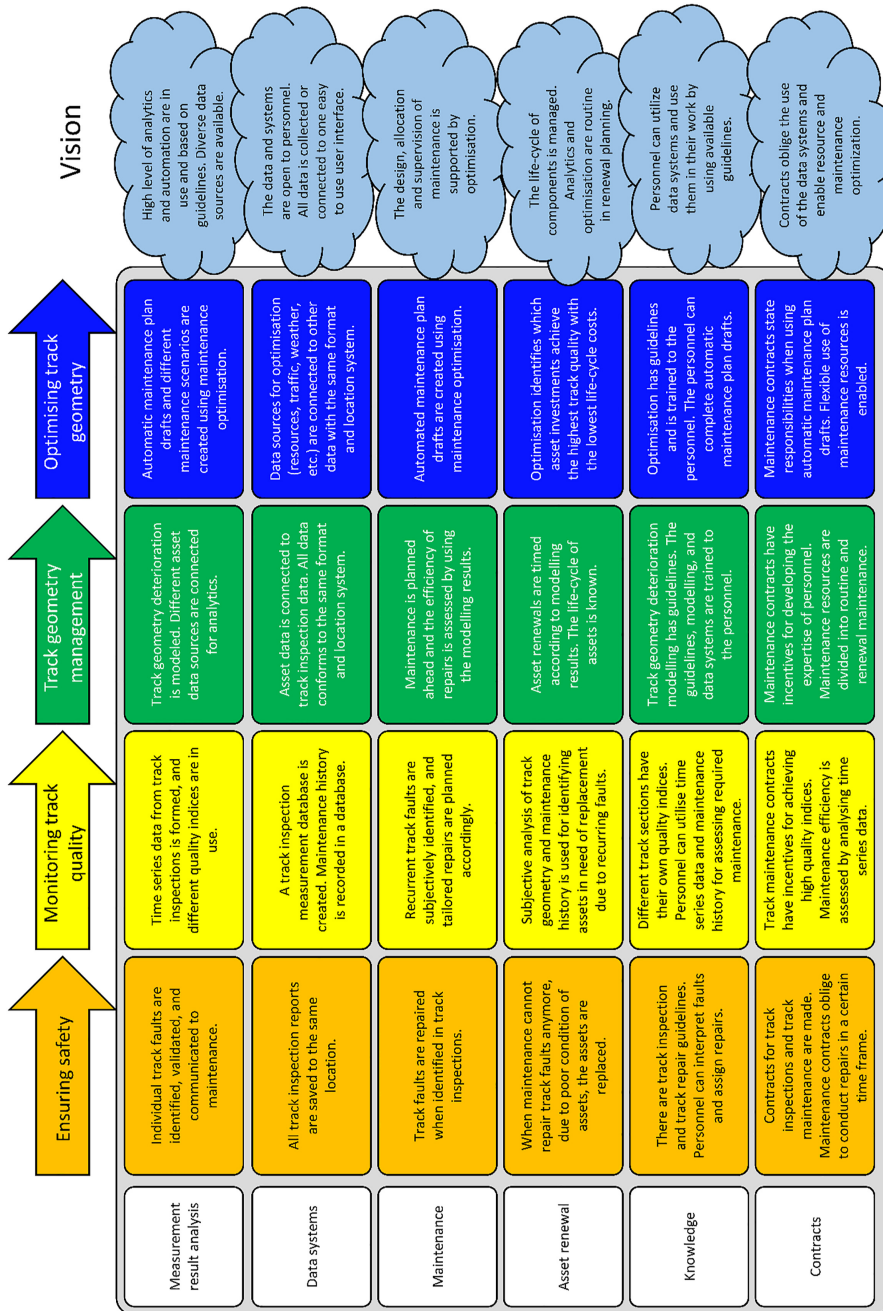
Figure 7.
Framework for
advancing TGDA

implementation of a step must be individually planned, as one step may require years of development, whereas others only slight amendments to guidelines. The framework should not be seen as a development project but as a tool for turning a vision into a series of development projects.

The practical implications of the TGDA development framework include improvements to the way data are utilized in safety and condition monitoring in railway asset management. Currently, much of the data are subjectively assessed, which creates opportunities for human error. With advanced TGDA, human errors in safety and condition monitoring can be avoided with, for example, automatic alerts and predictive analytics. Furthermore, maintenance can be planned more efficiently, thus reducing costs by eliminating redundant maintenance. These benefits are obtainable by any asset management organization that increases their capabilities in data analytics.

5. Conclusion

In recent years, research on TGDA has evolved greatly, and novel information on the condition of railway tracks can be produced to streamline the use of maintenance resources. However, the implementation of TGDA into railway asset management is lagging due to the complexity of altering ongoing safety critical processes. Therefore, the implementation of TGDA requires in-depth research to narrow the gap between research and practice to obtain tangible societal benefits from previous research.

In this study, a framework for implementing TGDA into railway asset management was developed. The framework was developed, tested and applied in the Finnish state rail network asset management. The framework was established in three parts: (1) a maturity model was adapted as the basis for the framework, (2) semi-structured interviews were conducted to evaluate the current maturity level and (3) workshops were held to construct the detailed content of the framework.

The main contribution of this study is the novel framework presented in Figure 7. When an asset manager identifies their placement within the framework and applies the framework into designing their development projects, they can create a vision that can be reached with incremental development. This is especially useful when the asset manager wants to create a long-term strategy for TGDA development, while keeping the implementation of development highly practical. Furthermore, the incremental and cumulative progress achieved with using the framework is much easier to communicate to stakeholders and implement than abrupt revolution.

The practical implication of this study is the possibility for an asset manager to advance their TGDA, thus improving the efficiency of condition monitoring, which reduces safety risks and maintenance costs. The framework was successfully tested and applied in Finnish state rail network asset management; The current maturity level in TGDA was identified and development paths were tailored. However, the limitation of this study was that the framework was validated only in the workshops in a Finnish operating environment, even though the framework was designed to be universally applicable. The validation of the framework into different operating environments is a source of future research. Further research on the topic could also include different asset management processes, for example, the life-cycle management of track components.

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Corresponding author
Mikko Sauni can be contacted at: mikko.sauni@tuni.fi