

Increased Railway Infrastructure Capacity Through Improved Maintenance Practices

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PREFACE

The research work presented herein has been carried out between Aug. 2010 and Nov. 2012 at the division of Operation and Maintenance Engineering, Luleå University of Technology and Luleå Railway Research Centre (JVTC). The interest and financial support of Swedish Transport Administration has been the means to this end.

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Stephen Mayowa Famurewa
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ABSTRACT

The expansion of economic activities and increasing mobility of people on short, medium and long distance trips is an issue that requires attention in the transport industry. The need to address this demanding issue in a sustainable and economically efficient way is the core of general capacity challenge in railway industries. This informs the strategic objective of ensuring an efficient and competitive mode of transportation by many infrastructure managers including Swedish Transport Administration. An aspect of railway infrastructure management which is promising for the enhancement of existing infrastructure capacity is the improvement of maintenance process. The frequency of traffic interruption due to infrastructure failure, reduction of functional performance due to infrastructure degradation and length of track possession time are incidences limiting operational availability of railway infrastructure and capacity thereof. Achieving the goal of supporting the inherent capacity of existing railway infrastructure requires implementation of effective & efficient practices for large and small impact maintenance tasks.

This research has addressed the above mentioned concerns by studying the opportunities which maintenance presents towards enhancing the capacity of existing railway infrastructure. Outsourcing aspect of maintenance organisation has been studied and a conceptual framework to facilitate the implementation of performance based maintenance contracting is proposed. This will enable the achievement of quantity and quality requirements of traffic performance. Furthermore a risk assessment procedure has been presented to identify bottlenecks restricting the capacity on any line and also for continuous improvement has been suggested. A model for planning and scheduling of tamping action has been presented. This will lead to reduced track possession time and minimum cost of intervention while geometry quality is kept at desirable level. Case studies on the above procedures and model have been presented to demonstrate their application for maintenance improvement.

The outcome of this study is development of effective maintenance principles that should serve as basis for maintenance improvement programme to support reliable and inherent capacity of existing railway network. This improvement covers organisational and technical performance, all enhancing the possibility to increase the capacity of railway network.

Keywords: maintenance improvement, railway infrastructure, track possession time, performance indicator, capacity, outsourcing, bottleneck, tamping, schedule optimization.

LIST OF PAPERS

LIST OF APPENDED PAPERS

PAPER 1

Famurewa, M. S., Asplund, M., Galar, D., Kumar, U. (2012). "Implementation of performance based maintenance contracting in railway industries", *International journal of Systems Assurance Engineering and Management* (Accepted).

PAPER 2

Famurewa, M. S., Asplund, M., Rantatalo, M., Kumar, U. (2013). "Maintenance improvement: an opportunity for railway infrastructure capacity enhancement" *International Heavy Haul Association Conference*.

PAPER 3

Famurewa, M. S., Asplund, M., Parida, A., Kumar, U. (2012). "Application of maintenance performance measurement for continuous improvement in the railway industries", *International journal of Strategic Engineering Asset Management* (Accepted)

PAPER 4

Famurewa, M. S., Xin T., Rantatalo, M., Kumar, U. (2012). "Optimum allocation and utilization of maintenance track possession time: a case study of tamping" *Submitted for publication*.

LIST OF RELATED PAPERS

Famurewa, M. S., Asplund, M., Kumar, U. (2012). "Framework for performance based maintenance contracting" *Nordic maintworld congress*.

Stenström, C., Famurewa, S. M., Parida, A., Galar, D. (2012). "Impact of Cold Climate on Failures in Railway Infrastructure" in *Proceedings of the 1st Maintenance Performance Measurement and Management Conference*.

Asplund, M., Famurewa, M. S., Rantatalo, M., (2012). "Prognostic and health management of wheel condition: integration of wheel defect detection and wheel profile monitoring data" in *proceedings of 2nd International Workshop and Congress on eMaintenance*.

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INTRODUCTION

1.1 Background

Railway transportation is a very important mode of transportation for reasons of safety, cost, carbon emission and energy requirements. These present it as a sustainable, safe and cost effective mode of transportation with a distinguished role in economic expansion in terms of passenger and freight services.

The expansion of economic activities and the increasing mobility of people on short, medium and long distance trips is an issue that requires attention in the transport industry. The need to address this demanding issue in a sustainable and economically efficient way is the core of the general capacity challenge in the railway industries. In effect, infrastructure managers (IM) are tasked with the ambitious targets of increasing the competitiveness of railway transport through capacity and service quality improvement.

The situation is rising and there are notable indications of the emerging trend of this capacity challenge for both freight and passenger traffic. These indications include high seat & vehicle utilization, recurring unpunctuality, poor robustness & irregularity of time schedule, increasing demand for train path, shifting of freight operation from day to night period and difficulty in getting track possession for maintenance [1]-[3]. Furthermore, in the EU 15 countries there has been 15% and 28% increase in rail freight tonnage-kilometre and passenger-kilometre respectively over the period 1990-2007 [4]. In Sweden there has been a noticeable increase in the annual tonnage-kilometre and passenger-kilometre except in 2009 when there was a drop due to reduced global economic activities [5]. Furthermore, there is an anticipated increase in traffic volume on the heavy haul line in Sweden, for example from the present 28MGT on the northern section of the line to 45MGT in 2015. This will most likely necessitate axle load increase from 30 to 32.5 tonnes and large improvement in the railway infrastructure management

philosophies and practices.

The evolution of railway industry has witnessed several re-organisations until the present modern railway infrastructure management was reached [6], [7]. The responsibilities of the modern infrastructure management with either private or public ownership can be summarised as below:

- Creating and allocating the capacity of the infrastructure
- Control of the traffic on the infrastructure
- Ensuring the quality, safety, reliability and availability of the infrastructure

The vision of Infrastructure Manager (IM) usually depicts the above responsibilities and their strategic challenges or objectives are informed by the vision as well as other stakeholders' requirements. The structure of IM organisation is often divided into functional/business units of traffic management, operation & maintenance management, investment management, public relations management and other additional functions. The performance of any IM with respect to the above mentioned responsibility especially meeting the capacity demand of the stakeholder depends on the contribution of the functional department.

An essential aspect of railway infrastructure management necessary for the enhancement of existing infrastructure capacity is the improvement of maintenance process. This will entail the development of effective principles for reinvestment and routine maintenances for both large and small impact maintenance tasks. Furthermore, the increasing technical demand on the quantity and quality of railway transport system requires continuous improvement of the maintenance process from the strategic point of view to the operational perspective. The changing structure, demands of stakeholders, complex technology, legislations and also business goal to optimally utilize the existing railway infrastructure capacity are also factors necessitating effective maintenance practices [6], [8].

It is marked that effective capacity management is a key requirement to the success of railway sector. Thus several research efforts within the railway industries in recent years were centred on managing the capacity and service quality of the existing railway infrastructure network. The researches extend from improvement of rail services, rail management system and rail technology, all of which contribute towards a sustainable and more competitive railway transport [4]. Capital expansion of infrastructure is a cost intensive means and it requires long term plan for increasing capacity [1]. Thus other cost effective and short term means of supporting the capacity of existing railway infrastructure including effective utilization of infrastructure possession times are potential opportunity for capacity enhancement.

Achieving the goal of supporting the inherent capacity of existing railway infrastructure entails optimization of maintenance decisions and actions which will influence infrastructure performance, reliability, degradation and availability.

1.2 Problem Statement

A deduction from the rail traffic statistic of Trafikanalys - the knowledge agency for transport politician on Swedish rail traffic statistic, shows that the length of operated track in Sweden have remained apparently unchanged for the last decade [5]. On the other side the traffic volume in terms of tonnage kilometre for the freight traffic and passenger-kilometre for passenger traffic has increased by 17% and 28% respectively over the same period of 10 years [5]. This has led to increasing capacity utilisation and low quality of service including punctuality [9]. Reliability issue or infrastructure failure is one of the significant root causes of delay and capacity limitation on the Swedish railway network [10]. A substantial proportion of the annual delay on the network is linked to infrastructure failure and this could be due to usage profile mentioned above, environmental impact or deficiency in maintenance. An interesting concern at this point is to check the effectiveness of maintenance function and its contribution towards supporting a reliable railway system even in the face of increasing utilisation.

Furthermore recent capacity evaluation done by Trafikverket has shown that most of the sections in metropolitan areas and some other routes with high socioeconomic impact such as the iron-ore line have high capacity utilisation greater ($>80\%$) [11]. This kind of utilisation is likely to be characterised by high failure frequency and impaired service quality due to maintenance deficiency. Should there be any improvement in the current maintenance practices and philosophies, both management and engineering aspects of maintenance function require critical study and review.

1.3 Research Purpose and Objectives

The purpose of this research work is to suggest effective maintenance principles and decision support tool to optimise the allocation and utilisation of track possession time for maintenance function. This will serve as capacity enhancement plan for existing railway infrastructure. The objectives of the research work in precise terms are itemised below:

- Study capacity influencing parameters and the measures deployed for enhancing railway infrastructure capacity.
- Study the present maintenance practice in Trafikverket, to identify deficiency in maintenance as related to its expected outcome and performance level and suggest a continuous improvement plan
- To develop decision tool to support augmented utilisation of track possession time and also effective maintenance.

1.4 Research Questions

The following research questions have been formulated to achieve the set purpose and listed objectives of this study, and also to serve as cardinal points around which the research centre.

- What opportunities does maintenance present for enhancing the inherent capacity of existing railway infrastructure?
- How can a system of indicators be used for continuous improvement of maintenance performance with respect to quantity and quality of delivered service?
- What should be the strategy for optimum allocation and effective utilisation of track possession time with consideration to track quality and cost aspects?

1.5 Research Scope and Limitation

This study covers the organisation, planning, scheduling, assessment and improvement aspects of railway infrastructure maintenance process as related to track possession time and dependability performance. Selected routes are considered in this investigation and also in the demonstration of the methodologies proposed in this study and not the entire network of Swedish Transport Administration. The investigation is limited to routes with high capacity utilisation for obvious reasons. New innovations for high performance maintenance and inspections are not considered in this study and it is also limited to existing railway infrastructure. Thus engineering aspect of investment process is not studied.

1.6 Research structure

The thesis consists of five chapters and four appended papers describing relevant literature and theoretical background to this research work, the methodology, result, discussion and concluding remarks of the research. A tabular presentation showing the connection between the appended papers and research questions is given in Table 1.1 and thereafter a brief description of the thesis content is done.

Table 1.1: Mapping of appended papers and research questions.

| | Paper 1 | Paper 2 | Paper 3 | Paper 4 |
|------|---------|---------|---------|---------|
| RQ 1 | X | X | | |
| RQ 2 | | | X | |
| RQ 3 | | | | X |

The first chapter herein introduces the research with background information and other information giving the pedagogic description of the research process. This serves as foundation for understanding the relevance of the research and also put it in contextual perspective. The second chapter gives a detailed review of the state of the art on the evaluation and management of railway infrastructure capacity and also maintenance process as it applies to railway infrastructure. Maintenance schedule optimisation is reviewed, with special emphasis laid on track possession time and delay minimisation. The methodologies and approaches used in the appended papers are explained in chapter 3. The result of the analysis, modelling, survey and literature study done in this research is presented in chapter 4. The findings and contribution of each article is also explained in the fourth chapter. Finally concluding remark and future works are given in chapter 5.

Paper 1 has studied the organisational aspect of maintenance and its impact on productivity of maintenance. It has described essential elements for implementing a successful performance based maintenance contracting which will enhance achievement of maintenance objectives.

Paper 2 described the framework for the entire research. It described a framework to explore the opportunities which maintenance presents for enhancing the inherent capacity on a network. This framework will facilitate the identification of both critical systems and activities with the largest impact on capacity and also some root causes for non performance.

Paper 3 has investigated the application of maintenance performance system for the identification of bottlenecks and demonstrated its continuous improvement perspective necessary for supporting line capacity and quality of service.

Paper 4 presented an approach to quantify maintenance need, optimally allocate track possession time and effectively utilise it. A case study of tamping action is used to demonstrate the approach.

LITERATURE REVIEW

Issues on railway infrastructure capacity assessment and management is largely becoming of global concern as railway transport is identified to have significant role in economic expansion among other transport modes [3]. In recent years several research efforts within the railway industries has been centred on enhancing the capacity of the existing railway infrastructure network. The researches extend from improvement of rail services, rail management and rail technology, all of which contribute towards a sustainable and more competitive railway transport [4]. This review presents the study done on capacity challenges and enhancement plans especially from the perspective of maintenance functions.

2.1 Railway infrastructure capacity management

The concept of capacity has been defined in different ways over the years; nonetheless an attempt has been made to give a uniform and standard view to the concept of railway capacity. The capacity of railway infrastructure is defined as the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the infrastructure manager's assumption in some nodes, lines or part of the network and quality demand from the market [12]. The following terms are identified in the description of capacity given in Literature [1], [13]-[15].

- Quantity of traffic
- Definite railway infrastructure
- Time span
- Level of service
- Set of given Resources
- Defined threshold

On a given railway infrastructure, capacity is a measure of balance mix of number of trains, average speed, heterogeneity and stability [14]. A specified mix of these four capacity elements describes the consumption and utilization of railway capacity. A Typical mix of these elements that describes the capacity balance for metro and mixed traffic is shown in Figure 2.1. Maintenance function affects infrastructure performance which in turn contributes to the stability or quality of service.

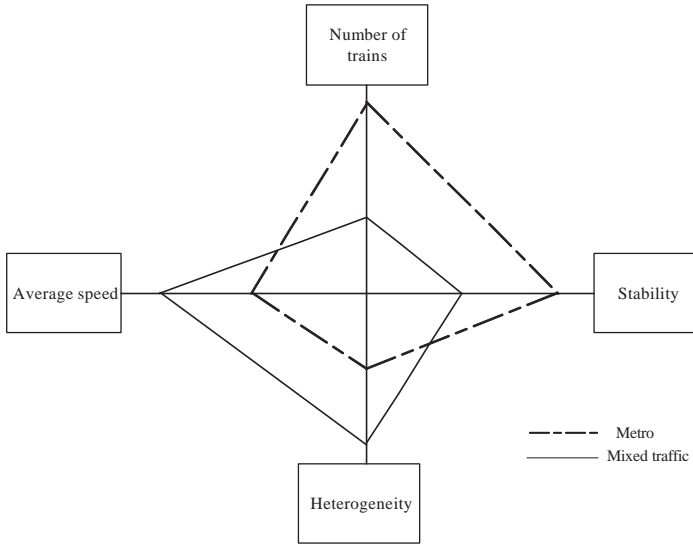


Figure 2.1: Balance of capacity [12].

2.1.1 Types of capacity

In railway transport, capacity of infrastructure could mean different things based on the object of discussion. It could be defined based on inherent, practical or operational considerations. Assessment of the different types of capacity is necessary to prompt augmentation of infrastructure utilization and also improvement of service quality of railway operations. Furthermore it is necessary to identify improvement opportunities in relevant railway transport functions such as maintenance. The different types of capacity mentioned in literatures [1], [3], [12], [13] are described in Figure 2.2.

Another important aspect of Figure 2.2 is available capacity, it is an indication of additional capacity which can be managed by the network or route if best practices and improvement are both identified and implemented. Here is the focus of promising capac-

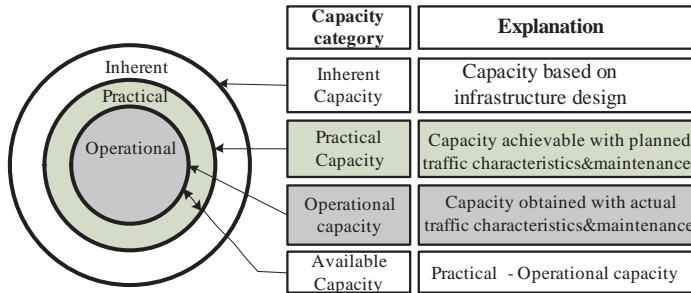


Figure 2.2: Types of capacity measures.

ity management research.

2.1.2 Railway capacity evaluation

The available tools and techniques that are used for the evaluation of railway capacity are in three categories; Analytical, optimization and simulation methods. The analytical methods are capable of modelling the railway system by means of mathematical expressions. Analytical models are sensitive to input parameters but can accommodate limited parameters at a time. The recommendation of international union of railways in UIC leaflets 405 OR is an example of analytical method. It calculates the capacity of line sections taking into consideration the order of trains, buffer time for specified level of service quality and it identifies restrictive segments or bottlenecks [1].

The optimization method is based on obtaining optimal saturated timetables by using mathematical programming techniques. This is achieved by either saturation or compaction of the railway timetable so as to obtain a line capacity with maximum number of train services in a timetable. This involves the use of the principles of operation research such as mixed integer linear programming, game theory, heuristics algorithm, tabu search etc. to obtain feasible schedule with maximum train paths [1], [16].

Thirdly, the simulation method of evaluating capacity is able to model the dynamic behavior of the railway system with respect to its capacity. The models of this method are able to imitate the operation of a real process or system over time and can as such validate a given timetable as well as detect delay and interferences in timetable [13], [17]. Examples of these simulation tools as reported by [1], [18]-[20] and used in both research and operation include; Multirail, Opentrack, VirtuOS, SIMONE, MOM, Railsys.

The general process flow in the calculation of railway capacity as recommended by international union of railways [12] and further demonstrated by [21], [22] is shown in

Figure 2.3. The first step is to define the characteristics of the railway infrastructure; this includes the length of track subdivision, percentage double track, signal spacing, line spacing and so on. Furthermore the timetable with the traffic parameters should be defined; this includes train paths, running time, train mix, average speed, priorities etc. The next step is to divide the railway network into line sections in order to evaluate the capacity on a chosen line section. The division into smaller line is done at junctions, overtaking stations, line end stations, transition between single track and double track and etc. The next thing is to compress the timetable so that the minimum headway time between the trains is obtained, eliminating running time supplements and some other incidental time intervals. The resulting time is the infrastructure occupation time which is the time range for which the facility is occupied in operation.

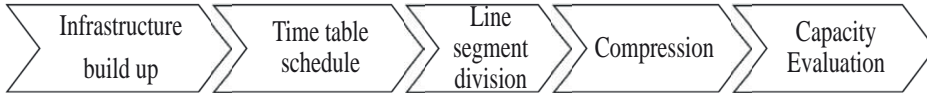


Figure 2.3: General work flow for capacity evaluation.

Capacity consumption in a defined time window is the sum total of infrastructure occupation time, time supplement for service reliability and supplement time for maintenance. Equations 1 and 2 give a simplified expression for capacity consumption recommended by [12].

$$k = A + B + C + D \quad (2.1)$$

$$K = k/U * 100 \quad (2.2)$$

Where k= Total consumption time (min)

A= Infrastructure occupation (min)

B= Buffer time (min)

C= Supplement for single track lines (min)

D= Supplements for maintenance (min)

U= Referenced time window (e.g 1 day or peak time of 2 hours)

K= Capacity consumption (%)

2.1.3 Capacity-Quality of service relationship

The relationship between capacity and quality of traffic service is describes an important behaviour in capacity studies and railway infrastructure management. Basically a given operating condition and set of resources will give specific practical capacity [1], [13]. To

this end an increase in capacity could result in a consequential fall in the level of service over a railway network. Quality or level of service is considered to be a function of capacity, a change in the capacity of a railway network will affect the level of service (LOS) expected on the network. However since most railway systems define capacity at a specific LOS, it is then technically right to express capacity of a railway network as a function of LOS as shown in the hypothetical presentation in Figure 2.4.

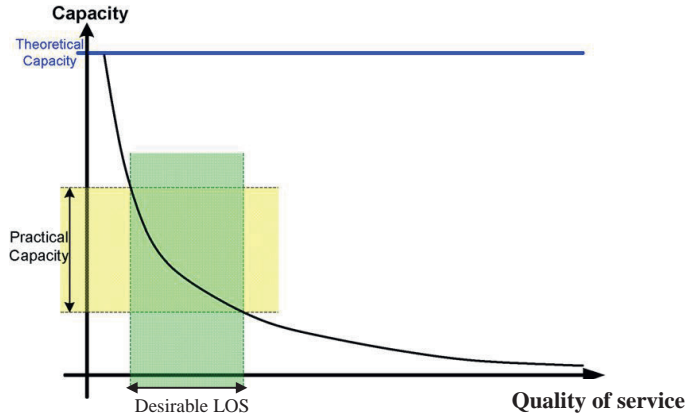


Figure 2.4: Capacity QOS relationship [1].

The quality of service is an important indicator in the railways. It describes the collective effect of service performance which determines the degree of satisfaction of a user of the service [23]. It is characterised by service integrity and other factors related to traffic. Quality of service identified in literature [10], [24]-[26] include:

- Punctuality or delay
- Regularity
- Reliability
- Robustness
- Safety
- Congestion
- Comfort

2.1.4 Railway capacity parameters

Capacity analysis of railway infrastructure is a vital but complex issue, it is not only determined by infrastructure build up, but there are other parameters which have either main or interacting effects on capacity. The characteristic capacity parameters are categorized into three: infrastructure in the system, traffic condition and the operational incidences [13], [17], [27]. A particular combination of these three parameters will have a fixed capacity value, thus changes in any of these parameters will result in the dynamic response of capacity.

- a. Infrastructure: Length of subdivision, track geometry & layout, signalling system, double/single track, meet pass planning point spacing etc.
- b. Traffic: Traffic peaking factor, priority, average speed, heterogeneity etc.
- c. Operation: Track interruptions, speed reduction regime, train stop time, maximum trip time threshold and desired stability/quality.

The scope of this study is limited to maintenance of existing infrastructure and thus the operation parameters are of interest. This covers investigation into track interruptions and outages especially those of high impacts on capacity. In essence the parameters related to the RAMS characteristics of the infrastructure, i.e. the indication of the degree that the infrastructure can be relied upon to function as specified and to be both available and safe.

2.2 Capacity scenario

Railway transport is a multi-stakeholder business and its capacity situation can be viewed from different perspective of the market, infrastructure planning, traffic scheduling and operations [12]. Though capacity is said to depend on the way it is utilized, the operational capacity and quality of service largely depends on the views and practices of the stakeholders. The ability of a defined rail line to move specific amount of traffic within a given resources and service plan largely depends on its design capability, operating conditions and maintenance conditions. Figure 2.5 shows the interaction among all the active parties in a typical railway business and the possible contribution to loss of quality/quantity of service. The figure consists of two scenarios: the present and ambitious scenario. The present scenario is the upper part of the figure and it reflects the present or operational capacity with the influencing parties. However the lower part shows the emerging ambitious targets inspired by political promise, recommendation of international bodies and demand from train operators. With this situation in view, there is need to improve the sector to enhance both the quality and volume of traffic.

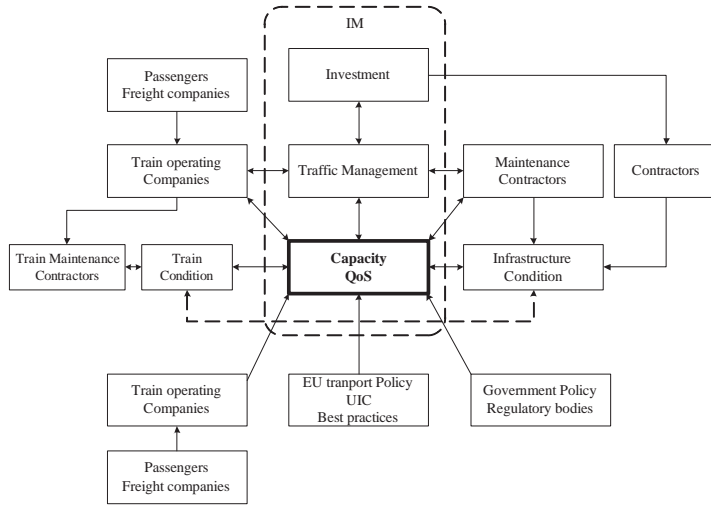


Figure 2.5: Framework for Capacity Management.

2.3 Infrastructure management

The responsibilities of modern infrastructure management with either private or public ownership have been highlighted in the background section of this thesis. The scope of this thesis is confined to infrastructure maintenance management. To this end the research has focused on the responsibility of ensuring the quality, safety, reliability and availability of the infrastructure. In principle, two important tools that are practical for performance management during the life cycle of railway infrastructure are; functional need analysis at the design stage and maintenance need analysis at the operation stage [28] [29]. These are essential tools to meet the infrastructure requirement in terms of functional, traffic, technical and maintenance conditions.

Infrastructure maintenance is the total process of maintenance and renewal necessary to satisfy the availability, safety and quality requirements of the constituent systems at minimum cost [30]. The maintenance functions are aimed at meeting the designed track geometry, functional performance of track structures, level crossings, turnout, power, signal and communication systems [31].

The concerns of infrastructure management on the impact of maintenance function on the capacity consumption of existing railway infrastructure as explained by [28] are highlighted below;

- a. Extended track possession for maintenance activities
- b. Increase frequency of system functional failure and interruption of planned train operations.

- c. Reduced Infrastructure functional performance due to the state of the asset, this set restriction on rail services below the design level.

2.4 Common track problems

Functional deficiency of track structures and traffic interruptions due to failure of track structure is a major limitation to achieving the inherent capacity of existing infrastructure. In one of the EU projects INNOTRACK, detailed research has been conducted to develop cost effective high performance track infrastructure by providing innovative solutions towards significant reductions of both investments and maintenance costs [32], [33]. The project has identified principal track problems facing Europe's IMs, their underlying causes, possible solutions and methods of evaluating performance [33]. Furthermore the criticality of the common track problems were ranked based on the number of IMs that have considered it as a principal problem and also a priority list was created on the basis of impact on cost. Table 2.1 shows the list of problems that were commonly identified by eight IMs involved in the project. An interesting aspect of the table is the mapping of the principal track problems with categories of intervention measures using the underlying cause as a basis.

Table 2.1: Common Track Problems with categories of interventions [32].

| Track problems | Categories of Interventions |
|---|---|
| Track: bad track geometry ^{3,1} | 1. Geometry restoration; Tamping, ballast cleaning, stabilizing, regulation |
| Rail: cracks and fatigue ^{3,2} | 2. Grinding |
| S+C: switch wear ^{3,2} | 3. Inspection |
| S+C: cracked Manganese crossings ^{3,2} | 4. Rail Lubrication |
| Rail: corrugations ^{3,2} | 5. Rail change |
| Rail: wear ^{3,2} | 6. S+C component repair/replacement |
| Fasteners: worn/missing pads ¹⁰ | 7. Re-Sleepering |
| Sleepers: renewal optimisation ⁷ | 8. Joint repair/replacement |
| S+C: geometry maintenance ^{3,1} | 9. Rail pad renewal |
| S+C: loss of detection ⁶ | 10. Fastener repair/replacement |
| Ballast: ballast wear ¹ | 11. Sub-grade rehabilitation |
| Rail: low friction/adhesion ⁴ | 12. Welding |
| Joints:weld quality&insulating joint failure ^{2,8} | 13. Drainage maintenance |
| Ballast: stone spray | 14. Minor periodic maintenance (vegetation +snow clearance) |
| Culverts/pipes: flooding ¹³ | |

Since these problems are considered to be the top ten problems with highest impact on cost, it could be inferred that they are the problems with:

- Highest frequency of occurrence
- Highest track possession time for preventive intervention
- Highest unplanned track possession for corrective intervention
- Highest contribution to reduction in quality of service or operational hindrances.

Therefore to enhance the capacity of existing track with effective maintenance practices and principles, the track problems listed in Table 2.1 with their causes and intervention measures should be well managed.

2.5 Maintenance process

Maintenance process is the course of action and series of stages to follow in order to define appropriate strategy and implement the same [34]. In making significant contribution to or identifying potential improvement in maintenance function, it is essential to map and describe the distinct stages or activities in maintenance process. These activities form the stages of any maintenance process; there are review, adaptation and variants of the conventional description of maintenance process given in the standard [35]. Table 2.2 gives the description of maintenance process from different perspectives; general maintenance process [34]-[36], railway infrastructure specific [37] and also Trafikverket specific [29].

2.6 Maintenance improvement

The description of maintenance process given in the previous section put the different maintenance actions in perspectives; this forms the basis for improvement to enhance capacity of existing network. Improvement in maintenance is achieved by making changes to the concept, procedure, techniques, methods, resources and level of maintenance [34], [35]. Hartmann [38] explained why maintenance productivity is often low and also gave an eleven-step program for improving it. Among the aspects suggested for improvement are work order systems, maintenance planning & scheduling, maintenance control and organisation. One should not expect any additional value by doing the same thing in the same way, change is inevitable if the performance of maintenance in terms of efficiency and effectiveness is anticipated. Such change should be adequately supported by adequate data gathering, analysis, engineering consideration, management support, communication and other case specific issues [34].

Established techniques such as lean process, TPM, six sigma, and other quality and reliability assurance programmes have been deployed for improvement of maintenance

Table 2.2: Maintenance process.

| Generic maintenance process | Maintenance process in the railway industries | Maintenance process in Trafikverket |
|--------------------------------|---|--|
| Maintenance budgeting | Budget determination | Budget allocation |
| Setting maintenance objectives | Defining objectives by IM | Identifying objectives from regulation & handbook (BVH800) |
| Formulating Strategy | Developing strategy by IM | Establishing strategy from existing handbook |
| Establishing Responsibilities | Insourcing or Outsourcing | Procurement of contract |
| Planning | Long term quality prediction Project prioritisation & selection Project identification & definition | Condition assessment Maintenance need analysis |
| Scheduling | Possession allocation and time tabling of track possession | Track possession schedule (BAP and BUP) |
| Execution | Implementation | Execution |
| Assessment | Work Evaluation | Assessment & verification |
| Improvement | Feedback loop | Follow up of contract |

functions in different industries [34], [39]-[41]. Production assurance program is a methodology that has been implemented in the oil and gas industries for improving plant production performance in the operational life cycle phase [39]. This programme facilitates the generation of improvement alternatives that will ensure that the dependability requirement and the planned production capacity of the plants are achieved. Also the description of the implementation of lean maintenance as an improvement technique to reduce cost and increase productivity has been done by [40].

In specific term, studies on the improvement of railway infrastructure maintenance with interest in both capacity and punctuality enhancement had been done by [10]. Information and requirements related to systematic improvement of railway punctuality has been explored and described. Also the required target of availability performance and other related parameters for maintenance improvement of railway infrastructure has been studied by [15]. Approaches and models to estimate RAMS (Reliability, Availability, Maintainability and safety) targets based on the capacity and service quality was presented. Also identification and management of performance indicators which are related to railway infrastructure and necessary to inform performance improvement have been studied by [9], [42]. These studies have identified essentials of maintenance performance management and also suggested detailed maintenance performance measurement frameworks for analysis and improvement of railway infrastructure performance. Considering the organisational aspect, [6] has studied maintenance strategy for a railway infrastructure in a

regulated environment. The study has addressed some aspects of client contractor relationship in infrastructure maintenance and has given adequate attention to enhancing contractor performance through partnering. In general, the different aspects of maintenance improvement from literature are highlighted in Figure 2.6.

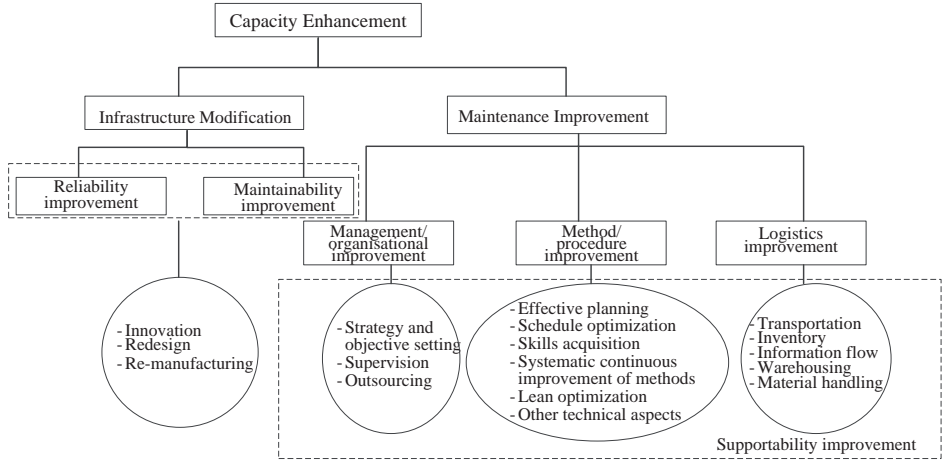


Figure 2.6: Capacity enhancement with high performing infrastructure.

2.7 Review of maintenance schedule optimization

The requirement of improving the technical performance of railway infrastructure is essential to achieve the goal of supporting inherent capacity and improving service quality of railway transport. Moreover, the continuous increase in demand for safety and capacity for both freight and passenger traffic requires adequately supported intervention measures with optimum allocation and utilisation of track possession time. These intervention measures are categorized into track maintenance and renewal tasks [30]. In the past, different principles have informed the planning, scheduling and implementation of maintenance actions, some of which are based on manufacturer's recommendations, experience within the railway organisation, assumed deterioration, availability of maintenance equipment and other basic principles. As a matter of fact, these could not support the growing demand for capacity, safety, cost effectiveness and other service quality of railway transport. To this end several techniques and methods have been developed to plan and schedule railway infrastructure maintenance in an optimum way. The parameters of interest in several maintenance optimization tools and techniques include; maintenance costs, labour cost, life cycle cost, asset performance, track possession time, punctuality

and other service quality parameters [43], [44]. Basically, maintenance optimisation of railway infrastructure gives a short, medium or long term plan, on how preventive maintenance works will be performed on which segments in a definite horizon. An overview of railway infrastructure maintenance planning has highlighted two vital aspects of infrastructure maintenance planning: deterioration modelling and maintenance scheduling [37]. A list of relevant research work on optimisation of maintenance plan and schedule is presented in Table 2.3.

Table 2.3: Review on optimisation of railway infrastructure maintenance schedule.

| S/N | Problem | Objective | Remark | Reference |
|-----|---|--|---|--------------------------|
| 1 | Allocation of maintenance activities to time window and crews to activities | Minimise traffic disruption and completion time | Integer Programming model using tabu search algorithm for the solution | Higgins [43] |
| 2 | Track possession assignment problem-Assign railway tracks to a given set of scheduled maintenance tasks according to a set of constraints | Maximizes the assignment of job requests based on priorities and also satisfying all the constraints | Constraint- satisfaction techniques with heuristics was used | Cheung et al. [45] |
| 3 | Optimal maintenance schedule for track irregularities | Minimise tamping cost and maximize improvement of tamping operation | Integer programming model | Miwa [46] |
| 4 | Preventive maintenance scheduling problem (PMSP) | Minimise possession cost and maintenance cost | Mathematical programming which is NP-hard. Heuristics are used in the solution | Budai et al. [44] |
| 5 | Track maintenance schedules to improve track workers' safety | Maximise manageable work load per night for rail track workers | Developed a two-step method of constructing a four week schedule with each working zone of the main lines closed to trains at night exactly once. | Van Zantede Fokkert [47] |

Continued on next page

Table 2.3 – *Continued from previous page*

| S/N | Problem | Objective | Remark | Reference |
|-----|--|--|--|---------------------|
| 6 | Bi-objective optimization problem for maintenance and renewal decisions related rail track geometry. | Minimise total cost of planned maintenance and total number of train delays caused by speed restrictions | Simulated annealing technique was used to solve the problem | Andrade et al. [48] |
| 7 | Optimizing tamping operations in ballasted track | Minimise total nos. of maintenance actions on described track segment | Mixed binary linear programming | Vale et al. [49] |
| 8 | Monthly maintenance schedule of track on a network | Minimize total maintenance cost and travel cost | Genetic algorithm optimization technique | Zhang et al [50] |
| 9 | Production team scheduling problem as timespace network model and side constraints | Satisfying selected practical aspects of railway infrastructure including cost | Simplified scheduling model was used for initial solution and then a multiple neighbourhood search algorithm was applied to improve the solution | Peng et al. [51] |
| 10 | Track geometry inspection interval | Minimising total ballast maintenance cost per traffic load | Stochastic maintenance model which consider inspection, tamping costs, & cost of risk of accident due to poor quality | Iman et al. [52] |

RESEARCH METHOD

An investigation into a particular field of knowledge requires a systematic and scientific approach to establish a fact or principle. Such systemized effort in a scientific way is called research and can be described using the methodology and method deployed in the research process. The research methodology is the science of how research is done scientifically and it emphasises on various steps that are considered in a research process to get insight or solution to set problem along with the logic behind them [53]. The aim of this is to guide towards the implementation of correct procedures to solve the problem. On the other hand the instrument that is used in performing the research operations such experiments, test, observation, recording data, surveys etc. is called research method [53]. This research study is an applied research that is focused on pertinent problems within the railway industries described earlier in this thesis. To this end both quantitative and qualitative approaches are deployed to adequately address and provide solution to the problems put forward. The method of this research can be categorized into two for simplicity and enhanced understanding of the result given in the subsequent section.

1. **Data Collection:** An essential activity in any research process is the gathering of relevant data which give raw information about the process or phenomena under consideration. This category gives the methods that are used to gather the information needed to improve railway infrastructure maintenance in order to enhance capacity and quality of service. This includes the method for both qualitative and quantitative research approaches.
2. **Data analysis and modelling:** The transformation of data into useful information and for decision support is another relevant aspect of a scientific research. This category consists of statistical techniques and mathematical programmes which are used for establishing relationships between the data and the unknown aspect of the problem. These methods are actually used for knowledge discovery from the data and for objective explanation of phenomena and patterns which are considered to be valid, useful, novel or understandable.

3.1 Data collection

Data can be defined as fact which can be communicated and stored [54]. They are carefully collected according to acceptable procedures and in specific environment such as library, laboratory or field. There are three basic approaches used for the collection of required data for the purpose of this research.

3.1.1 Literature

Literature survey of previous works related to this study has been done. Among the sources for the literature survey are databases of conference, journal, libraries, PhD thesis, technical reports and EU projects related to railway infrastructure maintenance. The most remarkable searches were done with following keywords:

- Railway infrastructure maintenance
- Railway Capacity evaluation
- Track degradation
- Maintenance optimization
- Railway infrastructure management
- Maintenance performance measurement in the railway industries
- Continuous improvement

3.1.2 Survey

This forms the qualitative aspect of this research as there is need to gather vital information to map and describe the maintenance practices and principles in Trafikverket. This helps to identify the capacity bottlenecks and factors that impact the RAMS characteristics of the network. The instrument used in the survey is a questionnaire which was designed to consider the three main categories of parameters influencing RAMS indicators of railway systems. The categories are detailed in Figure 3.1 which was taken from the standard - specification and demonstration of RAMS for railway infrastructure [25]. Basically more attention was given to maintenance conditions since the research is focused on developing effective maintenance principles by identifying and eliminating bottlenecks in maintenance process.

In short the different interests addressed in the questionnaire can be described by Figure 3.2. The impact of different sub-processes of generic maintenance process on network capacity was investigated. Views on impact of external factors capacity consumption was also sampled and attempt was made to collect perceived solutions from the interviewed. The targeted respondents of the questionnaires are personnel of the maintenance contractors, Trafikverkets and train operators with relevant experience and job responsibilities.

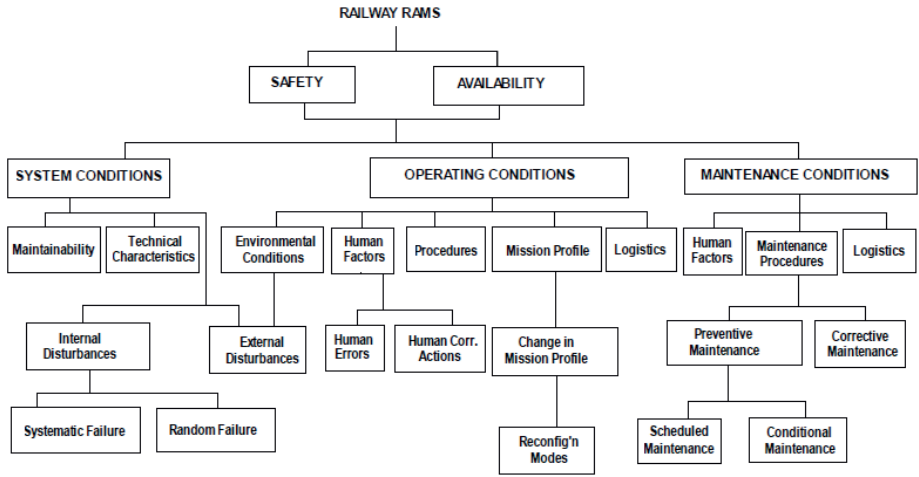


Figure 3.1: Factors influencing RAMS parameter [25]

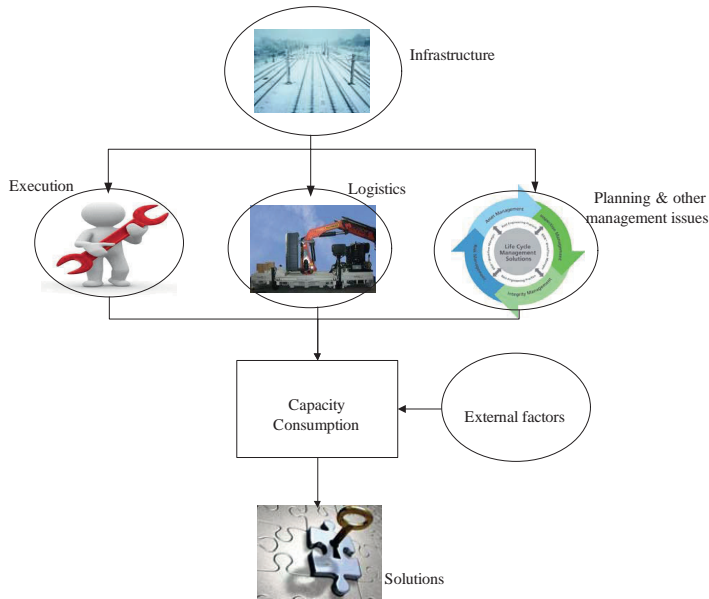


Figure 3.2: Framework for the design of the questionnaire

3.1.3 CMMS and CM data sources

For the qualitative aspect of this research, field data which have been recorded by the infrastructure manager Trafikverket collected. These data exist in disparate data sources

including, traffic, failure, preventive maintenance, inspection, inventory and other relevant asset information sources: Figure 3.3 shows the name of the data sources and their respective data type that are used in this research work. It should be noted that some other quantitative data were provided by experienced experts and literature.

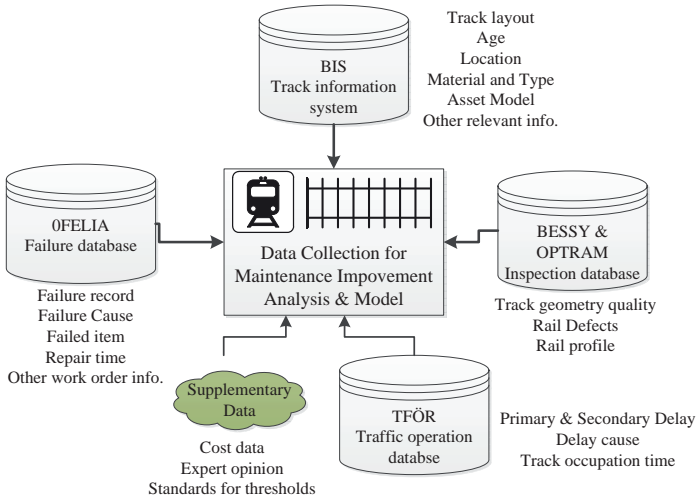


Figure 3.3: Data collection procedure for the research

3.2 Data analysis and modelling

Maintenance data, traffic data and other facts collected are further analysed to establish relationships and draw useful information to serve as knowledge base for decision making. Prior to the detailed analysis, a preliminary analysis was done to carefully check appropriateness of the data for analysis and modelling in the context of the objectives of the study. Also the data were cleaned by deleting data that were evidently incorrect, outliers were identified and missing data were checked. The aims of preliminary data analysis include: description of the key features of the data, overview of the information content of the data, preparation of the data in useful format for further analysis. The methods for the detailed data analysis and modelling used in the different appended papers are described below.

Summary for Paper 1 and 2

These two papers are conceptual papers and synthesis of practice. The factual data from the literature review and survey were keenly analysed and used in both papers. The method for the analysis is discussion with experts and extraction of best practices. This also entails synthesis of best practices in similar industries such as road management and maintenance. Basically the approaches to these two papers are both qualitative and descriptive with limited statistical analysis. In paper 1 a flow chart is used to present the proposed framework for maintenance improvement while a fish bone diagram was suggested as the method for the identification of bottlenecks and their root causes. In paper 2, the framework for successful implementation of performance based railway infrastructure maintenance (PBRIM) contracting was developed based on best practice in similar industry and relevant discussions. The method used for the evaluation of track geometry to monitor contractor performance in PBRIM contracting is the cumulative frequency plot of track quality index. This helped to characterise the track into different track quality classes and assess the performance of the maintenance service provider.

Summary for Paper 3

This paper presents the application of maintenance performance measurement system for continuous improvement in the railway industries. With the identification of performance aspects or maintenance result areas anticipated in infrastructure management, a system of indicators to quantify the contribution of maintenance in these areas was proposed. For further analysis, two of the maintenance performance indicators dependability and punctuality indicators were selected to identify bottlenecks improvement measures. In the first stage of analysis, graphical method of data analysis was used to explore the dependability characteristics and loss of punctuality from each traffic zone on the selected line section. At the second stage, risk assessment matrix shown in Table 3.1 was used to combine the information in the individual indicators. The procedure for risk assessment presented in the standard EN 50126 [25] was adapted, in order to categorize the contribution of each segment to risk of loss of service quality capacity reduction. This will facilitate the hierarchical listing of the traffic zones and lower level systems based on their need for maintenance. In the matrix, frequency of infrastructure failure and the operational consequence of the failure in terms of delay were considered. It is remarkable to mention that the punctuality indicator or delay for each traffic zone was modelled using lognormal distribution.

Table 3.1: Risk assessment matrix [25].

| <i>Frequency</i> | <i>Likely impact or consequence of failure</i> | | | |
|-------------------|--|-----------------|-----------------|---------------------|
| | <i>Insignificant</i> | <i>Marginal</i> | <i>Critical</i> | <i>Catastrophic</i> |
| <i>Frequent</i> | Undesirable | Intolerable | Intolerable | Intolerable |
| <i>Probable</i> | Undesirable | Intolerable | Intolerable | Intolerable |
| <i>Occasional</i> | Tolerable | Undesirable | Undesirable | Intolerable |
| <i>Remote</i> | Negligible | Tolerable | Undesirable | Intolerable |
| <i>Improbable</i> | Negligible | Tolerable | Undesirable | Undesirable |
| <i>Incredible</i> | Negligible | Negligible | Tolerable | Undesirable |

A hypothetical grading of the frequency of failure and consequential delay were done to demonstrate the mentioned methodology.

Summary for Paper 4

This paper proposed an optimization model to support maintenance decision especially for maintenance tasks with high possession requirements. A mathematical model was developed to facilitate optimum allocation and utilisation of track possession time for tamping operation. The line section considered in a case study is 130 km single track from Kiruna to Riksgränsen It is a freight line with actual speed limit between 70-130km/h but for the sake of geometry quality intervention limit required in this study it is considered to fall speed category 80-120km/hr. The maximum allowable axle load on the line section is 30 metric tonnes and the annual accumulated tonnage is over 22MGT. The standard deviation of the longitudinal level was used to characterise the geometry quality of the line section. Exponential model has been used to describe the deterioration of each 200m segment on the track section of the case study using inspection data between 2007 and 2012. An empirical model was also developed for the recovery of a segment after tamping intervention. The description of the model procedure is given in the flow chart shown in Figure 3.4. The outcome of this method suggests a tamping plan which when implemented will lead to optimum allocation of track possession time and as well maintain the track geometry quality within specified limit and classes.

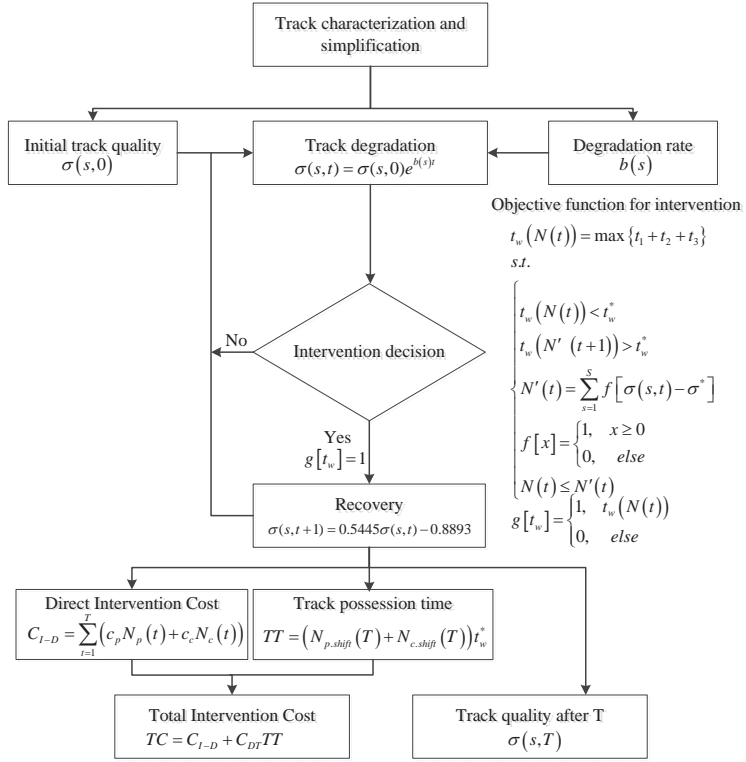


Figure 3.4: Flow chart for the optimization of track possession and cost of tamping

RESULTS AND DISCUSSION

The growing demand for capacity, safety, cost effectiveness and other service quality of railway transport requires improvement of infrastructure management responsibilities. Maintenance process is definitely a responsibility whose improvement is promising and achievable in short term. Different aspects of improvement which contribute to the effectiveness of maintenance principles and practices have been studied in this research. The outcomes of the study are presented and discussed in this section. The organisation of this section is in such a way that each research question is treated separately and accordingly. The details of these results can be found in the appended papers.

4.1 Maintenance improvement

Research Question 1: - What opportunities does maintenance present for enhancing the inherent capacity of existing railway infrastructure?

As highlighted in Figure 2.6, maintenance improvement for capacity enhancement has a broad scope involving both organisational and method improvement. The opportunities in both aspects have been investigated and frameworks for improvement are presented below.

4.1.1 Organisational improvement

The establishment of responsibilities and selection of appropriate contracting strategy is one vital aspect of maintenance management [34], [36]. This is an issue that influences the achievement of maintenance objective though considered as soft parameter. In developing an improvement programme to enhance the productivity of maintenance function, the essential concerns of contracting strategy selection process has been studied. Figure 4.1 shows the elemental features of maintenance contracting strategy, a balance mix of specification, delivery and costing methods is a requirement for a functioning maintenance organisation.

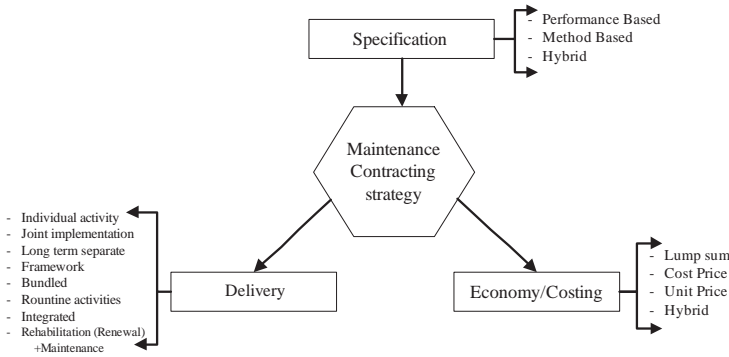


Figure 4.1: Elemental features of maintenance contracting strategy

In the emerging trend of maintenance outsourcing, the contractors are becoming largely involved in the maintenance process and not only limited to the operational level of task execution [32]. It is anticipated that this change in the organisational structure of infrastructure manager will facilitate maintenance improvement and the achievement of maintenance objectives. A well-structured framework for the implementation of innovative contracting strategy is a compulsory requirement to achieving a functional maintenance which will meet this anticipation. To this end, performance based railway infrastructure maintenance (PBRIM) has been presented and the framework for successful implementation suggested is shown in Figure 4.2.

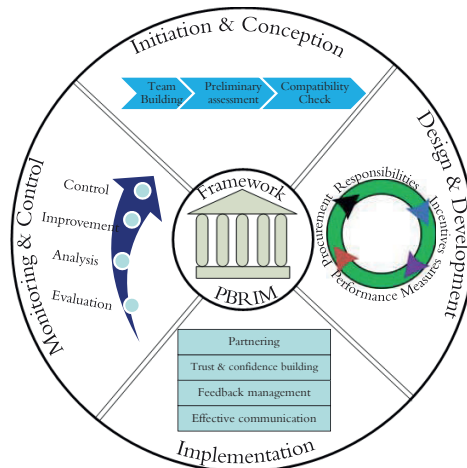


Figure 4.2: Framework for PBRIM

This practical framework for PBRIM contracting could be distinctively separated into four stages as shown in Figure 4.2, each of the stages has its own elements, all of which should be defined to enhance the potential of this outsourcing approach. The stages are initiation, design & development, implementation and monitoring & control stage. In summary, strategic alliance between the stakeholders plays a key role in the successful implementation of this approach. Trust and confidence as well as other success factors of partnering will facilitate good relationship and enabling atmosphere for performance. Monitoring and control of the performance of the contractor using a system of indicators is an important aspect for early detection of gap in asset condition and service quality and also for identification of improvement potentials. Details can be read in paper 1.

4.1.2 Method improvement

Maintenance improvement required to support reliable and track design capacity should increase the operational availability of the infrastructure and other related parameters. The required improvement is not only limited to planned maintenance but also extends to the strategy for handling unexpected interruptions. A typical improvement programme suggested for the enhancement of capacity and quality of service on existing infrastructure is shown in Figure 4.3.

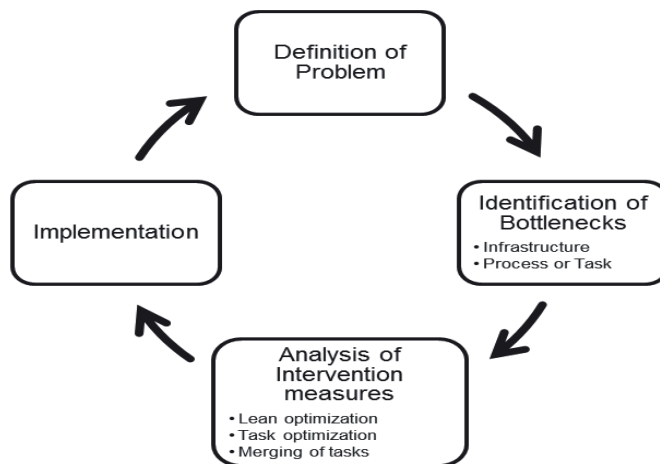


Figure 4.3: Maintenance improvement framework

Using maintenance performance measurement system, one can quantify the efficiency and effectiveness of past maintenance actions. This will give a clear description of gap which is essential to drive improvement process. Furthermore, it is essential to identify

the critical activities and systems which have the largest contribution to the observed gap (bottlenecks). Bottlenecks could denote processes, activities or even subsystems that restrain the flow of traffic through a line, or network. From maintenance point of view bottleneck could be hard measure (infrastructure) or soft measure (process).

A typical cause and effect diagram that could be used to analyse bottlenecks influencing the functional performance of railway system is shown in Figure 4.4.

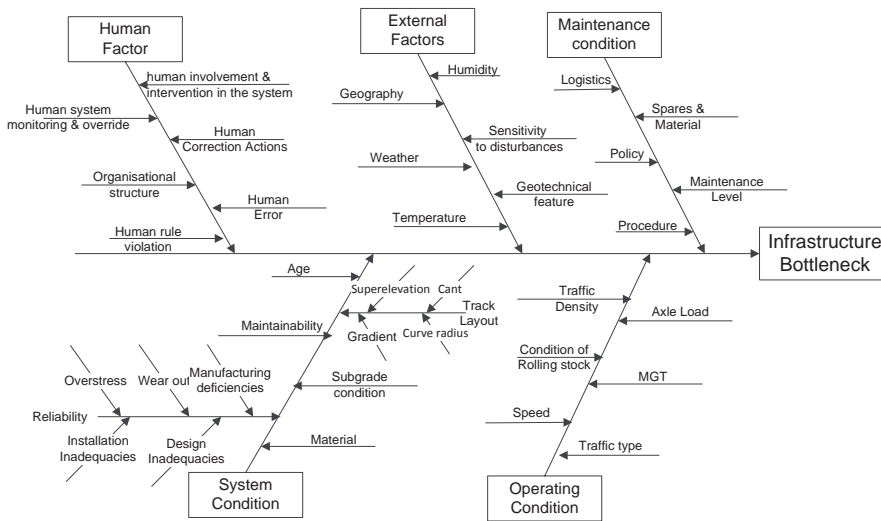


Figure 4.4: Root causes of infrastructure bottleneck

Having identified the gap between target and maintenance outcome, as well as pointing out critical asset and tasks, analysis of intervention measures is the next element in the improvement framework. Typical intervention measures could be changes in maintenance concept, level of maintenance, maintenance procedures, skills of maintenance and operations personnel, spare parts and materials, operating procedures and conditions, safety and environmental procedures, and system design. The analysis of intervention measures include:

- a. Hierarchical listing of maintainable components using risk assessment matrix for continuous improvement
- b. Mathematical optimization of the possession frequency of the tasks
- c. Bundling or grouping of related maintenance tasks: Mathematical models can be

used to investigate the possibilities of grouping related maintenance tasks in the same white period.

- d. Lean maintenance implementation of task with significant impact on capacity. This involves the deployment of lean thinking to identify non value adding activities in maintenance task which demands high track possession time. These are wastes and losses that can be eliminated and the process becomes efficient.

The last stage in the improvement programme is the transformation of the changes into actions. This will include strategic arrangement for the deployment of these changes at the operational level. The implementation procedure gives the detail of what to do, when to do and some other guidelines needed to execute the solution at the appropriate level within the organization. Improvement of organizational strategy is needed if the maintenance function is outsourced to external contractors and subcontractors. Management support and effective communication will facilitate the implementation of suggested intervention measures.

4.2 Continuous improvement

Research Question 2: - How can a system of indicators be used for continuous improvement of maintenance performance with respect to quantity and quality of delivered service?

Capacity is a function of most restrictive infrastructure segment [13]. It is therefore essential to create a methodology for identifying such segment and related maintenance activities. To this end, a system of maintenance performance measurement has been presented with relevant performance perspectives (see paper 3).

The procedure in the assessment matrix described earlier in Table 3.1 was adapted with punctuality indicator and dependability indicator to assess past maintenance actions and also motivate future decisions. Figure 4.5 shows the result of the case study carried out on a 168km long line section on the Swedish transport administration network. This categorizes the traffic zone (Zone 1 to 37) based on their contribution to risk of loss of service quality and capacity reduction. This will be resourceful information for prioritization during maintenance planning and scheduling and also capital investment during continuous improvement.

To meet the operational requirements of the line section under consideration, the zones with intolerable contributions should be subjected to detailed failure analysis to eliminate the bottleneck (using Figure 4.4). Zones with undesirable risk contribution should be maintained to reduce their impact. Zones with tolerable impact should be controlled with necessary measures while those with negligible impact should be observed and their maintenance should be standardised. This will facilitate the development of maintenance

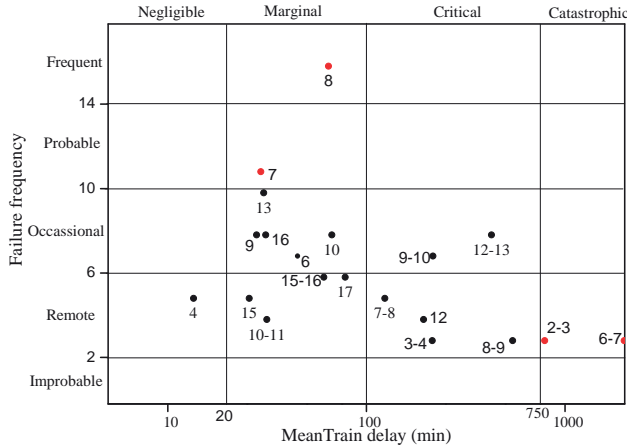


Figure 4.5: Risk contribution of the traffic zones to loss of punctuality and capacity reduction

programme that will homogenize the condition of the infrastructure along the line section. Furthermore, identifying critical spots or bottlenecks on the line sections also help to capture inherent locational problem. Finally, weight can be attached to the categories of the bottlenecks. This can be cascaded down to respective lower level system in the segments to determine maintenance significant items which should be subjected to detailed maintenance programme such as FMECA and root cause analysis. A hierarchical listing of the maintenance significant items can be generated, to inform maintenance decision.

4.3 Maintenance optimisation

Research Question 3: - What should be the strategy for optimum allocation and effective utilisation of track possession time with consideration to track quality and cost aspects?

Developments in railway management have led to increasing need for optimum planning and scheduling of maintenance activities to support the growing demand for capacity, safety, cost effectiveness and other service quality of railway transport. To this end a methodology for optimum scheduling of tamping is proposed to minimise direct cost of intervention and cost of track possession while the excursion of the geometry quality is within the desired level.

Using the exponential model given in the model procedure (see Figure 3.4), the growth rate of the longitudinal level defect for each 200m segment was estimated. The distribution of the growth rate for all the 592 segments is shown in Figure 4.6. This is well described by a Weibull distribution and the parameters of the distribution could be used

in a stochastic or probabilistic modelling of the geometric characteristics of the track section. More than 50% of the track section has an exponential growth rate between 0.00024 and 0.00060. The differential growth rate along the track sections reflects non homogeneity and variation of track components along the track length. In fact, the 200m track segments can be regarded as non-identical units in terms of quality deterioration. An indication of this plot is that continuous tamping of the whole length of the track section might not be the best strategy in terms of life cycle management of the track. An essential maintenance requirement informed by the figure is the balance of preventive and corrective tamping, since higher exponential rate will require more interventions than lower exponential rate.

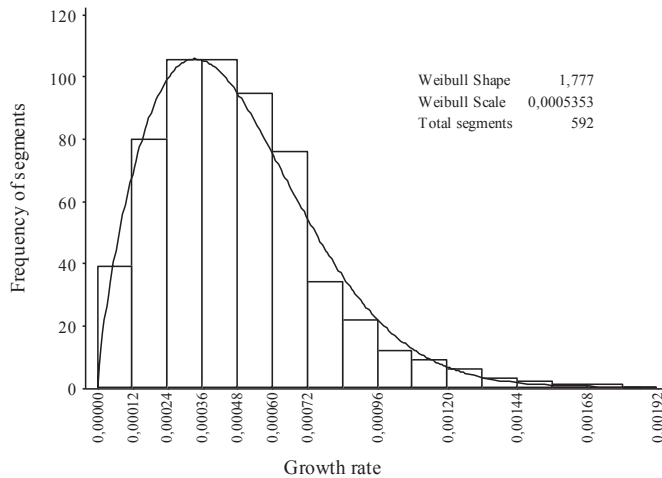


Figure 4.6: Illustration of the distribution of longitudinal defect growth rate.

In this study, empirical regression model from data collected in previous research [52] on the same route has been proposed. The model describes the relation between standard deviation of the longitudinal level before tamping and the improvement after tamping. Figure 4.7 shows the plot of the observed recovery against quality at intervention. 90% prediction limit is estimated and shown in Figure 4.7 in order to investigate the sensitivity of simulation outcome to variation in recovery. The indication of the linear model is that recovery depends on the quality at the point of intervention

Using the model procedure described in the flow chart in Figure 3.4, the number of corrective interventions that will be required in two years for different number of shifts allocated for preventive tamping is estimated and shown in Figure 4.8. The sensitivity of the result is also shown using 90% prediction limit of the recovery model fit. Increasing

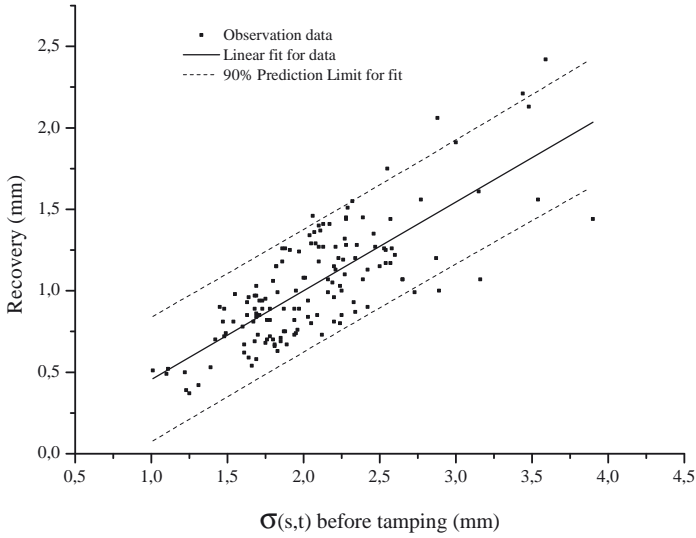


Figure 4.7: Improvement of tamping interventions with 90% prediction limit,

the number of allocated shifts for preventive tamping decreases the segment requiring corrective tamping up to a point where there is no need for corrective tamping besides the initial which was compelled at the beginning when few sections were above both intervention thresholds.

4.3.1 Cost of intervention and track possession

Using the proposed optimization procedure in Figure 3.4 with several cost ratios for the two tamping policies, the total cost for tamping interventions over a short period of two years is estimated and given in Figure 4.9. Higher ratio of C_p/C_c results into high cost of intervention when the number of preventive maintenance shift is increasing.

From Figure 4.10 the economic optimum policy considering a cost ratio of $C_p/C_c = 1$ is to have few preventive intervention shifts. However the track possession time and quality of the track are other criteria to consider.

The global cost model proposed by [55] is adapted to estimate the total cost of intervention by adding the direct and indirect cost of intervention. Following the model procedure in Figure 3.4 and using stochastic simulation for the recovery model (equal chances between the prediction limits, see Figure 4.7), robust estimation of the track possession time was obtained and also indirect cost of intervention (using $C_{DT} = 2C_c$). Figure 4.11 shows the total cost of intervention for the time horizon considered against different number of shift allocated for preventive interventions.

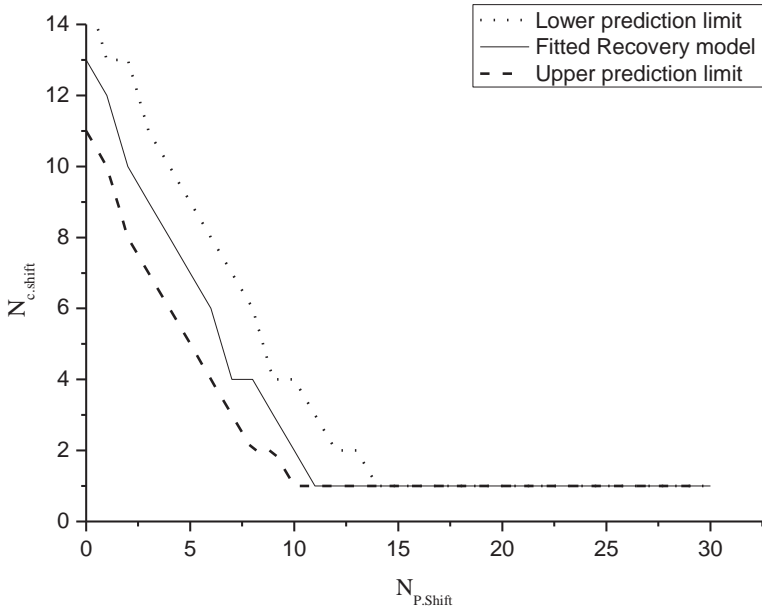


Figure 4.8: Corrective interventions and Scheduled preventive interventions

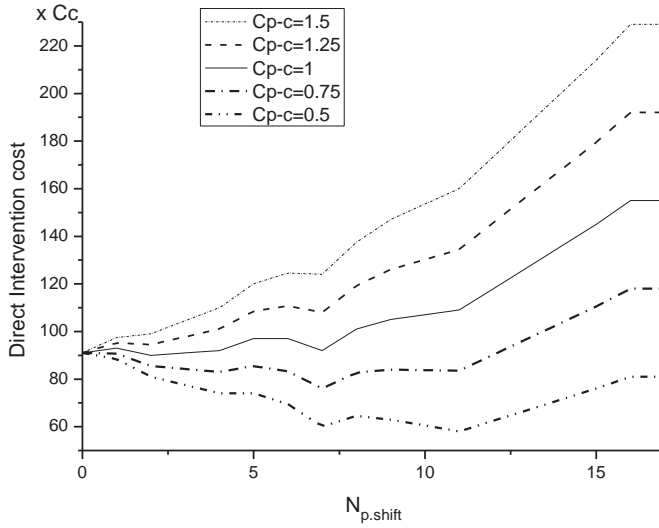


Figure 4.9: Total maintenance costs with different cost ratios

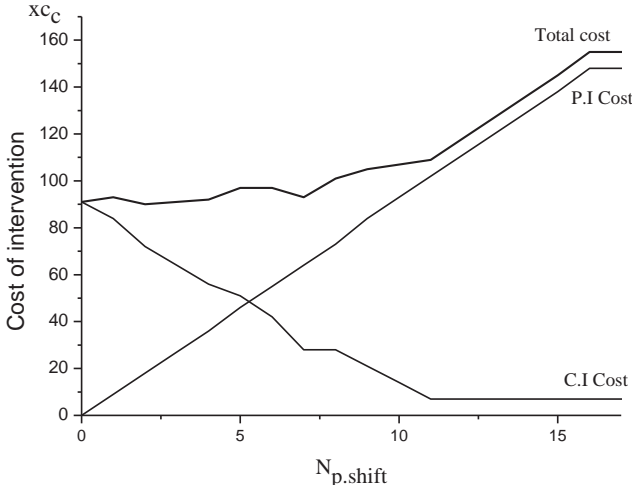


Figure 4.10: Maintenance costs for a finite horizon using cost ratio $C_p/C_c = 1$

According to the result shown in Figure 4.11, selecting strategies with more than 8 preventive maintenance shifts will result into additional cost due to too frequent track possession. Using any of the strategies ($N_{p.shift} \leq 8$) will result into track possession time lower than the present maintenance strategy whose planning is not model based. Furthermore, optimum strategy should have higher economic performance and process efficiency and as well satisfy the required effectiveness in terms of track quality. In view of this, strategies with $N_{p.shift}$ up to 8 are cost efficient since they are in the neighbourhood of the minimum total intervention costs. Nonetheless it is necessary to confirm the optimality of any of these strategies by assessing the resulting quality characteristics to see if it meets the quality requirement of the infrastructure manager. In this study $N_{p.shift} = 8$ is suggested since it is cost efficient and gives better quality than other strategies with lower preventive maintenance shifts.

4.3.2 Track quality characterisation

The preservation of track geometry quality is another aspect which must be proven satisfactory in any optimum tamping schedule. Therefore the tamping strategies are evaluated by characterising the predicted geometry quality using the procedure in the current state-of-the-art for description of track geometry quality [56]. Figure 4.12 presents the cumulative frequency distribution of the predicted longitudinal level over the length of the entire track section. The figure characterizes the initial quality and also track quality after two years for three different scenarios: no tamping, $N_{p.shift}$ equal to 8 and 16.

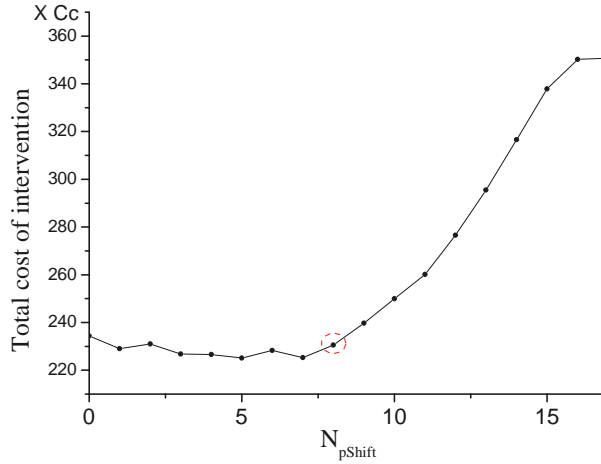


Figure 4.11: Total cost of intervention

If it is required by the infrastructure manager IM that at least 90% of the total segments on the track section should not exceed track quality class C ($\sigma_{LL} < 1.8$ mm) for safety, comfort, ride quality and life cycle management reason, then having 8 preventive interventions shift is sufficient.

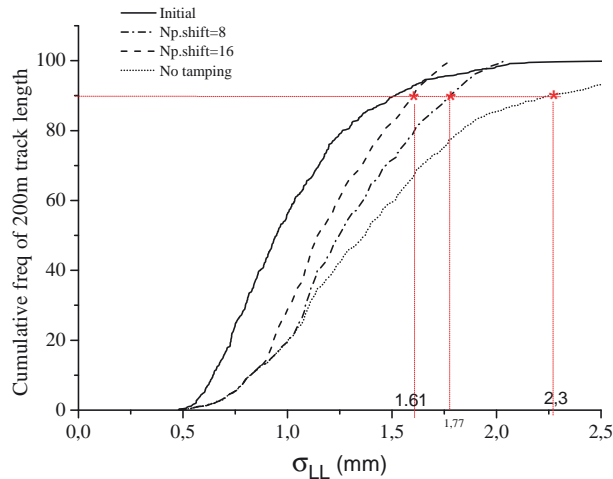


Figure 4.12: Cumulative frequency distribution of track quality indicator

Table 4.1 gives the detailed description and extended classification of the case study into track quality classes (TQC) for the 2 years under consideration using the procedure mentioned above. If the requirement of the IM puts limit on proportion of the track segments that is expected to be in each quality class in a certain time horizon then this can be checked.

Table 4.1: Characterization of the quality of the track.

| Scenario | Track Quality class with % composition (A-best and E-worst) | | | | |
|--------------------|---|---------------|--------------|--------------|-----------|
| | A <0.75mm | B 0.75-1.1 | C 1.1-1.8 | D 1.8-2.5 | E >2.5 |
| Initial | 24.16 | 41.55 | 30.07 | 4.22 | 0.17 |
| Np.shift=8 | 5.41 | 27.03 | 58.78 | 8.95 | 0.00 |
| Np.shift=16 | 5.41 | 37.33 | 57.26 | 0.17 | 0.00 |
| No tamping | 5.41 | 23.99 | 49.16 | 14.70 | 6.93 |

CONCLUSION

5.1 Conclusion

Infrastructure managers are tasked with the ambitious targets of increasing the competitiveness of railway transport through capacity and service quality improvement. An aspect of railway infrastructure management which is promising for the enhancement of existing infrastructure capacity is the improvement of maintenance process. This will require the development of effective principles for both large and small impact maintenance tasks. To this end this research has studied effective maintenance principles that should serve as basis for maintenance improvement programme to support reliable and track design capacity of existing railway network. The concluding remarks of this study are highlighted below.

- Deploying performance based railway infrastructure maintenance presents some strategic risks which could limit the overall performance of maintenance function. This research has presented a conceptual framework to facilitate the implementation of performance based maintenance contracting to meet both requirements of traffic performance (quantity and quality) and infrastructure performance.
- The present maintenance practice and principles of Swedish transport administrator requires improvement in order to enhance the inherent capacity of the existing infrastructure. A four stage improvement programme suggested in this work emphasises on implementation continuous improvement tool, lean maintenance, single task optimisation and merging of relevant maintenance tasks.
- The presented risk assessment matrix is a useful continuous improvement tool to categorize the contribution of each track zone to capacity reduction and also identify bottlenecks. This will be resourceful information for prioritization during maintenance planning and scheduling and also capital investment.

- Optimum allocation and utilisation of maintenance track possession time is a prerequisite in railway infrastructure capacity enhancement plan. The optimisation methodology for tamping action presented in this thesis will support decision making for planning and scheduling of tamping intervention. This will lead to reduced track possession time and minimum cost of intervention while geometry quality is kept at desirable level.

5.2 Future work

In continuation of the work done so far in this thesis and to take care of other essential aspects of this research, the following works are considered for future research:

- Consider boundary condition (limitation of maintenance intervention due to season) by simulating operational hindrances as a result of reduced track performance due to maintenance deficiency.
- Development of long term plan for tamping action using dynamic threshold for intervention
- Optimisation of other maintenance tasks that are considered to have large impact on capacity consumption of existing infrastructure.
- Optimum combination of different maintenance tasks to reduce track possession time.
- Development of composite indicator that will be used at strategic level to support decision making. This will enable continuous improvement of maintenance practices at the operational level to support reliable capacity of railway infrastructure.

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APPENDED PAPERS

Implementation of performance based maintenance
contracting in railway industries

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Implementation of Performance Based Maintenance Contracting in Railway Industries

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Abstract

The achievement of maintenance objectives is the pursuit of any maintenance department, as this will support the achievement of the overall business objectives. Using in-house or outsourced maintenance service provider is a decision which poses challenge in the management of maintenance function. Should the decision be for outsourcing, the next concern is the selection of the most appropriate strategy suitable for the business environment, structure and philosophy. Within railway infrastructure management, in an effort to improve maintenance function so as to deliver set objectives, some infrastructure managers (IM) reviewed their approach to outsourcing of the functions, giving larger responsibilities to maintenance service providers called contractors. Moreover, such change requires adequate attention to meet the pressing need of achieving the designed capacity of the existing railway infrastructure and also support a competitive and sustainable transport system. This paper discusses performance based railway infrastructure maintenance contracting with its issues and challenges. The approach of this article is review of literature and as well as synthesis of practices. A framework to facilitate the successful implementation of Performance Based Railway Infrastructure Maintenance (PBRIM) is presented. Also a performance monitoring system is proposed to assess the outcome and identify improvement potentials of the maintenance outsourcing strategy. A case study is given to demonstrate the monitoring of a typical maintenance activity that can be outsourced using this contracting strategy.

Keywords— outsourcing, performance based railway infrastructure maintenance, outcome indicators, performance measurement

1. Introduction

The rapidly evolving business environment of the railway transport requires continuous improvement of the maintenance process from the strategic point of view to the operational perspective. The demand for effective maintenance is increasing due to changing structure and demands of the stakeholders, complex technology, legislations and also business goal to optimally utilize the existing railway infrastructure capacity and as well create more capacity. Aggregation of all these factors is an obvious demand for a dependable asset which consequently requires an effective maintenance. This challenge could be approached by taking advantage of the possibility of outsourcing due to its potential benefits.

The conventional structure of railway administration entailed combined responsibilities of both train operation and infrastructure management. The demand for higher excellence both economically and quality wise in the delivered service and infrastructure management has led to the evolution of the traditional structure to a multi-stakeholder business environment. Over two decades ago, demands on increasing the effectiveness and efficiency of railway transport and other reasons of deregulation led to the segregation of the railways into traffic operators and infrastructure managers in some countries. An example is the Swedish Transport Administration, which was segregated into the Swedish National Railway Administration (now Swedish Transport Administration), with responsibility for the infrastructure management; and the Swedish railways with responsibility of running train services [1]. It has also become common to outsource the maintenance activities of both the rolling stocks and the infrastructure. This has led to client-contractor scenario involving a service buyer - infrastructure administration, and a service provider – maintenance contractor [2]. In the emerging trend of maintenance outsourcing, the contractors are becoming largely involved in the maintenance process and not only limited to the operational level of task execution.

Maintenance outsourcing is the contracting out of all or part of the maintenance activities of an organisation for a stated period of time [3]. As a matter of fact, outsourcing of maintenance in whatsoever level should not be seen as automatic strategy to achieving maintenance objectives [4]. The outsourcing of specific or general functions, in packages or full service is not an unquestionable path to maintenance excellence. Though it has the potential to cut cost, make the maintenance more effective by improving the infrastructure performance and as well improve the quality and quantity of service. The viable options of contracting out maintenance activities and the consequences of transferring maintenance management function to the contractor have been explored [5]. The different railway infrastructure maintenance contracts within the Swedish transport administration pertaining to scope, objectives, forms and outcome has been studied by Juntti et al [6]. The result of her gap analysis pointed out improvement areas and also risk areas.

The adoption of performance based maintenance contract though not widely accepted in railway industries is a well-established practice in road and building maintenance. Detailed description of the business process of performance based road maintenance contract and the in-depth study of its evolution, deployment, monitoring and improvement have been studied [7]-[9]. A description of the state of the practice of this outsourcing strategy in road maintenance is done in a synthesis report by the national cooperative highway research program [10]. Similarly, the potential and the need to adopt this approach in facility and building maintenance have been identified [11].

Moreover, a successful deployment of performance based maintenance contracting in the railway system will require an effective performance management process. An essential aspect of any performance management process is performance measurement system. In the light of this, two key issues to be checked for in the content and structure of a viable performance measurement system are integrity and deployment [12]. Kumar and Parida [13] discussed the need for maintenance performance measurement, issues on maintenance performance measurement MPM and also reviewed the existing MPM systems. Åhren et al [14] had also contributed to the identification and development of maintenance performance indicator for the railway infrastructure. All of these studies are instrumental in the assessment of the value contribution of maintenance function to the success of the business.

To harness the potential benefit of PBRIM contracting, a well-structured guideline with vital concerns has been described by this article and a monitoring system has been formulated to assess the outcome of the discussed maintenance outsourcing approach. This monitoring tool will indicate the level of the maintenance function and also the degree of asset preservation. The monitoring tool helps the IM to assess the performance of PBRIM contract and to identify improvement opportunities to achieve the maintenance objectives and add more values to the business objectives. This article however does not cover the detailed procedure, design and contents of the PBRIM contract documentation.

2. Outsourcing

Organisation of services including maintenance entails creating the structure for task and resource assignments, workflow, reporting procedure, and communication channels that connect people and works together at different levels [15]. As the willingness to give out part of the activities in a business to concentrate on those that are considered to be core is expanding, the organizational structure is changing as well [16]. Outsourcing received more acceptances in the 1970s, when large corporations were assessed to be underperforming; interestingly it became even more marked in the early 1980s with the onset of global recession [17]. Indeed, the drift in business strategy and management in the 1980s established the philosophy of concentrating on fewer activities.

Outsourcing has brought a lot of changes in the work place and attitude toward work. It has evolved from limited tactical practice to strategic philosophy and now adapted in large number of services. Furthermore outsourcing has been adopted in manufacturing, sales, marketing, administration, accounting, human resources, logistics, IT services, engineering, customer services and so on. In the case of maintenance function, outsourcing to external agent is often to manufacturer, supplier or other authorized service providers. The process of finding, evaluating and selecting outsourcing suppliers is undoubtedly challenging. Maintaining control over the process is also a peculiar concern which has been identified by both researchers and practitioners. To this end, the transition issues, control point, potential customer service issues and other essentials in outsourcing services

have been studied in the following literature [4], [6], [18], [19]. As “one size does not fit all”, tailored solution which entails analysis, investigation, planning and management is required for successful implementation of outsourcing. A practical guide to successful outsourcing is given by Peter et al [20]. Determination of the core competencies of an organization and the activities which are better performed externally has been presented by Quinn and Hilmer [21].

There are different types or forms of outsourcing based on its nature and involvement of the external agency. Task based outsourcing is the traditional type where the contractor provides some of the service components (people, equipment, system, material, facilities and technology) to deliver a specific task. This could be labour contracting, mixed or complete task based outsourcing [19]. Alternative form is the innovative type where outcome of the service to be provided is specified and not the service itself. The current and future trends of outsourcing indicate that it is an emerging strategic tool [17]. Innovative outsourcing in form of partnership alliances and performance based contracts are presumably getting prominence as the traditional task based.

Furthermore the trend in maintenance concerning ownership, operation and maintenance of asset has been from total in-house management to outsource strategy over the years though the practice of purchasing function is now adopted in some services [16]. The different scenarios of maintenance outsourcing could be described matching some key maintenance decisions and the responsible party. The decisions include: (i) What asset is to be maintained- planning, scheduling and improvement tasks (ii) When to maintain- planning and scheduling tasks (iii) How to maintain- execution task [22]. These scenarios of outsourcing are demonstrated in Table 1 with client as the infrastructure manager and the service provider as the maintenance contractor.

Table 1: Outsourcing Scenarios

| | What | When | How | Risk owner | Contracting |
|--------------------------|------|------|-----|------------|----------------------|
| Responsible Party | IM | IM | IM | IM | In-house |
| | IM | IM | MC | IM | Task or Method based |
| | MC | MC | MC | MC+IM | Target based |

MC- Maintenance Contractor, IM- Infrastructure Manager

Generally in a more detailed level, there are different maintenance outsourcing strategies, the categorisation is based on the mix of three elemental features: specification, delivery and costing scheme. Ultimately, maintenance contract strategies are described based on what is to be specified or delivered and how the payment is to be made. Figure 1 is adapted from Menches et al. [9] and it shows elemental features vital for the description of maintenance contracting strategy used in road maintenance though it also apply to other industries.

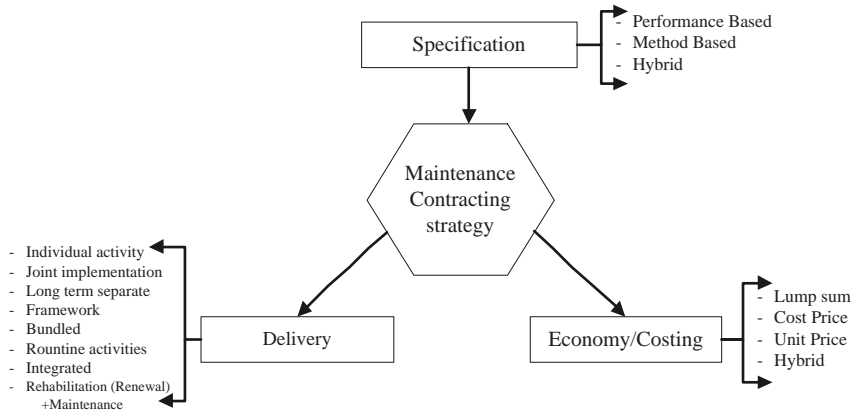


Figure 1: Elemental features of maintenance contracting strategy

3. Performance based maintenance contracting

It is the management practice of transferring or subcontracting some functions, activities and responsibilities performed in-house to external agents with a specified level of service to be met. A performance based maintenance contracting is an approach to contracting that gives incentives or penalties to the contractor for exceeding or falling below specified targets of measurable outcomes [10]. The performance measures are related to the condition of the different asset type and also the outcomes of maintenance on operation, safety and economy.

A remarkable feature of performance based maintenance is that asset owner or IM does not specify the maintenance technique but rather define the performance requirement of the maintenance function. Its appellation differs in various industries but the concept remains the same. It is often called functional guarantee contract, performance based maintenance partnering, output based contract, full service maintenance, performance specified maintenance contract, total maintenance contract, performance contract etc.

The delivery method of performance based maintenance contracts could be defined in two dimensions: activity scope and asset coverage [10], [23]. It could be single activity such as snow clearing, grinding, lubrication or single asset such as track maintenance, tunnel maintenance, level crossing maintenance. It could be more comprehensive in the form of work package on few asset types such as maintenance of all track structures, maintenance of all signal facilities. Furthermore a more intensive performance based maintenance contracts entails bundling of nearly all the maintenance activities on all infrastructure asset types for a contractor or a team of contractors with an expectation of a certain level of outcome. Figure 2 shows the two dimensions and the different schemes of performance based maintenance contracting.

| | | | |
|---------------------------------|---------------------------------|-------------------------------------|---|
| Maintenance activities bundling | Single Asset All activities | | All Asset types All activities (Full service) |
| | | Some Asset types Some activities | |
| | Single Asset Single activity | | All Asset types Single activity |

Asset bundling

Fig. 2: Delivery method of performance based maintenance contracting

4. Motivation for Performance Based Maintenance Contracting

The motivation and advantages of performance based maintenance contracting as identified by both practitioners and researchers [6], [7], [10], [11], [17], [21] include;

1. Potential to reduce maintenance costs
2. Potential to improve level of service
3. The transfer of risk to the contractor
4. It encourages practical innovation
5. Better competence and skills with higher availability
6. Enhanced asset management
7. Change in performance criteria from a focus on inputs and outputs to customer-oriented outcomes
8. Reduction in contract administration requirements
9. Promise of stable financial obligation and reduced lifecycle cost

5. Issues of performance based maintenance contracting

The fundamental issues to be addressed in outsourcing maintenance activities using any strategy can be technical, management, economic or even legal. Some of the issues include; identifying core competence and what to outsource, readiness of the company to outsource, appropriate length of the contract, strategic risks involved in outsourcing, as well as evaluation of the contract performance [4], [6], [10], [21]. These issues are even more pertinent in PBRIM contracting just as it has huge benefits such as mentioned above. For example, its strategic risks include: losing control over methods, material & equipment, loss of critical skills, loss of cross functional communication, risk of resistance to change in culture, risk of increase in maintenance costs etc. Another example of the peculiar concern of PBRIM contracting is the assessment of the performance of the contractor. If these issues are not adequately addressed at the appropriate time they can lead to failure of the management approach

Furthermore, considering maintenance of railway infrastructure to be either one of the core activities in infrastructure management or strategic support function, PBRIM could contribute extra value to business if the above issues are well addressed. This thereby informs the need to design a framework for the initiation, design & procurement and implementation of PBRIM contracting. It further demands a well-structured monitoring system of the appropriate performance measures. If done properly, performance based maintenance contracting can be more effective than in-house maintenance, facilitating the achievements of maintenance objectives and greater business productivity.

6. Framework for PBRIM contracting

The involvement of external agents in the management of maintenance means a large influence of the agents on the productivity of the client. The deficiency of the maintenance function under PBRIM contracting when unnoticed could be costly, catastrophic and in worst scenario lead to the exit of the client in business. The attainability of the maintenance objectives (dependable asset, safe and comfortable traffic and also support for capacity expansion) together with the sustainability of the relationship of the client-contractor requires a well-structured procedure or framework. This practical framework of a PBRIM contracting could be distinctively separated into four stages as shown in Figure 3 and each of the stages has its own elements, all of which should be defined to enhance the potential of this outsourcing approach. The stages are initiation or conception, design & development, implementation and monitoring & control stage.

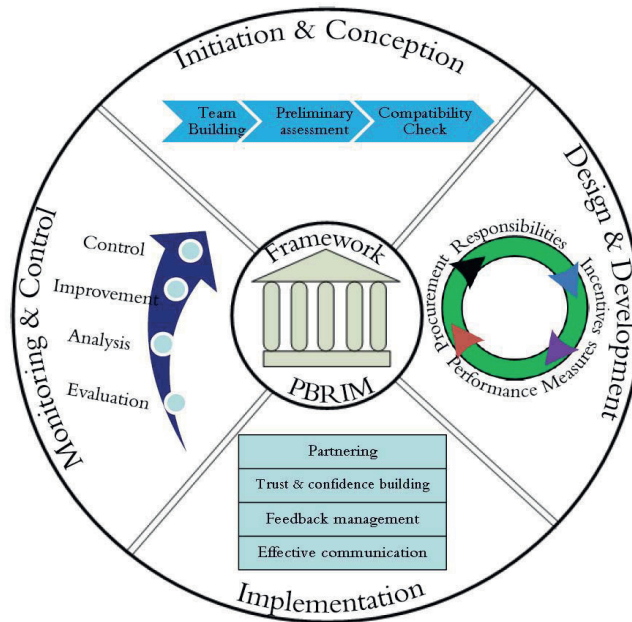


Figure 3: Framework for PBRIM contracting

6.1. Initiation or conception stage

This is the first stage in the process of PBRIM contracting, it is essential to check the suitability of this strategy for the infrastructure manager. The existing IM maintenance policy, tradition, business objectives, regulations and government legislations should be properly checked for conflicts. It is a preliminary assessment of the feasibility of PBRIM, this entail an initial comparison analysis of the possible alternatives for getting the job done. A methodological identification of the need for PBRIM, and also justification of the evaluation criteria for the decision is done. Preferably, a team should be formed which will be committed and responsible for the entire procedure. At this stage in a critical assessment of the business environment and criteria for PBRIM contracting, it is of necessity to answer the questions below:

Are the in-house resources, skills and competence insufficient to meet the desired criteria?

What are the deficiencies in the employment of traditional outsourcing strategy where single maintenance services are outsourced or services are bundled in packages with specification of maintenance methods?

Are the evaluation criteria specific, measurable, achievable and realistic under the specified conditions?

The above questions are guidelines for the assessment of the appropriateness of the discussed outsourcing approach at the conception stage. Clear and positive answers to this preliminary assessment would be a spring board to the second stage of the process towards a goal oriented maintenance function.

6.2. Design and development stage

This is a significant part of the framework as most of the work is done here. A logical design and development of the PBRIM contracting is needed for objective oriented infrastructure maintenance. It is no automatic path to maintenance success thus a gradual build-up of the elements of this stage is of great importance. The elements of this stage include;

- ✓ Definition of responsibilities and conditions of assets
- ✓ Determination of incentives and disincentives
- ✓ Performance measures, targets and procedure
- ✓ Procurement

All the four elements mentioned above must be well defined; their procedures and modalities should be clearly stated. The infrastructure manager should specify what is expected of the contractor in terms of cooperation forms, responsibilities and scope of the contracts. Though the maintenance technique or policy is not given but the vivid description of the railway lines to be maintained should be given. The asset register should be updated with a detailed description of the asset condition. It is also needful to define the responsibilities of the IM for conflict avoidance and other undesired negligent scenarios. A significant issue to be addressed in any maintenance program is the degradation of the asset. Since degradation is connected to the operational profile, or traffic on the infrastructure, it is the responsibility of the IM to ensure the traffic characteristics agreed upon. Changes in traffic volume, speed, axle load and other traffic parameter should be communicated to the contractor for a review of maintenance. Also, important note on the condition of the asset during the contract are the boundary conditions, which can affect the outcome of the maintenance function. Boundary conditions are those factors that might alter the maintenance performance below what the contractors are able to have any influence over. It is necessary to consider factors such as age and climate (snow, wind and thunderstorm), especially when setting the expected outcome for contract.

Another important element at the design stage is the determination of what to do when the performance target is either surpassed or not met. The target should preferably be in a range, the upper limit, which is often called the goal limit and the lower or contractual limit. This specifies the performance level for incentives to encourage maintenance excellence and disincentives to penalize poor maintenance performance. The gainshare- painshare approach as described by Levery [24] is crucial in the design of the reward and penalty for the performance of the contract. A well designed risk reward process will contribute immensely to the success of PBRIM as both IM and contractors are confident that their respective goals will be reached. The risk taken by contractors to meet some performance target will be rewarded when met which leads to good return for the contractor and dependable asset for the IM. This encourages the contractor against unnecessary cost cutting which could be detrimental to the infrastructure performance. A typical risk and excellence reward process is shown in Figure 4. It is noteworthy to mention that the target for any performance measure is not a fixed value but rather a constraint function which depends on inherent capability of the asset, operating condition, age, environmental condition.

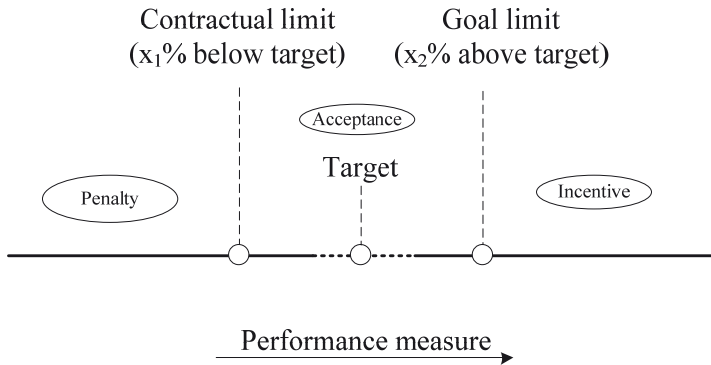


Figure 4: Prototype of performance target

The third element is creating a monitoring tool for the performance of the PBRIM contract. The performance measures, targets and the procedure should be developed before the maintenance procurements. The questions of what to measure, how to measure and also the target to meet are cogent for the success of PBRIM and thus should be really given enough concentration during the design stage. A detailed description of the monitoring tool is given later in the article.

The procurement process of the maintenance comes before the PBRIM outsourcing technique is implemented. A multi-criteria decision making technique might be needed to examine the potential contractor market for the desired contractor selection criteria. These criteria might include; contractor's technical understanding of the maintenance work, organisational competence or staffing, past experience, cost and so on. For further reading on low bid - best value procedure and detailed procurement process for a typical performance based maintenance contract, references [8], [10] are relevant.

6.3. Implementation stage

This is the stage where the contractors take over the maintenance function with the focus of meeting the established targets. The IM monitors and assesses the performance of the contractors and deficiency is penalized with disincentives while excellence is rewarded with incentives. A vital aspect of this stage is the sustenance of a successful working relationship between the IM, contractors and other stakeholders and also efficient management of the existing interfaces. It is essential that this relationship be considered as a strategic alliance or partnering thus the framework for partnering developed by Olsson & Espling [2] can be used in enhancing the relationship factor in this outsourcing approach. Attention should therefore be given to the vital elements of partnering process and its success factors to create an enabling platform that facilitates the potential for achieving the business goal.

During implementation, emphasis should be laid on feedback management, client contractor meetings, effective communication, contract review process, conflict resolution, goal clarification, good flow of information and data between clients and contractors - this data should include: failure data, maintenance data, operation data, renewal data, condition data of infrastructure and also rolling stock. The frequency of the client contractor meetings could be relatively high at the initial period but gradually reduces as the volume of pressing issues and conflicts would be decreasing with time due to improved trust, confidence and mutual understanding. Nonetheless it is expedient to have periodic schedule for the meeting (monthly, quarterly etc.) to review the outsourcing process, especially the performance target. Furthermore it is necessary to involve the manufacturers, suppliers, and train operators at some points in this relationship management as they are significant stakeholders that could influence the potential of this approach. All of these contribute towards trust and confidence building which is a critical success factor in a partnering business strategy.

6.4. Monitoring and Control stage

It is supposed that the monitoring tool or system would have been designed at the earlier stage of this process. The monitoring system specifies what is to be assured in terms of both quality of the asset and quality of the service. During the period of the contract, a major responsibility of the IM is to manage the contract by making room for enabling working environment and likewise monitoring the performance of the process. Generally, the strategic monitoring and control of maintenance evaluates the input and efficiency of activities. It also checks consequential outcome of the maintenance function as well as some other requirements and specifications in the contract. In this contracting strategy, the most relevant aspect of maintenance which is expected to be tracked is the outcome or additional value of the function to overall business objectives. The monitoring process is a continuous process that involves evaluation, analysis, improvement and control of the outsourced function. This approach becomes difficult to steer towards achievement of maintenance objective if there is no room for coordinated and cooperative analysis of the outcome measure for improvement purpose. The frequency of the assessment depends so much on availability of data. For example data such as inspection data that requires track possession for its acquisition, the frequency of analysis depends on the inspection regulation for maintenance or safety needs of the route or section of interest. Other measures could be monitored randomly, periodically or based on complaints by passengers.

7. Performance Monitoring Tool

Performance measurement of maintenance function is a complex task involving the measurement of various inputs and outcome of the maintenance process. It is essential that maintenance performance measurement system considers different perspectives of the maintenance process in an integrated manner [13]. The performance measures should be robust enough to detect shortfalls, predict negative consequences and perhaps insight into the root cause of deficiency. The challenging questions are what to measure, how to measure and how to extract necessary information for improvement purposes. Identification and analysis of some performance indicators for railway infrastructure maintenance is done in literature [14], [25], [26]. Some of the indicators are used in the development of the monitoring tool for PBRIM contract; additional measures are also gathered from similar studies and practices in other industries [27]-[29]. A broad classification of the maintenance performance indicators could be done considering the different phases of maintenance shown in Figure 5, the classifications are:

1) *Input indicators*: The measure of the commitment and effort of the contractor into the maintenance process is defined as input indicators. The resources which are expended on the maintenance service could be quantified and analysed. The input measures are lead or forecasting indicators since they are performance drivers which steer maintenance performance. They can be either soft or hard indicators. Examples are total maintenance man hour per track kilometre, number of training per personnel, number and skills of each maintenance crew. These are not key indicators for a PBRIM service since focus is on the outcome of the task.

2) *Internal process Indicators*: The measure of the efficiency of maintenance process is referred to as internal process indicators. It defines the rate of performing the maintenance activities and quantifies process parameters such as response timeliness, rate of task, number backlog, mean time to repair and number of failures. These are intermediate measures between input and outcome indicators as they are influenced by input and in turn give indication of outcome. In an ideal situation input and internal process indicators are monitored by contractor to explain the outcome indicator and for continuous improvement.

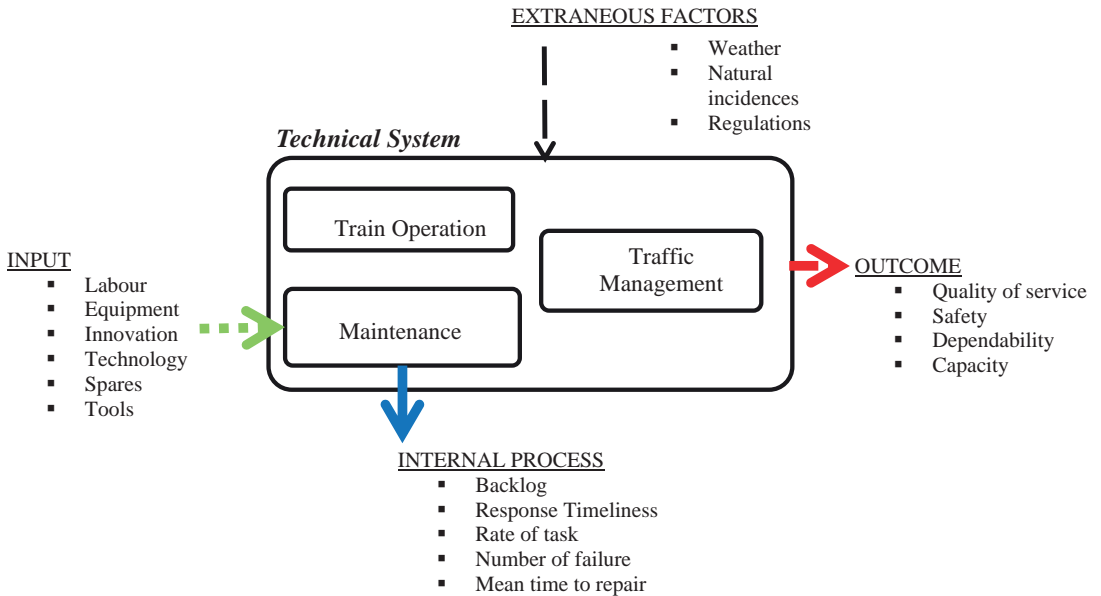


Figure 5: Characterisation of system of indicators

3) *Outcome Indicators:* These are indicators that give the level of performance of the maintenance process and also quantify the benefits or additional value of maintenance to traffic operation. This is the most important category of indicators for performance based railway infrastructure maintenance service, since the outcome or contribution of maintenance to both asset and operational performance is the core of the approach. They provide basis for assessing the deviations of maintenance performance from targets at preferred periods. As mentioned in previous section of this article, one the contributions of this research is the development of a monitoring tool to follow up the outcome of the discussed maintenance outsourcing strategy for railway infrastructure. A systematic management of these indicators will not only help to assess if the specified performance target is achieved by the contractor but could also be instrumental to early detection of gap in asset condition and service quality and prompt an alert for quick intervention. The outcome indicators could be grouped into maintenance result areas which in turn support different strategic objectives. The outcome measures quantify different aspects of performance that is anticipated of the outsourced activities. Considering relevant strategic objectives of infrastructure management and related maintenance result areas from literature [14], [25], [27], [28], the performance measurement system in Table 2 below is suggested.

Table 2: Performance measurement system for the outcome of PBRIM service

| Strategic Perspective | Maintenance Result areas | Indicators |
|-----------------------|---------------------------|--|
| Safety | Safety Performance | <ul style="list-style-type: none"> • Number of accidents • Number of critical incidents |
| | Environmental Performance | <ul style="list-style-type: none"> • Noise, vibration level |
| Finance | Cost performance | <ul style="list-style-type: none"> • Maintenance cost per tonnage kilometre • Maintenance cost per train kilometre |

| | | |
|----------------|---|--|
| Infrastructure | Asset Quality Performance (Dependability and Sustainability) | <ul style="list-style-type: none"> • Track quality index • Number of defects per track kilometre • Number of urgent inspections remark per track kilometre • Number of failures per track kilometre • Number of traffic influencing functional failure per track km |
| Customer | Punctuality performance Comfort performance | <ul style="list-style-type: none"> • Delay hour per passenger kilometre • Freight train delay hour per tonnage kilometre • No of cancelled trains • Track quality index |

Note: All the measures are only infrastructure related quantification

8. Case study

A case study is selected to demonstrate the monitoring of performance based contract for railway infrastructure maintenance. As mentioned earlier in the two dimensional description of performance based maintenance contract, there exists different forms of this innovative approach. The case study is an example of single maintenance activity form of the contracting approach. The line section considered is a 130km long section and it is the northern section of the iron ore line of the Swedish Transport Administration network. It belongs to the line category with high socio-economic importance and high requirement on maintenance for quality delivery in terms of both punctuality and comfort. It could be apparently accepted that the speed range over this section falls in the category of 80-120km/h.

The maintenance activity considered is tamping - task intended to restore or retain the geometry quality of the track for good ride quality, passenger comfort and also life extension of the track. This maintenance activity has the possibility of been outsourced using the PBRIM approach. Evaluation of maintenance service provider for this kind of task using a derived track quality index has been investigated [30]. Other track quality indices that can be used to characterised geometry quality and also asses tamping action under performance based contract can be found in the current state-of-the-art of description of track geometry quality [31]. Furthermore overview of track geometry quality on a track section can be presented using cumulative frequency distribution of the longitudinal level and combination of cross level with alignment.

The track geometry data from the line section described above is used to demonstrate the monitoring of PBRIM approach described in this article. The data is the standard deviation of the longitudinal level of 3-25m wavelength signal from the track measurement vehicle between 2010 and 2012. Using the procedure in the state-of-the-art of description of track geometry quality [31], the cumulative frequency distribution of the mentioned parameter for the track section is plotted in Figure 6. Table 3 shows the classification of the track section into track quality classes (TQC) for the three years under consideration using the procedure mentioned above. Furthermore if 70 % of the cumulative length of the section is required by the IM to meet at least TQC B then the performance of the contractor over the years can be assessed. Following the contract target drawn on the plot, if the frequency plot intersects the target line below the upper boundary of the TQC B 1.10mm, it shows the contractor performance is acceptable. A reward is given if the intersection is below the lower boundary of the specified track quality class. On the other hand, the performance is not acceptable if the intersection is above 1.10mm, and the contractor would be penalised. From the track geometry data plotted in Figure 6, it shows the performance in the year 2010 and 2012 meets the requirement of the IM though without additional reward, but the performance in 2011 falls below the acceptance level. Further information given in table 3 gives the IM more knowledge about the asset condition. This approach for monitoring PBRIM does not only ascertain the performance of the contractor but it does quantify the track geometry quality and assign the track into standard track quality classes as shown in Table 3. The result of the evaluation using the combination of cross level and alignment is similar to longitudinal level and thus not shown. Finally, for creating detailed working plan for track maintenance additional information on lower level of aggregation is necessary.

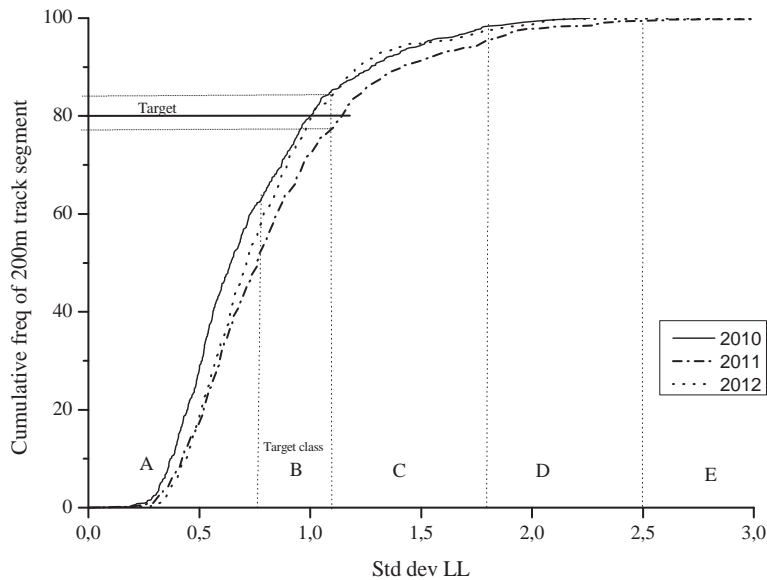


Figure 6: Cumulative frequency distribution of track quality index

Table 3: Characterisation of the quality of the track

| Year | Track Quality class with % composition (A is the best and E is the worst) | | | | |
|------|---|----------------------------|---------------------------|---------------------------|----------------------------------|
| | A <math>< 0.75\text{mm}</math> | B $0.75-1.1$ | C $1.1-1.8$ | D $1.8-2.5$ | E $> 2.5\text{mm}$ |
| 2010 | 61.5 | 23.8 | 13.0 | 1.8 | 0 |
| 2011 | 48.3 | 28.9 | 18.1 | 4.0 | 0.6 |
| 2012 | 54.7 | 29.3 | 13.2 | 2.4 | 0.2 |

9. Discussion and Conclusion

It is important to comment that maintenance expertise within the client's (IM) organization should not be wholly discarded; they are needed to administer and supervise PBRIM contracts. This is necessary since the inspection of the asset and monitoring of the performance of the contractors is retained by the IM. In addition, the renewal or new investment should be the sole obligation of the IM, the strategy for this should be developed by the IM and not the contractor [32]. The collaboration between IM and contractors should not be underestimated as this might be helpful in developing a good maintenance strategy. The contribution of the IM maintenance expert would be valuable for the success of the PBRIM service due to the long experience and knowledge with the infrastructure.

The performance measurement procedures should be handled by the IM and the result of the analysis should be promptly addressed for improvement. As practiced in road maintenance, a third party might be employed for the

measurement procedure [10], though this might result in reduced need for skilful expert within the IM organization which is undesirable. Furthermore, the performance measurement procedure should be clearly known by the contractor. In addition, collaboration between the IM and contractor in the analysis of the performance measure and target would enhance the identification of improvement areas in the maintenance process [6].

The performance target should be specific, realistic and should reflect the past performance, present state and traffic operation on the infrastructure. Standards and Benchmarks could be used in developing the target where necessary. It is important to review the performance targets since it is dynamic and a function of the age, usage profile, and environment of the asset. A review of the contracting process including the target should be initiated when the target are not met and not just a kick out of the contractor

Finally, this article has identified important considerations in the development and implementation of PBRIM and also presented a framework for successful implementation. Strategic alliance between the stakeholders plays a key role in the successful implementation of this approach. Trust and confidence as well as other success factors of partnering will facilitate good relationship and enabling atmosphere for performance. A systematic management of the presented system of indicators such as one demonstrated in the case study helps to assess if the specified performance target is achieved by the contractor and also useful for early detection of gap in asset condition and service quality.

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Maintenance improvement: an opportunity for railway
infrastructure capacity enhancement

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Maintenance Improvement: an Opportunity for Railway Infrastructure Capacity Enhancement

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Abstract

The continually increasing demand on railway service in terms of the quantity and quality of both passenger and freight train operations is the core of the general railway capacity challenge. Moreover, this challenge has been the driver for some improvements in the technical system, traffic operation & management as well as maintenance process, although the room for improvement in the maintenance function is still large. An effective capacity management entails critical study of the three essential capacity parameters: infrastructure, traffic and operating parameters. To further explore the fundamentals of capacity management, this paper investigates some essential issues on railway infrastructure capacity. A review of the general railway infrastructure capacity challenge and management is presented, including some strategic measures to enhance capacity and quality of service of existing infrastructure. We have proposed maintenance improvement framework to explore the opportunity of improving the capacity situation on a network. This framework will facilitate the identification of both critical systems and activities with the largest impact on the capacity and also some root causes for critical system. The framework has suggested methodology to improve allocation and utilisation of track possession time, giving room for capacity expansion of existing railway infrastructure.

1.0 Introduction

The expansion of economic activities and the increasing mobility of people locally and globally is a major concern to the transport sector. The need to cater for both essential growths in a sustainable and economically efficient way is the core of the general capacity challenge in the railway industries. In effect, infrastructure managers (IM) are saddled with the ambitious targets of increasing the competitiveness of railway transport through capacity and service quality improvement.

Notable indications of capacity challenge for both freight and passenger traffic as identified in literature include: high seat & vehicle utilization, recurring unpunctuality, poor robustness & irregularity of time schedule, increasing demand for train path, difficulty in getting track possession for maintenance etc. [1-3]. Furthermore, in the EU15 countries there has been 15% and 28% increase in rail freight tonnage-kilometers and passenger-kilometers respectively over the period 1990-2007 [4]. In Sweden there has been a noticeable increase in the annual tonnage-kilometers and passenger-kilometer except in 2009 with large drop due to reduced global economic activities. There is an anticipated increase in traffic volume of the 473km long heavy haul line in Sweden from the present 28MGT to 45MGT in 2015. This will most likely necessitate an axle load increase from 30 to 32.5tonnes.

In recent years several research efforts within the railway industries has been centred on managing the capacity and service quality of the existing railway infrastructure network. The researches extend from improvement of rail services, rail management system and rail technology, all of which contribute towards a sustainable and more competitive railway transport [4]. Effective capacity management is a key stratagem to the success of railway sector. Primary solution to capacity challenge would be capital expansion of infrastructure but this is a cost intensive means and long term plan for increasing capacity [1]. This explains the need for a cost

effective and feasible way of managing the capacity of existing railway infrastructure through effective utilization of infrastructure possession times.

Achieving the goal of improving the capacity of existing railway infrastructure entails optimization of maintenance decisions and actions which will influence infrastructure performance, reliability, degradation and availability. An overview of techniques used in planning infrastructure maintenance and determination of best practices has been done [5]. This includes an overview of degradation model and scheduling models. Optimization model for determining the allocation of maintenance activities and crew to minimized train disruption was developed by [6]. Among other track possession and planning models developed are those in [7-9].

However in this article we present a conceptual framework for the enhancement of capacity through reduced track maintenance possession time. The article is arranged as follows; description of capacity situation with various actors, review of capacity assessment process, capacity parameters and enhancement measures. Finally, the conceptual framework proposed is described.

2.0 Capacity Situation

Railway transport is a multi-stakeholder business and its capacity is a complex issue which can be viewed from different perspective of the market, infrastructure planning, traffic scheduling and operations [10]. Though capacity is said to depend on the way it is utilized, the operational capacity and quality of service largely depends on the views and practices of the stakeholders. The ability of a defined rail line to move specific amount of traffic within a given resources and service plan largely depends on its design capability, operating conditions and maintenance condition. Figure 1 shows the interaction between all the active parties in a typical railway business and the resulting quantity/quality of railway service. The figure consists of two scenarios: the present and ambitious scenario. The present scenario is the upper part of the figure and it reflects the present or operational capacity with the influencing parties. However the lower part shows the emerging ambitious targets inspired by political promise, recommendation of international bodies and demand from train operators. With this situation in view, there is need to improve the sector to enhance both the quality and volume of traffic.

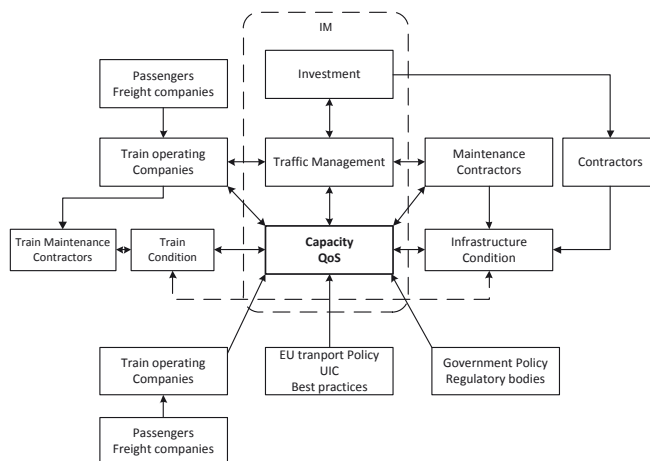


Figure 1: Capacity scenario and involved stakeholders (QoS-Quality of service)

3.0 Capacity Management

3.1 Capacity Assessment

Railway capacity measures the ability of a specific railway infrastructure to move a volume of traffic satisfying the requirements of the infrastructure manager and quality demand of the customers. This ability can be evaluated, factors affecting it can be identified and the influence of these factors can be analyzed. The several available tools and techniques for the evaluation of railway capacity are in three categories: analytical, optimization and simulation methods. Examples of the simulation tools are; Railsys, Multirail, Opentrack, CMS, VirtuOS, SIMONE, MOM, SIMON etc. For detailed information on capacity assessment and the different tools, we refer to the following references [1], [11], [12].

The general process flow in the calculation of railway capacity as recommended by international union of railways (2004) and further demonstrated by Landex [13] is shown in Figure 2. The first step is to understand the characteristics of the railway infrastructure; i.e. parameters describing the infrastructure in terms of the length of track subdivision, percentage double track, signal spacing, line spacing and so on. Furthermore the traffic parameters in form of timetable should also be known, this include the train paths, running time, train mix, average speed, priorities etc. The next step is to divide the railway network into line sections, thereafter compress the timetable so that the minimum headway time between the trains is obtained. The outcome of this assessment is the length of time which the facility is occupied in operation or the infrastructure occupation time; this is otherwise referred to as capacity utilization.



Figure 2: General work flow for capacity evaluation

The description of capacity situation on a line or network is often categorized into 3 based on the utilization of the inherent capacity and additional demand; Large problem (81-100%), averagely high problem (61-80%) and Low problem ($\leq 60\%$) [13], [14]. The result of the capacity assessment of the Swedish network performed by [14] is used to illustrate the evolution of the capacity situation from 2009 to 2011 in Figure 3. The capacity situation is the outcome of increasing traffic and enhancement measures. This is indicating challenging situation in the future as some line segments including three line segments on the heavy haul are still in the large problem categories (81-100%) even in the presence of capacity enhancements plans. This requires both continuous improvement and new investments to achieve the business goal of the IM.

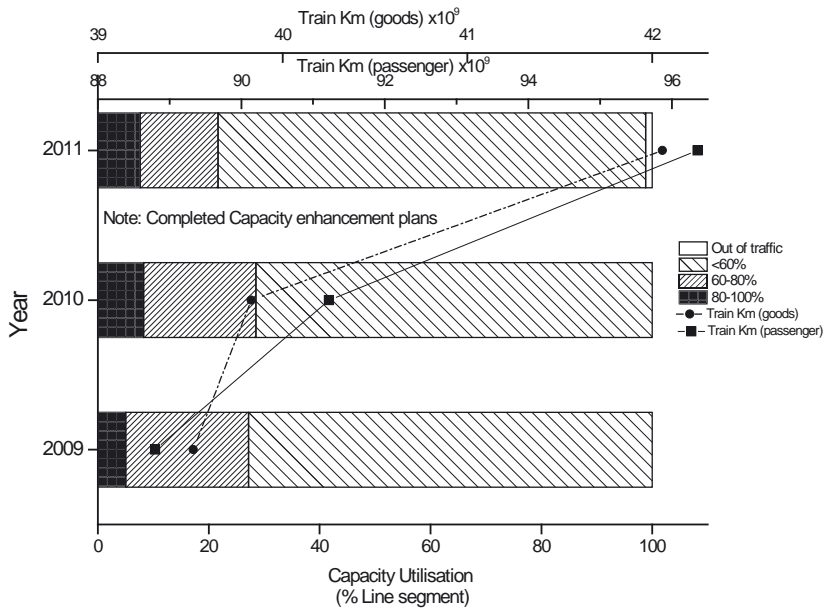


Figure 3: Capacity assessment of Swedish transport administration network

3.2 Railway capacity Parameters

Capacity analysis of the railway infrastructure is a vital but complex issue, it is not only determined by infrastructure build up, but there are other parameters which have either main or interacting effects on capacity. The characteristic capacity parameters are categorized into three: infrastructure in the system, traffic condition and the operational incidences [1], [11]. A particular combination of these three parameters will have a fixed capacity value, thus changes in any of these parameters will result in the dynamic response of capacity.

Infrastructure: Length of subdivision, track geometry & layout, signaling system, double/single track, meet pass planning point spacing etc.

Traffic: Traffic peaking factor, priority, average speed, heterogeneity etc.

Operation: Track interruptions, speed reduction regime, train stop time, maximum trip time threshold and desired stability/quality.

The focus of the researchers is very much on maintenance and thus the operation parameters are of interest. Track interruptions and outages are indications of the RAMS characteristics of the infrastructure and their random nature makes it even more critical capacity parameter.

3.3 Capacity enhancement plans

There are several strategies and plans which have been deployed to enhance the capacity situation of infrastructure network, these ranges from short term straight forward measures to complex, expensive and long term measure. Some of the measures are listed below [1], [12]:

- Increase in the length of trains, platforms and sidings
- Closing down less busy stations to homogenize traffic
- Improving logistics of rolling stock - sharing maintenance facilities among operators, expanding the track yard and marshaling facilities.
- Adopting computer based system with enhanced facilities for planning, optimizing and simulating track possessions.
- Optimization of train schedule using the techniques of operations research for time table compaction & saturation.
- Upgrading tracks to accommodate higher axle loads
- Changing layouts of junctions & curves, building capacity enhancing structures such sidings, flyovers, tunnels etc.
- Implementation of traffic management strategies such as route utilization strategies,
- Installation of modern signaling system which is capable of reducing block length on track for train occupation. Thus improving traffic volume and massive flow.
- Other special measures e.g track repair patrol team in critical areas.

4.0 Conceptual Framework for maintenance improvement

A major concern in capacity management is the operation related parameter especially when existing infrastructure is under consideration. The management of outages or track possession time for maintenance is still an aspect with promising potential. The allocation and utilization of possession time for maintenance requires improvement if the track design capacity and reliable service is to be achieved. The required improvement is not only limited to planned maintenance but also extends to the strategy for handling unexpected interruptions. Such improvement programme should be holistic and it should address several issues which are considered essentials. This should be well presented in a supporting structure or framework for successful implementation like other improvement methods such as the Deming cycle.

Maintenance improvement being an integral part of maintenance process is inspired by the assessment of maintenance performance, benchmarking with best practices or request from stakeholders. A typical improvement programme designed for the enhancement of capacity and quality of service on existing infrastructure is shown in Figure 4. There are four distinct elements in the programme.

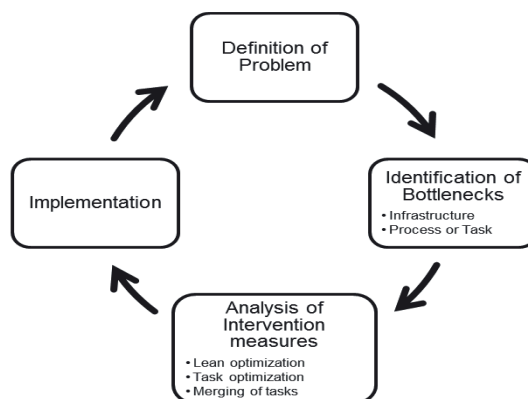


Figure 4: Maintenance improvement Framework

4.1 Definition of Problem

An essential pre-requisite to the definition of problem is a maintenance performance measurement system which helps to quantify the efficiency and effectiveness of past maintenance actions. The achieved outcome of past maintenance decisions and actions can be compared with set objectives or benchmark, and the ensuing gap is apparently the core issue in an improvement programme. In some cases the problem could be unsatisfied customer need, stakeholder request or an idea from technical development. A clear description of such gap is essential to drive the improvement process and also to validate any proposed solution measure. In this study, reduction of track possession time is the subject of the improvement programme.

4.2 Identification of Bottlenecks

Maintenance management of railway infrastructure is an elaborate process with large system and several activities. It is essential to identify the critical activities and systems which have the largest contribution to the observed gap or deficiency in maintenance function. This phenomenon or incident is referred to as bottlenecks. Bottlenecks could denote processes, activities or even subsystems that limit the capacity of an entire system or cause delay. In this case it restrains the flow of traffic through a line, or network. From maintenance point of view it could be hard measure or soft measure.

Hard Measures: These can be referred to as infrastructure bottleneck or critical point on a line or network. Traffic flow is limited at such point due to pronounced failure and consequential impact of the resulting interruptions. Bottlenecks can be identified at different system level depending on the purpose of the investigation. It can be a segment or line section in instances of high level system while for others it can be low level system such as turnouts, bridge, signaling boxes and catenary system. These critical points have impairing contribution to the RAMS characteristics of a line or network. This does not only affect the availability and safety of the network but also capacity and other quality measures. Since railway RAMS describes the confidence with which a network can guarantee the achievement of a defined quantity and quality of traffic, identifying negative contribution from any part of the entire system is an essential task for improvement. A typical cause and effect diagram showing the factors that could influence RAMS of a system, segment or sections are shown in Figure 5. In other words the diagram supports the process of identifying bottlenecks on a network and their root causes. Some relevant techniques and methodology which can be used to identify critical areas can be found in [15], [16].

Soft Measures: These are measures related to processes or tasks which have high impact on the operational capacity and quality of service. In some researches these are referred to as cost drivers or performance killers, but we have used the term bottleneck since we are concerned with track possession time or limitation to capacity utilization. Investigation in one of the EU projects [17] has shown that most important cost drivers are international. This indicates that maintenance tasks with high cost and most likely track occupation time could be similar for different Infrastructure Managers. The project has mapped most significant track problems into categories apparently representing corresponding maintenance interventions. A deduction from the project is that the following track maintenance tasks have the greatest impact on cost and perhaps on capacity: line tamping, grinding, inspection, re-sleepering, rail change, welding, vegetation control, joint renewal, turnout repair etc. However, it is recommended to conduct similar mapping into task categories using track possession time as performance measure.

It is noteworthy to mention that investigation and identification of critical assets or tasks require detailed study of historical data, failure data, maintenance data and operation data as well.

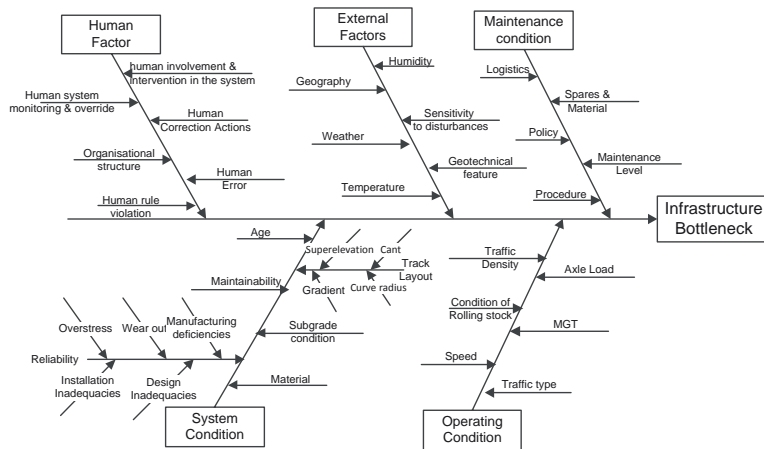


Figure 5: Root causes of infrastructure bottleneck

4.3 Analysis of intervention measures

This is another important element in the maintenance improvement programme. Having identified the gap between target and maintenance outcome, as well as pointing out critical asset and tasks, analysis of intervention measures is the next element in the framework. Typical intervention measures could be changes in maintenance concept, level of maintenance, maintenance procedures, skills and training of maintenance and operations personnel, spare parts and materials, operating procedures and conditions, safety and environmental procedures, equipment and system design. Moreover a detailed analysis of the intervention measures or suggested changes is necessary to accomplish an optimize maintenance principle and practice which supports optimum possession of the track for maintenance. There are three important perspectives of the optimization in this framework

- Lean Optimization of task with significant impact on capacity: This involves the deployment of TPM principles to identify non value adding activities in maintenance task which demands high track possession time. These are wastes and losses that can be eliminated and the process becomes efficient.
- Mathematical optimization of the possession frequency of the tasks: Operation research principles are to be used together with some existing physical degradation model of the system.
- Bundling or grouping strategy of the relevant tasks: Mathematical models can be used to analyze related maintenance tasks for possibilities of grouping them in the same white period. This will reduce the frequency of track possession for maintenance.

4.4 Implementation

The last stage in the framework for the improvement programme is the transformation of the changes into actions. This will include strategic arrangement for the deployment of these changes at the operational level. The implementation procedure gives the detail of what to do, when to do and some other guidelines needed to execute the solution at the appropriate level within the organization. It is essential to customize the implementation plan to fit the business environment of the infrastructure organization. Adequate strategy is needed if the maintenance function is outsourced to external contractors and subcontractors. Management support and effective communication will facilitate the implementation of suggested

intervention measures. It is essential to mention that the improvement programme should be integrated with the overall maintenance process to ensure a holistic maintenance procedure.

5.0 Conclusion

This paper has given capacity scenario with the views and influence of different stakeholders. The three broad classification of capacity parameters are mentioned with emphasis on operation parameter. Some practical capacity enhancement plans that have been implemented by some IMs are presented. The key contribution in this paper is the proposal of maintenance improvement framework which is practically oriented to improve the RAMS of railway infrastructure. The outcome of this will be reduction in track outages due to planned or unplanned maintenance thereby improving the capacity situation of railway network. The authors are currently working on further development of the framework especially development of optimization model for improved allocation and utilisation of track possession time for high impact maintenance tasks.

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Application of maintenance performance measurement for
continuous improvement in the railway industries

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Application of Maintenance Performance Measurement for Continuous Improvement in the Railway Industries

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Abstract— Railway transport system is complex and requires effective maintenance to achieve the business goal of safe, economic and sustainable transportation of passengers and goods. The maintenance service either provided by internal or external agents is anticipated to reach specified objectives. The major objective of maintenance is to assure dependable infrastructure with the available resources, so as to meet operational target and other business objectives of infrastructure management. This however requires continuous improvement through effective performance measurement and management. This article has identified some salient criteria or perspective of maintenance process that are essential to quantify the impact of past maintenance decisions and actions. The challenges of developing and implementing maintenance performance system in the railway industries are discussed. A synthesised system of maintenance performance measurement is also suggested, this emphasises the important performance aspects. A case study of a line section on the heavy haul line of the railway network belonging to the Swedish Transport Administration is presented to demonstrate the application of a risk assessment procedure for continuous improvement using selected indicators. This will enhance the identification of improvement opportunities in railway infrastructure maintenance. Such improvements will support the overall business goal of meeting service quality and capacity target of infrastructure manager.

Keywords— railway capacity, quality of service, maintenance performance indicators, improvement potential, bottleneck

I. INTRODUCTION

The railway system is a complex system with dynamic rolling stock, fixed infrastructure and other assets. The aggregated performance of these systems is directed towards achieving the business goal of transporting passengers and goods in an efficient, safe and environmentally friendly way. Moreover the management of this system is not a trivial task in the presence of organizational challenges, technical issues as well ambitious target to be met by the operation of the system.

The technical demand on the railway system is increasing; there is a drive for increase in speed, axle load, volume of

traffic and other essential operational requirements [1]. However if the existing infrastructure is to meet the capacity demand without compromising the quality of service, the maintenance process should be improved. It is correct to state that the improvement of maintenance function requires an effective performance measurement system. Consequently an adequately designed performance measurement system would provide the basis for an effective performance management system which could be used as a management tool by strategic, tactical and operational levels of management [2].

Implementing effective performance measurement system helps to quantify the efficiency and effectiveness of past actions and thus facilitate decision making [3]. A performance measurement system is an important management tool which is not only limited to measurement of performance but extends to; evaluation & comparison of performance, diagnosing of strengths and weaknesses, setting of objectives and target; facilitating improvements, share the results in order to inform and motivate people, control of progress and changes over time [4]. The interest in performance measurement is enormous in academic research based on the high publication and conferences [5]. Similarly the interest within organisations is high since more and more organisations using balanced performance measurement systems as the basis for management perform better than those that do not [5].

The interesting questions to be investigated in this research are:

- (i) what are the common challenges of identifying improvement potentials with performance measurement system within the railway industries?
- (ii) can the analysis of dependability and punctuality indicator data be used to identify bottlenecks or critical higher level systems and suggest improvement measures?

The organisation of the article is as follows: section II gives the description of some aspects of railway infrastructure management. Section III is an overview of maintenance

performance measurement (MPM) and some existing frameworks. Section IV discusses some issues and challenges of MPM peculiar to railway infrastructure maintenance. Section V presents a case study of the analysis of available indicator data on a selected line section. The final part is the discussion of the findings, improvement potentials and the concluding remark.

II. RAILWAY INFRASTRUCTURE MANAGEMENT

The management of railway infrastructure by public or private organisation often covers the responsibilities of:

- developing and allocating the capacity of the infrastructure
- control of the traffic on the infrastructure
- ensuring the quality, safety, reliability and availability of the infrastructure

The vision of Infrastructure Manager (IM) is in the light of the above responsibilities and their strategic objectives are informed by the vision as well as other stakeholders' requirements. Figure 1 connects the overall business plan of infrastructure management with the maintenance function. The maintenance service is either provided by internal or external agents and the input into the function is huge. For example the budget for operation and maintenance of railway infrastructure by the Swedish Transport administration is around 15% of the total budget from Swedish transport national strategic plan [6]. With such input, the maintenance process is anticipated to reach determined objectives which in turn contribute towards the overall IM objectives. This definitely requires a robust MPM system that will assess the outcome of the maintenance. The phases of a robust MPM system include; design of measures, data collection, analysis and suggestion of improvement & control measures.

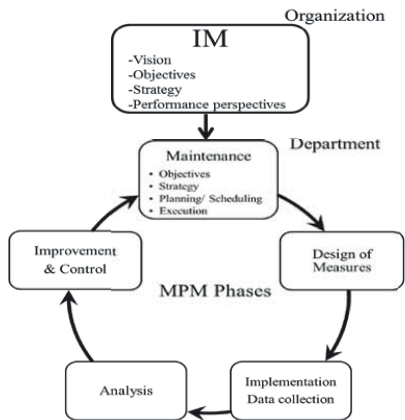


Figure 1: Infrastructure management and performance measurement

III. MAINTENANCE PERFORMANCE MEASUREMENT

The outcome of the utilization of resources in implementing actions to retain an item in, or restore it to, a state in which it can perform the required function is referred to as maintenance performance [4]. The need for an adequate system of indicators to capture and control achieved or expected outcome is indispensable. In order to meet maintenance objectives and contribute towards the achievement of overall business objectives, adequate strategy and action plans are necessary. However such plans are facilitated by a robust system of indicators or maintenance performance measurement system.

The evolution of performance measurement systems from financial to both financial and non-financial measures facilitates the achievements of competitive advantages, and overcoming the pitfalls of the traditional financial measures [7]. There are several integrated frameworks which have been developed by researchers to measure performance of system, function or organization. Detailed study of these frameworks can be read in the following literature [5], [8]. The systems are often structured into different categories representing distinct perspectives of the overall business plan. Example of such integrated performance measurement framework is balanced scorecard with focus on four perspectives: financial, customer, internal business process and learning & growth perspectives [7]. Other existing integrated Performance measurement (PM) systems have considered aspects of performance measures including: Quality, Productivity, Cost, Flexibility, Quality of work life, Innovation, Health Safety & Environment, Employee satisfaction, Resource Utilisation, Delivery, Process time, Customer satisfaction, Timeliness, Human factors and other financial measures such as Return on investment (ROI), Return on assets (ROA), Return on sales (ROS), sales per employee etc. [3], [8]-[10].

Furthermore, Åhren has reported a modification of balanced score card that is used in railway administration. The modification include renaming financial perspective to commission perspective, dividing learning & growth perspectives into two separate perspectives, co-operator perspective and development perspective. Others remain unchanged, that is, Customer perspective and Process perspective [11].

Some reasons for implementing performance measurement system in railway infrastructure management include: measuring value created by maintenance, justifying investment or renewal, improving resource allocations, ensure compliance with safety recommendation and standard benchmarks, control and follow maintenance contracts (task based or performance based) [8]. Another important reason is to improve maintenance strategy and support future decision making as well as action plans.

It is however necessary that a practical MPM framework should be a reflection of the business objective and should be simple enough to encourage easy acceptance and implementation. It should be presented clearly enough to show the link from the overall business goal/perspectives down to the common operational activities which are

measurable (on either ratio scale or ordinal scale). Figure 2 shows a simple interconnection (cascading and aggregating) from the strategic or top management level to the operational level in a robust PM system. The level 1 on the system denotes the different performance perspectives which represent the business goals of the infrastructure administration. The tactical level gives the objectives at different departments which can be aggregated up within or across the departments to give the strategic level perspective. For maintenance department, the objectives could include but not limited to facility efficiency, task efficiency, and contractor efficiency, dependability performance, health, safety & environment aspect, employee satisfaction etc [8], [12], [13]. These could be referred to as the performance criteria at the departmental level

In railway infrastructure management, to measure the contribution or impact of maintenance on the overall transport objective, clear maintenance performance indicators MPI are essentials. These indicators could be directly related to the condition of the asset or contribution of maintenance to operational quality & quantity. These take into consideration the constraint of limited resources available for maintenance function.

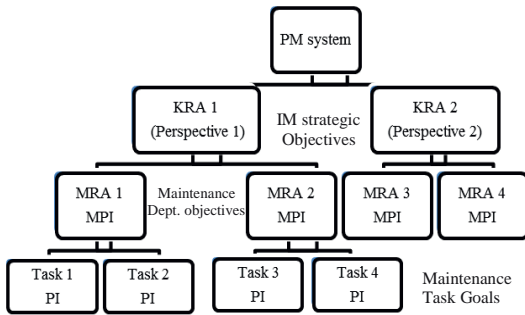


Figure 2: PM model
KRA- Key Result Area, MRA- Maintenance Result area, MPI- Maintenance Performance Indicator

Some identified maintenance result area or performance criteria of railway infrastructure maintenance are:

- ❑ Safety: Critical incident and catastrophic events such as derailment or rail break due to deficiency in maintenance function.
- ❑ Dependability and sustainability: The performance attribute of a system that describes its integrity or overall quality. These are aggregate of reliability (measure of unexpected interruptions), maintainability (ease of restoration), other quality and future aspects.

- ❑ Punctuality and Train disruption: Occasion of interruption in the planned travel times of train due to reduction or termination of functional performance of infrastructure.
- ❑ Robustness: Recovery potential in case of immobilising or major failure.
- ❑ Maintenance cost: Basically direct cost of restoration or retention of functional performance
- ❑ Possession time on track or capacity consumption: It shows how much time the track is not available for train operation due to both corrective and preventive maintenance.
- ❑ Passenger comfort or ride quality
- ❑ Resource utilization: The amount of resources (excluding labour) which are expended to meet an outcome is also criteria of performance. These are often included in the indirect cost of maintenance.

It is noteworthy to mention that there are various views about the significance or weight of the above listed criteria. Different IM will definitely have dissimilar weight for these criteria. Such weight can be used to aggregate the indicators of these criteria to a single index to evaluate full service maintenance contract or for other purposes. In the same vein, a priority listing of the criteria is a reflection of the expected additional value of maintenance to the overall business goal.

IV. ISSUES AND CHALLENGES

Maintenance performance measurement system is a management tool which can be used to identify and facilitate maintenance improvements within railway administration. To achieve this it is necessary that the design, implementation and analysis phases should be well structured like other process improvement methods. However, for MPM system to be a useful tool to facilitate improvement it is important to critically review the different phases of the system in view of the prevailing issues and challenges. These challenges are set back to the successful implementation and management of the system within the railway industries. The implementation process of MPM system has been studied both in literature [2], [3], [5], [7], [8], [11] and interaction with railway maintenance experts; the following challenges have been identified.

A. Identification of relevant indicators

The indicators that measure the contribution of maintenance is still of much concern in a MPM system that is improvement oriented. Though there are so many indicators that have been identified in literature, the relevance of those indicators is still unanswered question. When a performance measurement

system has too many indicators, it leads to inefficiency of the system as it becomes difficult to manage and follow.

B. Management support:

Going beyond ordinary measurement tool to improvement tool requires a well-designed process with the support of management. There is no doubt that management support is one of the critical factor to the success of other continuous improvement methods such as define-measure-analyse-improve-control or plan-do-check-act. On the contrary MPM systems within the railway industries are not duly supported at the strategic level. There is no clear breaking down and dissemination of the overall goal down the organisation. Also there is reluctance to implement improvement suggestions since such are not often regarded as recommendation and not regulations with management support.

C. Collection and gathering of data:

The heart of any data-driven improvement tool is data collection since analysis is absolutely limited by quality, type, quantity and format of the data collected. Needed data for the implementation of MPM are not readily available in the right format, right time and for right person. In a multi stakeholder environment such as railway administration, the challenge is aggravated. Contractors, sub-contractors, train operators and other actors might be reluctant to give some necessary data. Also the responsibility of data collection is not adequately spelt out in contracts or relevant documents. Much is needed of trust and confidence building to facilitate gathering of relevant data.

D. Integration of information from different departments/IT system

The existence of data in different universes is another challenge in the implementation of MPM system. The usefulness of such data becomes limited as it demands extra efforts to integrate them. Most of the time, the quotient of MPI requires data from different tasks handled by different departments, with different recording code and philosophy. In other cases it is difficult to integrate the hard data in the existing databases with new soft measures which are assessed through interview or other data collection instruments. A holistic solution of data management system or computerised computer management system is needed to enhance MPM system.

E. Number of stakeholders:

Another critical challenge to a successful implementation of MPM system as an improvement tool is the number of active stakeholders in railway infrastructure management. Outsourcing almost all maintenance activities to external service providers (contractors) often result into many interfaces and distribution of useful data among the parties. Lack of strategic collaboration between the different actors is a challenge to MPM system due to trust and confidence.

F. Frequency of measurement

The question of measurement frequency is relevant for inspection and other tasks that require track possession for the purpose of data collection. Due to high demand for train operation, the planning and scheduling of railway infrastructure maintenance becomes more challenging. There is steady reduction of track possession time for planned maintenance work which includes data collection and reporting. Making a balance between available resources, allocated track occupation time and desired input into the system is a difficult task which limits MPM system. This in turn triggers an issue of what is the appropriate frequency for the analysis of the PI and also dissemination of the new information.

G. Setting a realistic target or benchmark

Besides the challenge of identifying relevant indicators, the target to be achieved is another question that emerges. It is common to set a benchmark based on best practice or some other recommendations. This however becomes unrealistic if the benchmarks are not normalised with essential parameters such as inherent capability of the asset, operating condition, age, environmental condition. It requires a good understanding of the deterioration of technical capability of the asset to set a realistic target. This expertise is quite uncommon within the IM organisation, especially if most of the maintenance function is outsourced.

H. Analysis and interpretation of MPI

A link between collection of data and desired improvement is data analysis and interpretation. Data itself does not support decision making, but analysis transforms the data into knowledge base and useful information. Exponential expansion of data within railway industries has not been optimally utilised since some are not in useful format and other useful ones are not well analysed & interpreted. A holistic analysis and interpretation of MPI is necessary and not just a tool to evaluate the performance of a unit or contractor. A proper analysis links the leading indicators (input into maintenance) with the outcome indicators.

Among other challenges limiting the successful implementation of MPM system within the railway industries is: structural changes in the organization,

V. CASE STUDY

Following the information in section II and III and as well using existing maintenance performance measurement frameworks [8], [11] a synthesised MPM system for railway infrastructure is shown in Table I. Relevant strategic perspectives, maintenance result areas and performance indicators are identified and related in the table.

TABLE I
synthesised maintenance performance system

| Strategic Perspective | Maintenance Result Area | Performance Indicators |
|------------------------|--|---|
| Process related | <ul style="list-style-type: none"> Capacity consumption | <ul style="list-style-type: none"> Total maintenance hr/ Time period* Corrective maintenance hr / Total maintenance hr Response timeliness |
| Infrastructure related | <ul style="list-style-type: none"> Dependability & Sustainability | <ul style="list-style-type: none"> No of traffic disrupting failure No of urgent inspection remarks No of failure related incidences (work orders) Train delay minute/Total travel time** |
| Customer related | <ul style="list-style-type: none"> Punctuality Comfort | <ul style="list-style-type: none"> Train delay minute No of cancelled trains TQI for a track section |
| Safety related | <ul style="list-style-type: none"> Safety | <ul style="list-style-type: none"> No of derailment & rail break No of critical incident |
| Financial related | <ul style="list-style-type: none"> Return on maintenance investment | <ul style="list-style-type: none"> Maintenance cost per tonnage Km & train Km |

*Achieved Unavailability

**Operational Unavailability
TQI-Track Quality Index

To facilitate improvement, the dependability and punctuality aspects of maintenance performance are analysed in a case study. A line section on the network of Swedish transport administration (Trafikverket) is considered in the case study. A brief description of the classification of the railway network belonging to the administration is shown in Table II. The table gives an overview of the challenge confronting maintenance management in terms of capacity utilisation, difficulty to get track possession time and requirement for service quality. The line section understudied is 168 km, from Boden to Gällivare and it's the longest section (about 39% of the track length) on the heavy haul line named "Malmbanan" which belong to Line class 2. To meet the requirement in table II, it is essential to analyse performance of past maintenance actions and decision using system of indicators. This will create room for improvement.

The data analysed is the record of all train delays on the chosen line section in 2011, out of which there are 159 records of infrastructure failure resulting into train delay.

TABLE III
LINE CLASSES IN TRAFIKVERKET AND THEIR DESCRIPTION

| Line class | Transport Value* | Capacity Utilisation* | Difficulty for track maintenance time* |
|------------|------------------|-----------------------|--|
| 1 | Very important | High Medium to | Very High |
| 2 | Very important | High | High |
| 3 | Important | Medium | Average to High |
| 4 | Less Important | Low | Low |
| 5 | Less Important | Low | Low |

| Traffic Sensitivity to disturbance* | Requirement on Punctuality* | Requirement on Comfort* |
|-------------------------------------|-----------------------------|-------------------------|
| Very High | Very High | High |
| High | High | Very High |
| Medium | Basic | High |
| Low | Basic | Basic |
| Very Low | Basic | Basic |

*Detailed description of the categories are found in [14]-[16]

Transport value is the significance of the line from socioeconomic perspective

Safety requirement for all the Line classes is the same i.e. very high

Train delay in the year 2011 on the line section under consideration with associated causes is presented in Figure 3. Unidentified causes account for the largest proportion of train delay, about 33% in 2011. Significant observation is the impact of infrastructure failure which is about 20% of the train delay in the same year. Interesting to see is the contribution of the different categories to monthly delay on the track. Unidentified and secondary causes are on the high side of contribution to whole section delay for the twelve months. On the other side, infrastructure failure is outspread from low to high delay consequence, this typifies the expected randomness of failure event. Also it shows the variation in maintenance performance, operation profile and weather condition over the months of the year.

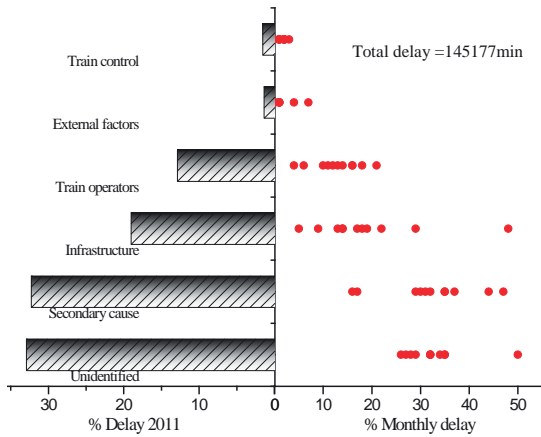


Figure 3: Punctuality measure and impacting causes

Furthermore, the evolution of the maintenance performance for the year 2011 in terms of dependability and punctuality is studied. Figure 4 shows the count of infrastructure related failure (with unexpected interruption of traffic) and train delay consequence. This is an indication of the operational availability which in turn reflects the achieved capacity and quality of service. In year 2011 traffic interfering failures caused the daily availability requirements of the infrastructure not to be met. Uninterrupted daily train operation was not met in about 33% of the daily traffic in 2011 from maintenance point of view. On day 193 though there was no failure, yet 263 minutes delay was recorded, this is due to failure that happened on the preceding day. The plot of daily failure frequency and train delay time are not well overlapping due to varying operational impact of the different failures. It is suggested that both parameters should be used simultaneously to assess maintenance function or contract.

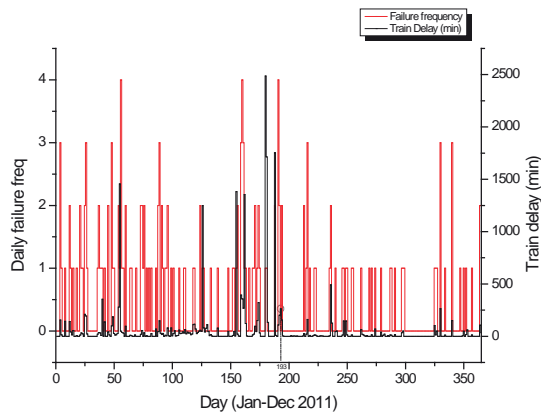


Figure 4: Evolution of maintenance performance

Figure 5 shows that track and switches & crossings (S&C) contribute the most to the number of traffic interfering failure on the line section. On the other hand, track, alternative power line, S&C and interlocking have the most operational consequence in terms of delay. However, this is collective information about the asset types which neither gives adequate information for decision making nor facilitates uniform improvement along the line.

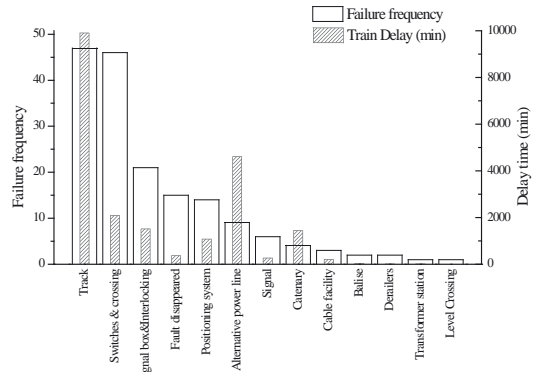


Figure 5: Contribution of each asset type to loss of punctuality and line capacity reduction

In order to meet the operational requirement of high punctuality and capacity utilization a further investigation is carried out on small segment level. In railway industries functional performance could be described on different indenture levels. It could be high level indenture such as network, lines, sections, traffic zones, or low level such as system, subsystem and maintainable component etc. Assessment of capacity, quality of railway service and other operational goals are often done on higher indenture level such as network, lines, line section, segment etc. Thus it is necessary to analyse maintenance performance indicators on this level. For maintenance staff at the operational level, the lower indenture level such as turnout, signal, catenary and their components are of interest but at strategic management level the object of interest is line or even line sections.

Furthermore studying and analysing available performance measures on a line section is promising since the line section becomes the system of interest and reasonable improvement potential can be suggested. Among several benefits of such case study is the opportunity to identify critical areas that are bottlenecks to the fulfilment of availability and operational capacity goals on a line section or network. Also, it helps to identify sections which are in worst condition on the line contributing to a higher risk of quality loss and capacity reduction.

The linear infrastructure on the line investigated is divided into 37 segments representing the technical divisions called traffic zones by the Swedish Transport Administration. The

segments are already established partitions used in traffic operational management by the administration. The 37 segments consist of: (i) traffic zones and (ii) line joining two traffic zones. The traffic zones include station areas where interlocking/signalling boxes are used to control the movement and path of train within its areas. It could also be a train stop point where passengers board and alight. At other instances it is a segment outside the station area with moveable bridge or S&C on main track that leads to industrial areas.

Graphical representation of the frequency of traffic interrupting failure on the 37 segments on the studied line sections is shown in Figure 6. This is resourceful in identifying critical locations contributing significantly to the capacity and punctuality problem on the line. The pareto plot shows that over 20% of the traffic impacting failure occurred on segments 8, 7 and 13 while about half of the segments is responsible for 80% of the line section failure in year 2011.

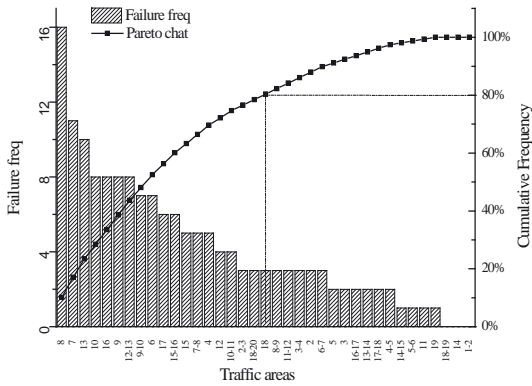


Figure 6: Pareto chart of higher level system failure (traffic zones)

However it is essential to investigate the operational consequence of these failures, since there are many subsystems or components that can fail. Figure 7 shows the train delay as a result of failure on any of the segments. 41% of the delay caused by infrastructure failure could be traced to segments (adjoining lines) 6-7, 12-13 and 2-3. Also 11 of the segments are critical based on the pareto 80% estimation of significance. Comparing Figure 6 and 7, it could be seen that the hierarchical listing of the state of the segments differs from the failure frequency and delay consequence point of views.

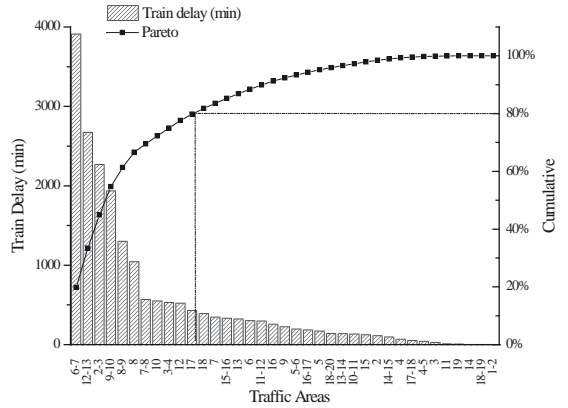


Figure 7: Pareto chart of delay consequence of higher level system failure (cancelled train are not included in the delay consequence)

The information extracted from Figure 6 & 7 is insightful in finding bottlenecks which are contributing significantly to the risk of quality loss and capacity reduction. To facilitate effective decision making it is needed to aggregate the performance indicators together in an index or visual representation.

Firstly the mean delay time on each segment is estimated using statistical distribution. According to literature, random events such as delay time can be modeled using exponential, gamma, lognormal or Weibull distribution [17]. It is assumed that the delay time considered in this study (failure related delay) will be adequately modeled by lognormal distribution. Using Anderson Darling's test procedure for goodness of fit test, lognormal distribution ranks among the best distributions with good fit. The general acceptability and simplicity of lognormal distribution was also considered in its choice.

In order to aggregate the two indicators, techniques such as criticality, state or risk assessment are considered appropriate. These techniques are used in RCM methodology and other philosophy for developing preventive maintenance programme [18]-[20]. In addition to these techniques, decision support tools such as analytical hierarchy process (AHP) and fuzzy logic are applicable in the aggregation procedure. The risk assessment procedure in Railway specifications – The specification and demonstration of RAMS [19] was adapted, in order to categorize the contribution of each segment to risk of loss of service quality capacity reduction. This will be resourceful information for prioritisation during maintenance planning and scheduling.

Table III is a typical risk evaluation matrices developed by [19] and modified by [20]

TABLE III
TYPICAL RISK EVALUATION MATRICES

| Frequency | Likely impact or consequence of failure | | | |
|------------|---|-------------|-------------|--------------|
| | Insignificant | Marginal | Critical | Catastrophic |
| Frequent | Undesirable | Intolerable | Intolerable | Intolerable |
| Probable | Undesirable | Intolerable | Intolerable | Intolerable |
| Occasional | Tolerable | Undesirable | Undesirable | Intolerable |
| Remote | Negligible | Tolerable | Undesirable | Intolerable |
| Improbable | Negligible | Tolerable | Undesirable | Undesirable |
| Incredible | Negligible | Negligible | Tolerable | Undesirable |

A hypothetical grading of the frequency of failure and consequential delay is done to demonstrate the mentioned methodology. This grading ought to be a subjective judgement of a group of expert within the IM organisation, and it should reflect both the acceptance limit and quality definition of the organisation. The last category of failure frequency from the above mentioned standard is omitted in the demonstration, as it suffices that improbable frequency can as well describe the incredible category in the case considered. The contribution of each segment to the overall risk of quality loss is clearly presented in Figure 8. From Table III and Figure 8, traffic zones 8, 7, 2-3, 6-7 are having intolerable contributions while 15, 17, 15-16 and 10-11 are having Tolerable contributions. All other zones are having undesirable contributions with the exception of zone 4 with negligible impact.

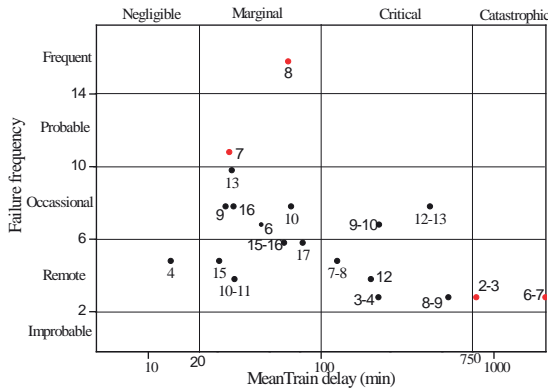


Figure 8: Risk contribution of the traffic zones to loss of punctuality and capacity reduction

In the development of effective maintenance programme, it is essential that its focus is not basically to avoid failure, but preference should be given to the avoidance or reduction of the operational & safety impact of failure. For a distributed system such as railway infrastructure, analysis like this help to make a hierarchical listing of the traffic zones (segments). To

meet the operational requirements of the line section under consideration (see Table II), the zones with intolerable contributions should be subjected to detailed failure analysis to eliminate the bottleneck. Zones with undesirable risk contribution should be maintained to reduce their impact. Zones with tolerable impact should be controlled with necessary measures while those with negligible impact should be observed and their maintenance ought to be standardised. This will facilitate the development of maintenance programme that will homogenise the condition of the infrastructure along the line section.

Furthermore, identifying critical spot or bottleneck on the line sections also help to capture inherent locational problem such as:

- Maintenance deficiency
- Concentration of system
- Poor subgrade or geotechnical feature
- Layout or geometry, curves and gradients
- Maintainability
- Sensitive and critical asset type
- Ageing
- Other relevant operating conditions

VI. DISCUSSION AND CONCLUSIONS

In conclusion, this article has addressed an essential concern within the railway industries. It has identified the issues and challenges of implementing and managing a successful MPM within railway industries. The identified issues and challenges have been insightful in proposing a simplified measurement system which can facilitate the identification of bottlenecks and deficiencies in maintenance. The proposed MPM system will help to quantify both internal and external effectiveness of past maintenance actions and thus enhance decision.

The analysis of the dependability and punctuality indicator data has shown the possibility of identifying improvement potentials in maintenance practice using the MPM system. Some of the concluding remarks include;

- Infrastructure failure has a significantly high impact on operational capacity and train punctuality.
- The hierarchical listing of the zones based on their contribution to loss of quality & capacity differs when using their failure frequency and their consequential delay impacts.
- Traffic zones 8, 7, 2-3 and 6-7 contribute significantly to risk of quality loss and capacity reduction of the line section. Thus critical maintenance procedure should be adopted with some preference in terms of nature and urgency of work. Also detailed maintenance analysis such as root cause should be carried out on these segments for improvement purpose.

- iv. Weight can be attached to the categories of the bottlenecks. This can be cascaded down to the respective lower level system in the segments to determine maintenance significant components which should be subjected to detailed maintenance programme such as FMECA, root cause analysis etc.
- v. Finally, decision on distribution of maintenance and reinvestment budget for the railway line can be supported with this analysis on the line section.

For future research, other relevant maintenance performance indicators can be included as criteria in the analysis. This will not limit the perspective and application of the analysis to punctuality and capacity improvement.

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Optimum allocation and utilization of maintenance track
possession time: a case study of tamping

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Optimum allocation and utilization of maintenance track possession time: A case study of tamping

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Abstract

Optimum allocation and efficient utilization of track possession time is becoming critical issue in railway infrastructure management due to increasing capacity demands. This development and other requirements of modern infrastructure management necessitate the improvement of planning and scheduling of large scale maintenance activities such as tamping. It is therefore needful to develop short, medium or long term plan, on how tamping can be performed on a network or track section in a definite time horizon. To this end, two vital aspects of infrastructure maintenance planning have been considered in this article, deterioration modelling and scheduling optimisation. In this paper exponential deterioration function has been applied to model the geometry quality of a series of 200m segments on a 130km line section and then developed an empirical model for recovery after tamping intervention. These two models are thereafter used to present a methodology to optimise schedule for tamping intervention by minimising total cost of intervention including cost of track possession while geometry quality is ascertained to be within desirable limit. The modelling considers two types of tamping interventions, preventive and corrective with different intervention limits and tamping machines. The result of this paper therefore suggests a tamping plan which when implemented will lead to optimum allocation of track possession time and as well maintain the track geometry quality within specified limits and classes.

Keywords: Tamping, track possession time, degradation, longitudinal level, optimization.

Introduction

The requirements of improving the RAMS of track structures is essential to achieve the goal of supporting design capacity and improving service quality of railway transport. Moreover, the continuous increase in demand for safety and capacity for both freight and passenger traffic requires adequately supported intervention measures with optimum allocation and utilisation of track possession time. These intervention measures are categorized into track maintenance and renewal tasks [1]. One of the most important maintenance concerns in track structure is how to predict and control degradation of track structure and how to maintain the geometry quality of the track [2]. This does not only influence the ride quality and passenger comfort during operation but it also contributes immensely to the dynamics of the entire train-track system. Nonetheless tamping is considered as maintenance task with large impact on capacity of a railway network based on its peculiar requirements such as track possession time, quality demand, heavy machinery involved, difficulty in predicting the required intervention in good time and also scheduling challenge.

Capacity impact of tamping operation

The time required to restore the geometry characteristics of track is significant when the capacity of an existing network is concerned. Depending on the maintenance philosophy and track management strategy, the track possession demand for tamping could vary for similar track sections. If effective tamping strategy is not deployed, track design capacity might not be achieved. Similar to other maintenance activities of permanent way, the parameters affecting the total track possession time are; the duration of white period for each possession, travelling speed of the machine, working speed, preparation time and other time for logistics consideration [3]. Even though the duration of each possession window and working speed are important, scheduling procedure is rather of interest in this study since re-design and innovation aspects are not within the scope of this work.

In the past, different principles have informed the planning, scheduling and implementation of maintenance actions, some of which are based on manufacturer's recommendations, experience within the railway organisation, assumed deterioration, availability of maintenance equipment and other basic principles. As a matter of fact, these could not support the growing demand for capacity, safety, cost effectiveness and other service quality of railway transport. To this end several techniques and methods have been developed to plan and schedule railway infrastructure maintenance in an optimum way.

Track possession scheduling and optimization

Developments in railway management have led to increasing need for optimum planning and scheduling of maintenance activities. The parameters of interest in several maintenance optimization tools and techniques include; maintenance costs, labour cost, life cycle cost, asset performance, track possession time, punctuality and other service quality parameters [4], [5]. Basically, maintenance optimisation of railway infrastructure gives short, medium or long term plan, on how preventive maintenance works will be performed on which segments in a definite horizon. To this end, an overview of railway infrastructure maintenance planning has highlighted two vital aspects of infrastructure maintenance planning: deterioration modelling and maintenance scheduling [6]. On the aspect of track deterioration, important parameters to be taken into consideration for prognostics are initial quality, initial settlement and rate of deterioration [3], [7]-[10]. The significance of initial quality of track at the time of installation has been investigated in [7] and also the life cycle management perspective of track structures had been studied. The rate of deterioration is a reflection of an integrated process of material degradation, traffic induced degradation and maintenance. These phenomena are due to design and layout of track, profile of rail, condition of ballast, bearing capability of subgrade, drainage problem and train track dynamic forces [3], [11]. On the scheduling part, maintenance activities are allocated to available time intervals or optimum track possession window are created for maintenance during time table schedule. Higgins [4] put forward a model to determine the best allocation of maintenance activities and crews to minimise traffic disruption and completion time. Miwa [9] developed a mathematical programming model for optimal tamping schedule, indicating the track division for which tamping must be implemented in a specified horizon. Cheung et al [12], developed track possession assignment problem to assign railway tracks to a given set of scheduled maintenance tasks according to defined constraints. The objective of the problem is to create an assignment plan that maximizes the assignment of job requests based on priorities and also satisfying all the constraints. A preventive maintenance schedule problem has been presented by Budai et al [5]

to cluster routine activities and projects for a link over a certain period such that the sum of possession costs and maintenance costs is minimised. They developed some heuristics such as most frequent work first and most costly work first to solve the formulated preventive maintenance schedule problem. Andrade et al [10] addressed preventive maintenance scheduling problem connected to track geometry using a bi-objective integer formulation with a balance of renewal and maintenance costs with train delay. Vale et al [8] developed a binary linear program to schedule tamping taking into considerations the evolution of track degradation over time, track layout, quality recovery of track and track quality limits from standards.

In general several mathematical programmes for preventive maintenance scheduling problems have been formulated and solutions have been proposed using multi-objective algorithm, artificial intelligence, heuristics algorithm and other techniques. There is need to further address optimum allocation and utilisation of track possession time for maintenance to enhance operational capacity. The contribution of this paper is an investigation of the differential deterioration along the length of the track and quantification of tamping intervention on a specific length of track over a finite horizon. Also a methodology for optimum scheduling of tamping is proposed to minimise direct cost of intervention and cost of track possession while the excursion of the geometry quality is within the desired level.

Theory and Model Formulation

The life of track structure as well as the quality of the track at any point in time can be described by both deterioration and recovery phenomena [7], [9]. In modelling this two phenomena of deterioration and recovery there are some basic principles and theories which are essential.

Track degradation

The passage of trains over a track generates enormous forces. This leads to deformation and wear of track components rails, sleepers, fasteners, ballast and subgrade and consequently deterioration of the track geometry quality over a long time [13]. This phenomenon is one of the most important aspects in railway infrastructure maintenance. Thus it is a vital requirement to adequately understand the pattern of deterioration of track geometry quality with accumulation of plastic and elastic deformation as a result of traffic loading.

The geometry quality and irregularity of ballasted tracks are monitored by some key parameters; these parameters include longitudinal level, alignment, gauge, cross level and twist [3], [14], [15]. To manage track geometry problems in degradation, infrastructure managers and researchers have monitored the evolution of principal parameters such as longitudinal level and alignment [2], [8], [15], [16] while others have used derived indices such as variation of acceleration (due to irregularity) [7] and combination of quality parameters to follow the growth of track quality defects. Moreover the mean and standard deviation of the longitudinal level defects over a certain track section have proven sufficient to describe and model the track geometry quality and also to support maintenance decision and actions [3], [15], [17].

The life cycle behaviour of track has been explained using different empirical models based on measurements records and load or time. These models include, grey model, linear model, exponential model and other empirical models [2], [7], [8], [11], [15], [16]. The exponential model in equation 1 is preferred in this study considering the established behaviour of track - high quality track or new track deteriorates slowly while low quality track or ageing track deteriorates rapidly.

$$\sigma(s,t) = \sigma(s,0)e^{b(s)t} \quad (1)$$

| | |
|---------------|--|
| $\sigma(s,t)$ | Std dev of long level for segment s and time $t < T$ |
| $b(s)$ | Degradation rate for segment s |
| T | Planning horizon (e.g 2years) |

Tamping and Recovery

The track geometry quality eventually deteriorates beyond allowable threshold for maintenance and safety giving rise to the need for intervention to restore it towards the designed geometry characteristics. The intervention level depends on the tamping strategy deployed. Common strategy in use by infrastructure manger include; correction of isolated defects and restoration of lines when specified thresholds are reached. The details of recommended intervention limits can be found in [17]. Ideally, from a life cycle perspective these thresholds should be dynamic, depending on the age of track structure or number of interventions carried out. This practice will enhance durability of track quality and also extend the life span of track. Other factors considered in tamping are availability of tamping machine and maintenance philosophies of asset owners. When prognostic tamping strategy is to be deployed the recovery or amount of improvement achieved after tamping must be known.

In reality the recovery or efficiency of tamping depends on several factors such as track quality at tamping, age of track component, tamping technique, number of previous tamping, ballast condition and human factor. In this study, empirical regression model from data collected in previous research [18] on the same route has been developed. The model describes the relation between standard deviation of the longitudinal level before tamping and the improvement after tamping. The model is used to predict the changes in the geometry parameter at any point in time when tamping is carried out. Figure 1 shows the plot of the observed recovery and quality at intervention and the regression model is given in equation 2. 90% prediction limit is estimated and shown in Figure 1 in order to investigate the sensitivity of simulation result to variation in recovery

$$\text{Recovery } R = 0.5445\sigma(s,t) - 0.8893 \quad (2)$$

The indication of the linear model in Figure 1 is that recovery depends on the quality at the point of intervention. Only the observation data that falls within the region considered most likely for good substructure and ballast condition in best practice guide for optimum track geometry durability [15] are shown in the figure.

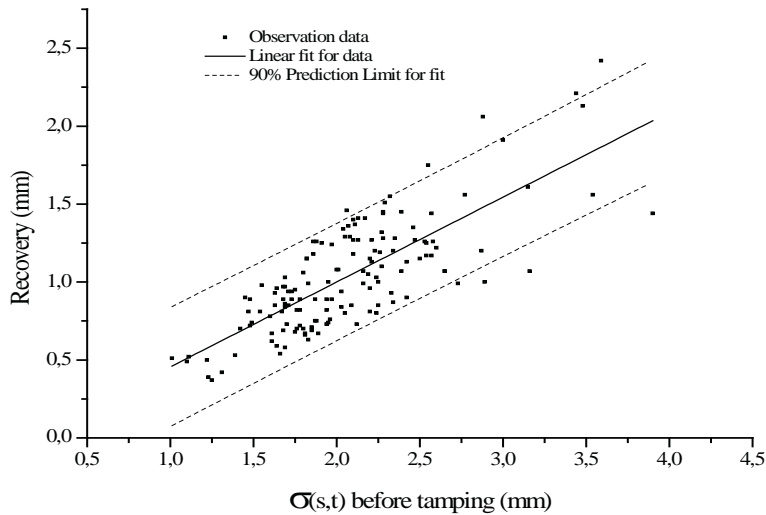


Figure 1. Improvement of tamping interventions for observation and best practice

Assumptions

In the tamping optimization done in this work, there are some assumptions which are taken before the model formulation, these include:

- The deterioration follows an exponential model based on the explanation given earlier that high quality track deteriorate slowly but that of a bad quality track proceeds rapidly and irreversibly (see equation 1).
- The degradation of each 200m track sections is considered to be constant in the time horizon considered for the scheduling in this study.
- The track section is considered to be having good ballast condition since the track structure is relatively new. Thus the tamping recovery is assumed to lie within the region considered likely for efficient tamping in a good ballast condition and follow the model described in the previous section. Same recovery model is used for all the segments.
- The segments with switches and crossings and other critical units will be maintained using spot tamping considering them as isolated defects. The reason for this is that so many engineering works are carried out on these segments thus to model their deterioration additional measurement is required.
- There are two tamping machines, one has limited availability, high tamping efficiency, and used for early intervention. The second one is available and has relatively low tamping efficiency and suitable for corrective tamping for low track quality. Optimum allocation seeks for a balanced mix of the two possibilities in terms of cost, quality and time on track.
- There are four different stations that can serve as temporary parks where the machines can be placed before and after tamping.

Optimization procedure

The activity breakdown structure shown in Figure 2 is a simplified intervention process for both preventive and corrective policies. The travelling time depends on the speed and location of the tamper before the shift while the set up and take down times are fixed.

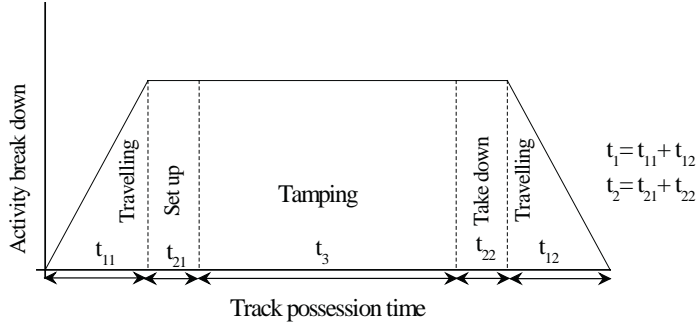


Figure 2. Track possession time for interventions.

Table 1. Notation

| Symbol | Description |
|---------------|---|
| c_p, c_c | Cost of preventive and corrective intervention per segment |
| C_{DT} | Cost of downtime per hour (depends on line class) |
| C_{I-D} | Direct cost of intervention in T days |
| C_{I-I} | Indirect cost of intervention in T days |
| TC | Total cost of intervention in T days |
| TT | Total track possession time |
| σ^* | Threshold for preventive $\sigma_p^* = 1.8\text{mm}$ and corrective interventions $\sigma_c^* = 2.1\text{mm}$ using the standard [17] |
| $N'(t)$ | Number of segments above preventive (N'_p) and corrective (N'_c) threshold on day t |
| N | Number of segments tamped in preventive (N_p) and corrective intervention (N_c) shifts |
| $N_{c.shift}$ | Number of corrective intervention shifts required for a specified preventive intervention shifts $N_{p.shift}$. |
| v | Tamping speed for preventive tamper $v_p = 1.4\text{km/hr}$ and corrective tamper $v_c = 0.8\text{km/hr}$ |
| v' | Travelling speed for preventive tamper $v'_p = 90\text{km/hr}$ and corrective tamper $v'_c = 80\text{km/hr}$ |
| t_p, t_1 | Time for each setup and takedown = 10mins, Total Travelling time during a shift |
| t_w | Duration of shift. Max. duration $t_w^* = 6\text{hr}$ |
| d | Length of segment = 200 m |
| p | location of start park $p(i)$ and end park $p(j)$ ($i, j \in 1, \dots, n_{park}$) |
| n_{park} | Total number of parks (In this study $n_{park} = 4$) |
| $s(i)$ | Location of tamped segments $\forall s(i) \in S$ and $i = 1, \dots, N$ |
| n_a | Number of adjacent segments among tamped segments |

The optimization procedure with associated conditions for tamping intervention is simplified in the flow chat shown in Figure 3.

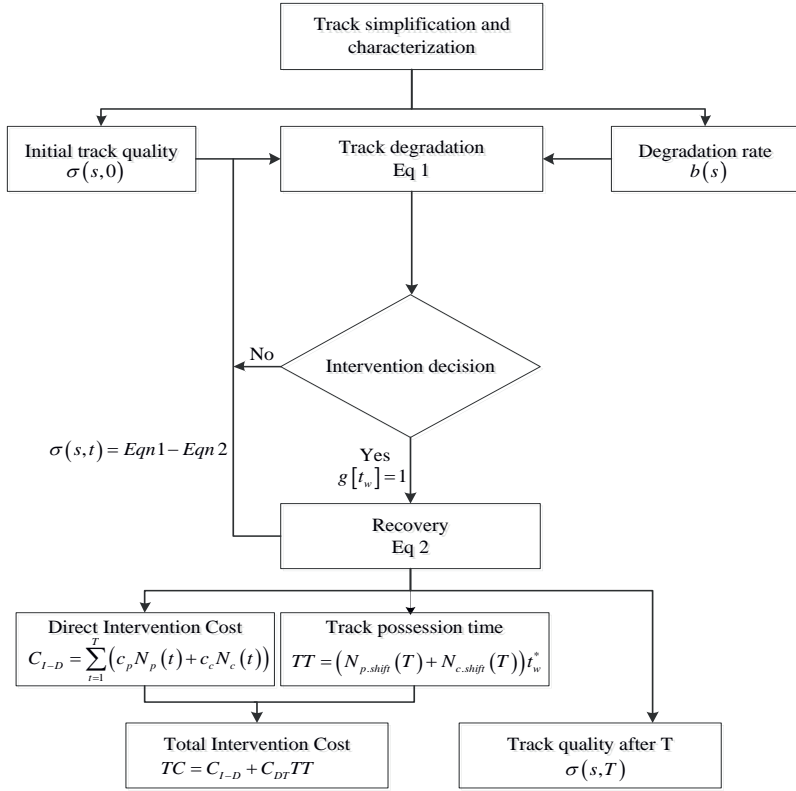


Figure 3: Flow chart for the optimization of track possession and cost of tamping

Objective function for intervention decision

$$t_w(N(t)) = \max \{t_1 + t_2 + t_3\} \quad (3)$$

s.t.

$$\begin{cases} t_w(N(t)) < t_w^* \\ t_w(N'(t+1)) > t_w^* \\ N'(t) = \sum_{s=1}^S f[\sigma(s,t) - \sigma^*] \\ f[x] = \begin{cases} 1, & x \geq 0 \\ 0, & \text{else} \end{cases} \\ N(t) \leq N'(t) \end{cases}$$

Decision function

$$g[t_w] = \begin{cases} 1, & t_w(N(t)) = \max\{t_1 + t_2 + t_3\} \\ 0, & \text{else} \end{cases} \quad (4)$$

Where

$$t_1 = \left[\min(|s(1) - p(i)| + |s(N) - p(j)|) + s(N) - s(1) - (N - 1) \right] \cdot \frac{d}{v'} \quad (5)$$

$$(i, j \in 1, \dots, n_{park})$$

$$t_2 = 2t_p(N - n_a) \quad (6)$$

$$t_3 = \frac{Nd}{v} \quad (7)$$

Number of corrective intervention shifts required to maintain the line section, given a specific number of preventive maintenance shift.

$$N_{c.shift}(T) = \sum_{t=1}^T g[t_w(N(t))] \quad (8)$$

$$g[t_w] = \begin{cases} 1, & t_w = \max\{t_1 + t_2 + t_3\} \\ 0, & \text{else} \end{cases}$$

Case study

Description of case study

A line section on the network of Swedish transport administration (Trafikverket) is considered in the case study. The line section is 130 km single track from Kiruna to Riksgränsen and it is the northern section of the iron ore line of the Swedish Transport Administration network. It belongs to the line category with high socio-economic importance and high requirement on maintenance for quality delivery in terms of both punctuality and comfort. It is basically a freight line since majority of the traffic is iron ore freight, although passenger trains and other freight trains also use the line. The actual train speed on the line is between 70-130km/hr but for the sake of geometry quality intervention limit required in this study it is considered to fall speed category 80-120km/hr. The maximum allowable axle load on the line section is 30 tonnes and the annual accumulated tonnage is over 22MGT. A remarkable note is that track structure on this line section was renewed between 2006 and 2009, this major work also include ballast renewal. In addition to the description above, additional information about this line section is the boundary condition of extreme climate which can influence RAMS characteristics of the infrastructure. The winter season do witness snowfall and extreme temperature. The annual temperature could vary between -40°C and +25°C.

Inspection data

Inspections are an important component of any effective preventive maintenance programme. Track geometry inspection though disruptive is very needful for prognostic tamping which is optimum in the allocation and utilisation of track possession time. It also gives useful information to avoid too early or frequent tamping which is deleterious on ballast condition and at the same time warn against too late intervention which can result in temporary speed restriction or failure. The inspection of track is done by the infrastructure manager based on two factors, speed and annual accumulated tonnage on the section. For the case study, track quality inspection is done between 3-6 times every year, basically between April and October. The inspection data extends from 2007 to 2012, and for each 200m segments only data after the completion of renewal is considered. Several geometry parameters are recorded by the train measurement vehicle but only the standard deviation of the longitudinal level over 200m track length is used in the geometry quality prognosis and maintenance optimization. The standard deviation of the short wavelength longitudinal level for 200m track segments from four measurements on the 130km line section investigated in this study is shown in Figure 4.

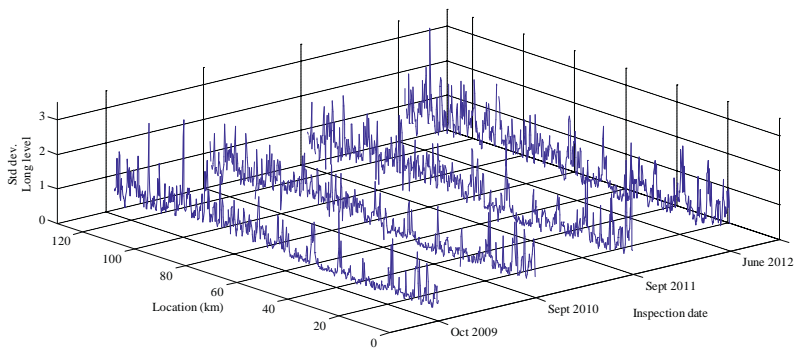


Figure 4. Standard deviation of longitudinal level over 130km line section

Result and Discussion

The results and findings of the deterioration and recovery phenomena that has been modelled and predicted in this study are presented in this section of the article.

Non homogeneity of track sections

Using the exponential model explained in previous section and the inspection data between 2007 and 2012, the growth rate of the longitudinal level defect for each 200m segment is estimated. The distribution of the growth rate for all the 592 segments is shown in Figure 5, it is well described by a Weibull distribution and the parameters of the distribution could be used in a stochastic or probabilistic modelling of the geometric characteristics of the track section. The growth rate is an indication of the evolution of the track geometry quality for each segment. More than 50% of the track section has an exponential growth rate between 0.00024 and 0.00060. Evolution of track geometry quality is a complicated process; the differential growth rate along the track sections reflects non homogeneity and variation of

track components along the track length. In fact the 200m track segments can be regarded as non-identical units in terms of quality deterioration.

An indication of this plot is that continuous tamping of the whole length of the track section might not be the best strategy in terms of life cycle management of the track. An essential maintenance requirement informed by the figure is the balance of preventive and corrective tamping, since higher exponential rate will require more interventions than lower exponential rate, this is also noted by [18].

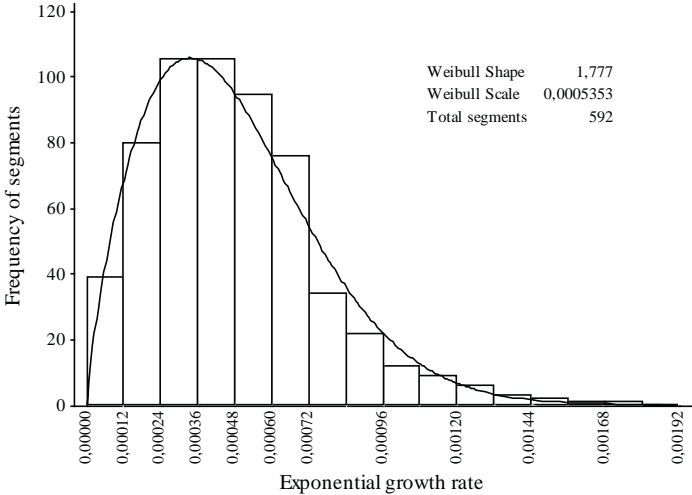


Figure 5. Distribution of exponential growth rate

Tamping strategy

Based on the observation of differential growth rate along the track length, there is need to optimize the preventive and corrective tamping interventions on the track section. Using the model procedure described in the flow chart and equation 6, the number of corrective interventions that will be required in two years for different number of shifts allocated for preventive tamping is estimated and shown in Figure 6. The sensitivity of the result is also shown using 90% prediction limit of the recovery model fit. Increasing the number of allocated shifts for preventive tamping decreases the segment requiring corrective tamping up to a point where there is no need for corrective tamping besides the initial which was compelled at the beginning when few sections were above both intervention thresholds.

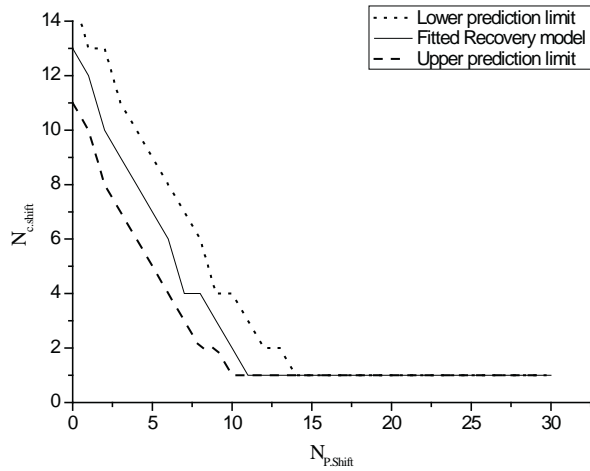


Figure 6. Corrective interventions and Scheduled preventive interventions

Direct cost of intervention

Using the proposed optimization procedure in Figure 3 with different cost ratios for the two tamping policies, the total cost for tamping interventions over a short period of two years is given in Figure 7. Higher ratio of C_p/C_c results into high cost of intervention when the number of preventive maintenance shift is increasing.

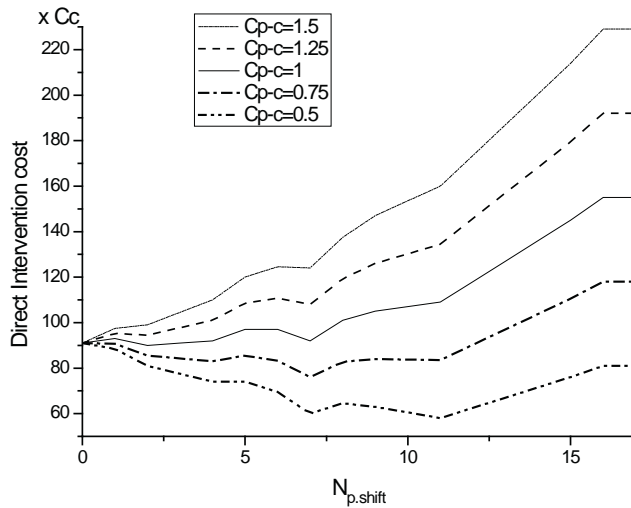


Figure 7. Total maintenance costs with different cost ratios

For all cost ratios, the direct cost of intervention is constant after sixteen shifts because no more segments will exceed the preventive maintenance threshold within the 2 year period of planning. For low corrective maintenance cost, the economic optimum plan in a short period will be to always carry out corrective maintenance. Nonetheless this is not the best policy

especially at the early life of the track, as it will reduce the service life. From Figure 8 the economic optimum policy considering a cost ratio of $C_p/C_c = 1$ is to have few preventive intervention shifts. However the track possession time and quality of the track is another parameter to consider.

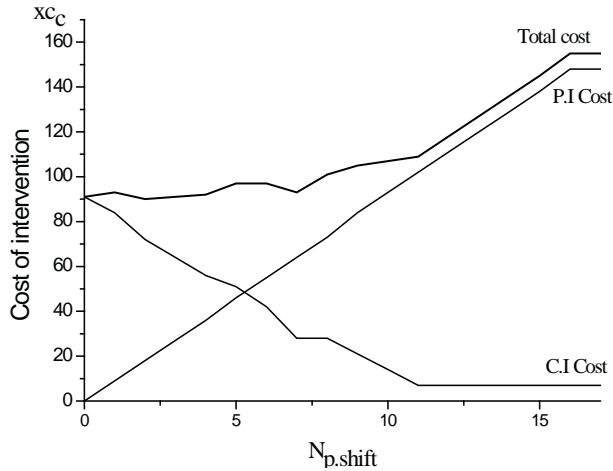


Figure 8. Maintenance costs for a finite horizon using cost ratio $c_p/c_c=1$
(P.I – preventive intervention, C.I – Corrective intervention)

Cost of intervention and track possession

The present demand on railway infrastructure requires an augmented allocation and utilisation of track possession time and thus there is need to implement optimum maintenance practice. In view of this, the global cost model proposed by [19] is adapted to estimate the total cost of intervention by adding the direct and indirect cost of intervention. Following the model procedure in Figure 3 and using stochastic simulation for the recovery model (equal chances of obtaining recovery within the prediction limits, see Figure 1), robust estimation of the track possession time was obtained and also indirect cost of intervention (using $C_{DT} \approx 2c_c$). Figure 9 shows the total track possession time over a short period of two years for different number of preventive intervention shifts. Strategies with $N_p.shift$ between 5 and 8 are efficient since they are in the range of minimum track possession time. Furthermore, Figure 10 shows the total cost of intervention with different number of shifts allocated for preventive intervention. According to the result shown in Figure 10, selecting strategies with more than 8 preventive maintenance shifts will result into additional cost due to too frequent track possession. Optimum strategy should have higher economic performance and process efficiency and as well satisfy the required effectiveness in terms of track quality. In view of this, strategies with $N_p.shift$ up to 8 are cost efficient since they are in the neighbourhood of the minimum total intervention costs. Nonetheless it is necessary to confirm the optimality of any of these strategies by assessing the resulting quality characteristics to see if it meets the quality requirement of the infrastructure manager. In this study $N_p.shift = 8$ is suggested since it is

cost efficient and gives better quality than other strategies with lower preventive maintenance shifts.

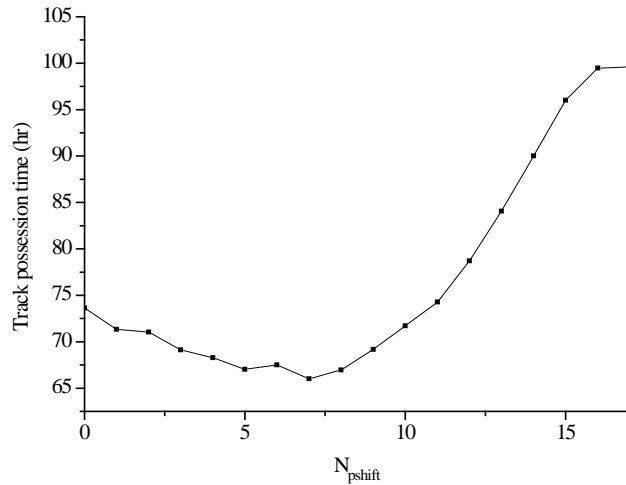


Figure 9. Track possession time

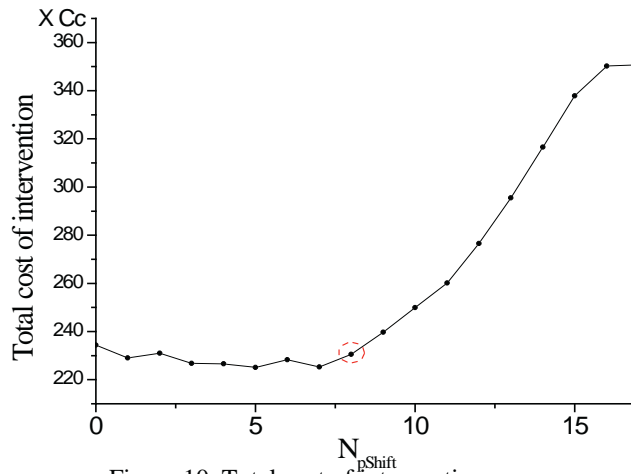


Figure 10. Total cost of intervention

Track quality characterisation

The tamping strategies are evaluated by characterising the predicted geometry quality using the procedure in the current state-of-the-art of description for track geometry quality [20]. Figure 11 presents the cumulative frequency distribution of the predicted longitudinal level defects over the length of the entire track section. The figure characterizes the initial quality

and also track quality after two years for three different scenarios: no tamping, Np.shift equal 8 and 16. If it is required by the infrastructure manager IM that at least 90 % of the total segments on the track section should not exceed track quality class C ($\sigma_{LL} < 1.8\text{mm}$) for safety, comfort, ride quality and life cycle management reason, then from Figure 11 having Np.shift equal to 8 is adequate.

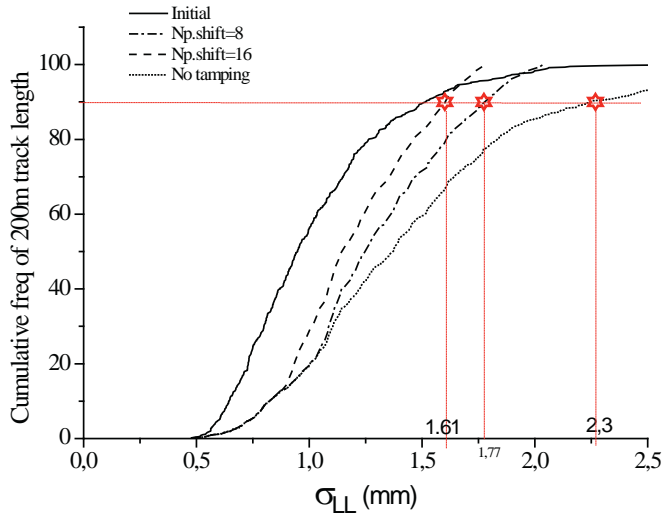


Figure 11. Cumulative frequency distribution of track quality indicator

Table 2 gives the detailed description and extended classification of the track section into track quality classes (TQC) for the 2 years under consideration using the procedure mentioned above. If the requirement of the IM puts limit on proportion of the track segments that is expected to be in each quality class in a certain time horizon then this can be checked.

Table 2. Characterization of the quality of the track

| Scenario | Track Quality class with % composition (A is the best and E is the worst) | | | | |
|-------------|---|---------------|--------------|--------------|-----------|
| | A <0.75mm | B 0.75-1.1 | C 1.1-1.8 | D 1.8-2.5 | E >2.5 |
| Initial | 24.16 | 41.55 | 30.07 | 4.22 | 0.17 |
| Np.shift=8 | 5.41 | 27.03 | 58.78 | 8.95 | 0.00 |
| Np.shift=16 | 5.41 | 37.33 | 57.26 | 0.17 | 0.00 |
| No tamping | 5.41 | 23.99 | 49.16 | 14.70 | 6.93 |

Conclusion

The demand on the allocation and utilisation of track possession time is increasing, and there is a need to develop model to support maintenance decision especially for maintenance tasks with high possession requirements. This paper has presented an optimization tool to support the allocation of track possession time in short term plan for tamping. It has considered the exponential function to model the deterioration of each 200m segment of the case study.

There is a differential growth rate of the longitudinal defect over the 130 km track section studied with about half of the segments having exponential growth rate between 0.00024-0.0006. The objective of the optimisation model is to minimize direct cost of intervention and cost of track possession while geometry quality is kept at desirable level. In the case study, the optimum tamping strategy for two year planning horizon will be to allocate eight shifts for preventive tamping while additional quality excursions will be restored using corrective intervention policy. This will support adequate planning and resource allocation including ordering of tamping machines. This approach gives knowledge of track behaviour, quantify tamping need and suggest tamping strategy such that track possession time and associated cost are reduced.

Finally, a future work is developing a long term plan considering dynamic intervention threshold levels for the two policies; low threshold levels at the early stage of the track life and high thresholds at the later part. Studying practical thresholds levels at the different life cycle phase of the track for efficient life cycle management of track structure is a future work.

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