NeTIRail

Needs Tailored Interoperable Railway Infrastructure

Deliverable D2.4

Application of lean and automotive industry techniques to produce a step change in railway S&C life and costs

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Executive Summary

Switches and Crossings (S&C) are a critical component in railway infrastructure, since they are at the centre of the railway routing operations and their malfunction often hampers the smooth operation along the concerned area. S&C failures and (urgent) maintenance tasks often result in delay of trains, bring a negative impact on the whole network and cause a great loss in terms of operation. In fact, unlike other trackside parts, due to some movable components, S&Cs often bring a great proportion of failures in all track failures. In addition, S&C have been clearly identified as responsible for a large proportion of track expenditure.

On the other hand, several studies and projects have investigated different techniques pertaining to the installation, replacement and maintenance of S&Cs. Such alternatives offer interesting opportunities in view of optimizing the management and LCC of S&Cs. In this respect, the application of Lean and automotive techniques is perfectly in line with such a target. Namely, the optimizing in terms of choices and operations related to S&Cs can offer valuable trade-offs that allow for valuable gains in terms of operation performance and LCC.

Based on the data collected in T2.3.1 and additional inputs (technical visits, state of the art, etc.), firstly this report provides an overview on the main features pertaining to safety in general and RAMS analysis (Reliability, Availability, Maintainability, Safety) of S&Cs. Then, the application of lean techniques and automotive techniques will be demonstrated as applied to S&C renewal activities in accordance with a number of impacting factors, such as for instance the traffic type/density, location, manpower, etc.

This task has been completed with no deviations from the description of work.

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Abbreviation / Acronym	Description
BV	Banverket
CBA	Cost-Benefit Analyses
DLD	Driving and locking device
IHA	Interface hazard analysis
IM	Infrastructure Maintainer
LCC	Life cycle costs
MDBF	Mean Distance Between Failure
MDT	Mean Down Time
MDTF	Mean Distance To Failure
MTBF	Mean Time between Failures
MTTM	Mean Time To Maintain
MUT	Mean Up Time
PHA	Preliminary hazard analysis
RAMS	Reliability, Availability, Maintainability and Safety
S&C	Switch(es) and Crossing(s)
SHA	System hazard analysis
SIL	Safety Integrity Level
THR	Tolerable Hazard Rate

1. Safety analysis of S&Cs

Switch(es) and Crossing(s) (S&C) are safety critical components in railway infrastructure, given that they enable the creation of a "real" network. S&Cs are not only placed in the infrastructure to connect different lines, but also to connect parallel tracks of the same line (crossovers) in order to give flexibility to track operation. Therefore, S&Cs must be kept in good condition to guarantee an adequate running of the train through switch, and thus, to minimize its degradation by dynamic loads.

The operational impact caused by an incident/accident on S&Cs is significant for railways. For instance, on 12 July 2013, a train crash occurred in the commune of Brétigny-sur-Orge in the southern suburbs of Paris, France, when a passenger train carrying 385 people derailed and hit the station platform. Seven people were killed and nearly 200 were injured. The accident was cited as the most serious rail crash in France since the 1988 Gare de Lyon accident in which 56 people were killed. Three investigations were initiated, by the Évry public prosecutor, the Land Transport Accident Investigation Bureau (BEA-TT) of the Ministry of Transport, and the SNCF. The train is believed to have derailed on the approach to Brétigny when passing over a switch 200 metres (660 ft) before the station. The investigation that has been launched to understand the causes of the accident has showed that a piece of metal has been unscrewed and moved to block the nominal switch movement, which caused the train derailments.

RAMS analysis is necessary to be performed for the aims of assessing the reliability, availability, maintenance and safety of S&Cs as critical points in the network, to ensure the smooth operation of railways. In fact, RAMS assurance helps the stakeholders in balancing performance requirements with Life Cycle Costs (LCC) and improves customer satisfaction along with the compliance of National/International regulatory requirements.

This chapter is dedicated to risk analysis of S&Cs. We firstly give a general introduction about RAMS analysis in railways (cf. section 1.1). Then, description of railway S&C is given in section 1.2. Section 1.3 is a literature review of S&C failures. Failure analysis of S&C is provided in section 1.4. Section 1.5 discusses the main features in RAMS analysis on S&C. Finally, some aspects related to maintenance is given in section 1.6.

1.1 RAMS analysis in railways

RAMS stands for Reliability, Availability, Maintainability and Safety. RAMS analysis of a system provides qualitative and quantitative indicators of the degree that the system, or the sub-systems and components comprising the system, can be relied upon to function as specified and to be available and safe over time.

RAMS characterises system's long-term operation and is achieved by the application of established engineering concepts, methods, tools and techniques throughout the system lifecycle. European Std. EN 50126 defines a process for managing RAMS in railways.

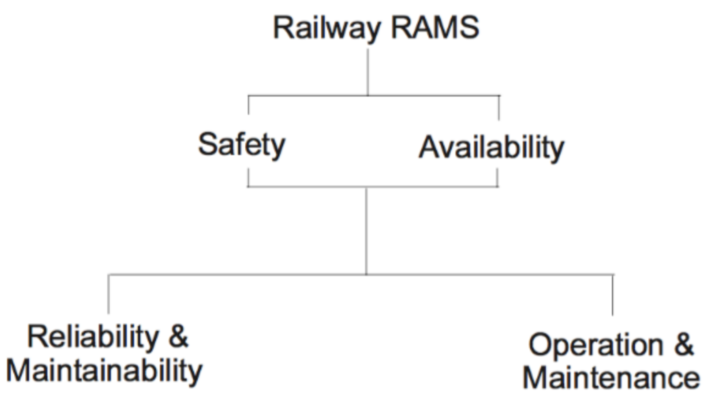


Figure 1.1 - RAMS

Safety is a major requirement for railway operations. This objective can be fulfilled by implementing RAMS principles and process as suggested by EN 50126/ EN 50128/EN 50129. In order to perform RAMS analysis, we need data on failure rates of the system, possible failure modes, Mean Down Time (MDT), maintenance operations, hazards and their consequences, etc. The output of RAMS analysis enables the life cycle specialists to calculate costs and to perform Cost-Benefit Analyses (CBA). But before the RAMS analysis at system level, input on known component failure data (rates, etc.) must be provided. There are then 3 different steps in the application of RAMS, all of which are interlinked. This is illustrated in Figure 2.1.

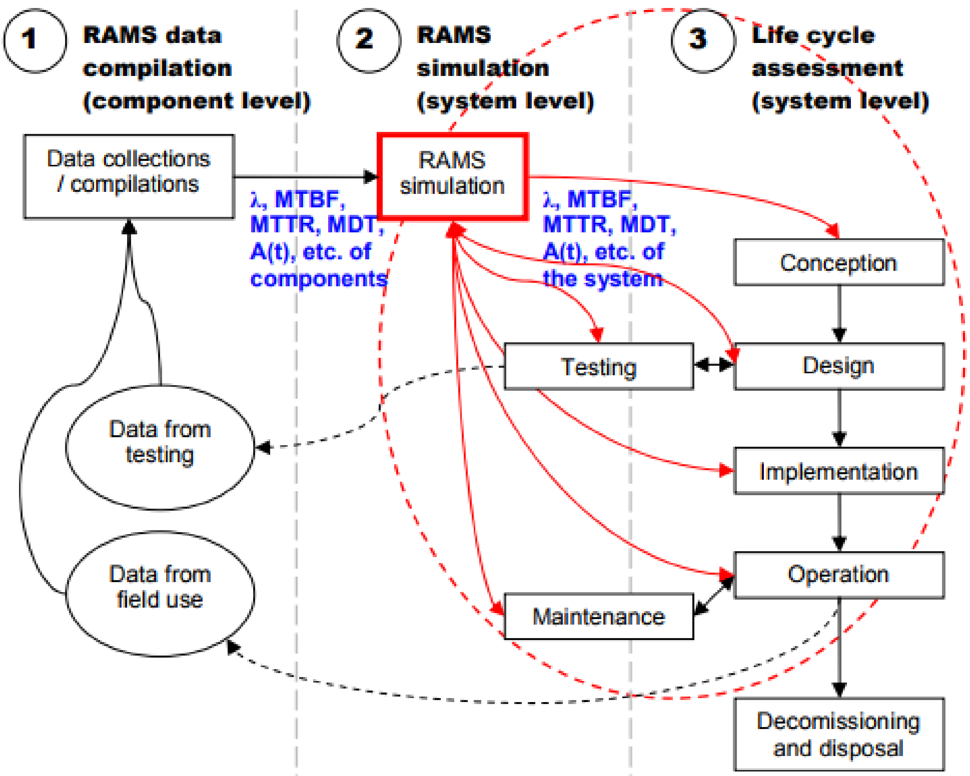


Figure 1.2 - Steps of RAMS

Undertaking RAMS analysis of a rail system allows us to describe and demonstrate the confidence with which we can claim that the system is going to achieve this goal. In fact, RAMS analysis has a clear influence on the quality of service delivered to the customer and is a high priority for any operator concerned with satisfied customers, be they passengers or freight clients.

Starting with clear and specific RAMS requirements is fundamentally important to any new or significantly changed rail system. Designing these requirements for the rail system through lifecycle verification and validation activities is crucial to reach the necessary confidence level in terms of dependability.

In the following sections, we present the main items pertaining to RAMS analysis (in general):

1.1.1 Reliability

Reliability: probability that an item can perform a required function under given conditions for a given time interval.

Reliability is quantified as Mean Time between Failures (MTBF).

$$R = 1 - \left(\frac{\text{Number of failures}}{\text{Total operating time}} \right)$$

The MTBF can be calculated as the arithmetic mean (average) time between failures of a system.

As for a series system including *n* components, reliability can be analysed as follows:

$R = R_1 \times R_2 \times \ldots \times R_n$;

$\lambda = \lambda_1 + \lambda_2 + \ldots + \lambda_n$;

$\text{MTBF} = 1/\lambda$;

Where R is the system reliability, λ is the system failure rate.

As for a parallel system including *n* components, reliability can be analysed as follows:

$R = 1-(1- R_1)\times(1-R_2)\times\ldots\times(1-R_n)$;

$\lambda = 1/((1/1*\lambda_1)+ (1/2*\lambda_2)+\ldots+(1/n*\lambda_n))$;

$\text{MTBF} = 1/\lambda$;

1.1.2 Availability

Availability: the ability of a product to be in such a state to perform a required function under given conditions at a given time interval.

Availability is the ratio of the total time a system is capable of being used (MTBF) during a given interval which includes both the operational periods (MTBF) and all downtimes (MDT).

$$\textbf{Availability} = \frac{\textbf{Uptime}}{\textbf{Uptime+Downtime}}$$

Mean down time (MDT) is the average time that a system is non-operational. It includes repair, corrective and preventive maintenance, self-imposed downtime, and any logistics or administrative delays.

1.1.3 Maintainability

Maintainability: the probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval.

Maintainability is quantified as the Mean Time to Repair (MTTR).

MTTR is the basic measure of the maintainability of repairable items and represents the average time required to repair a failed component or device

1.1.4 Safety

Safety: is the freedom from unacceptable risk of harm.

It is common in railways to describe this feature by means of the Safety Integrity Level (SIL).
The assignment of SIL is an exercise in risk analysis where the risk associated with a specific hazard to be protected against is calculated.
As shown in the following table (EN50129, 2003), the Tolerable Hazard Rate (THR) is a figure which guarantees that the resulting risk does not exceed the target risks.

Table 1.1 – SIL table

Tolerable Hazard Rate THR per hour and per function	Safety Integrity Level
$10^{-9} \leq THR < 10^{-8}$	4
$10^{-8} \leq THR < 10^{-7}$	3
$10^{-7} \leq THR < 10^{-6}$	2
$10^{-6} \leq THR < 10^{-5}$	1

1.1.5 Life Cycle Costs (LCC)

Although LCC is not a "component" of RAMS analysis, it is often considered to assess the economic aspects pertaining to the system. In fact, LCC highlights the cost of investment, operation, maintenance and unplanned interruption throughout the life cycle of a project. In railways, LCC is performed to obtain the sum of all recurring and one-time costs over the full life span of a railway system, which does not include the investment costs only but also operating and maintenance costs. RAMS and LCC analysis can be used to optimize the performance (Key performance indicator or KPI) of the project and make it economically viable (Wollny, 2017).

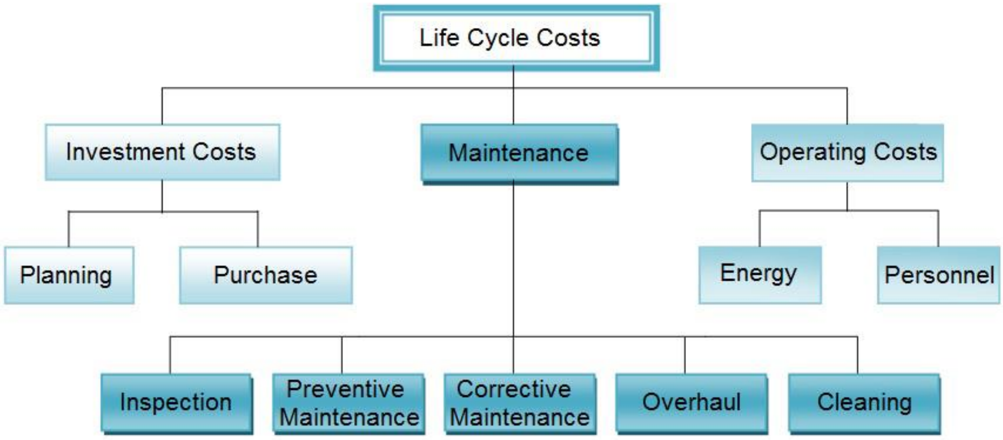


Figure 1.3 – Life cycle costs

In railways, incomes are relatively well known. The biggest share belongs to faring on passenger tickets or freight services. The main other part to quantify is the incurred costs. RAMS parameters play a very important role in determining the costs since, as stated above, failures obviously bring costs to the system, i.e. the cost of a train to be stopped/delayed due to a signalling system failure, the cost of a corrective maintenance operations on a rail track which forces the impediment of traffic, the cost of accidents which might involve serious injuries or deaths, among others.

1.2 Railway S&C

In this section, the introduction of S&C and its components is provided as follows. In fact, in the railway infrastructure, S&Cs are the devices that allow trains to change from one track to another.

Switches are not only placed in the infrastructure to connect different lines, but also to connect parallel tracks of the same line (crossovers) in order to give flexibility to track operation (NeTIRail-INFRA, 2016).

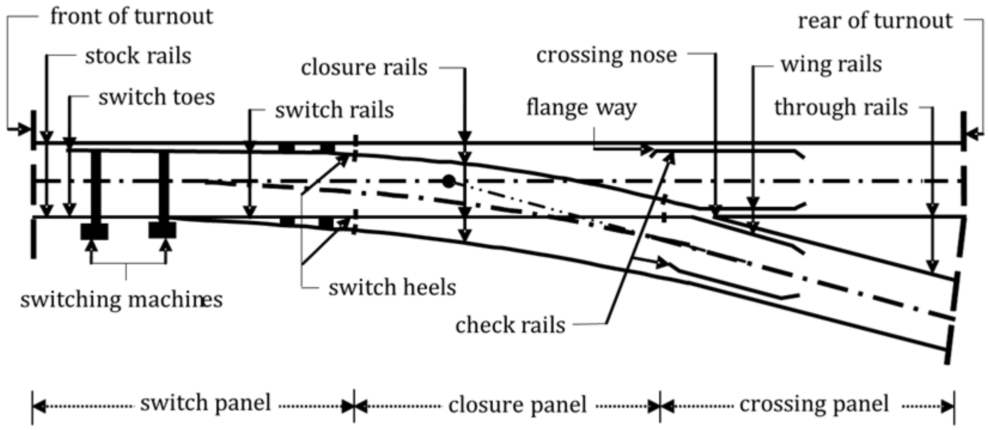


Figure 1.4 - A switch and its components

1.2.1 Switch (Turnout)

A switch (turnout) is the layout permitting the passage of rolling stock between two tracks and one common track.

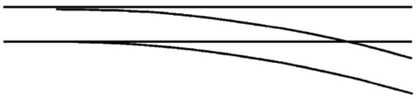


Figure 1.5 – A switch

1.2.2 Crossing

A diamond crossing is the layout permitting the passage of rolling stock on intersecting tracks.

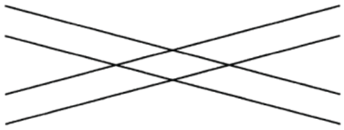


Figure 1.6 - A diamond crossing

1.2.3 Track designation

In the basic design, the straight track is called the main line, and the curved track is called the branch or turnout line.

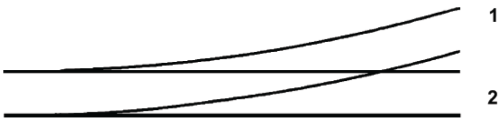


Figure 1.7 - A branch line (1) and a main line (2) in a turnout

1.2.4 Turnout designation

Turnouts are designated by the following symbols:

- RH: diverging to the right
- LH: diverging to the left
- S: symmetrical (or equal split)

When the branch line diverged to the right of the main line, it is a right-hand turnout.

Figure 1.8 - A right-hand turnout

When the branch line diverged to the left of the main line, it is a left-hand turnout.

Figure 1.9 - A left-hand turnout

When the two tracks diverge symmetrically from the common track, it is a symmetrical turnout. The machining of each switch rail will be equal, as will the horizontal set (if any) of each stock rail.

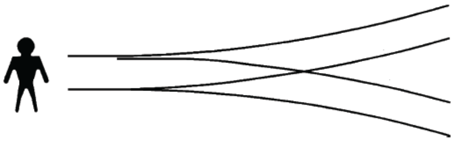


Figure 1.10 - An equal split turnout

1.2.5 Diamond crossing designation

A diamond crossing is either standard or non-standard.

A diamond crossing is standard when both tracks are straight or on curves of the same hand and radius.

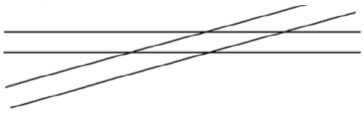


Figure 1.11 - A standard diamond crossing

A diamond crossing is non-standard when one track is curved and the other straight, or when both tracks are curved to different radii or when both tracks are to the same radius but of opposite hand.

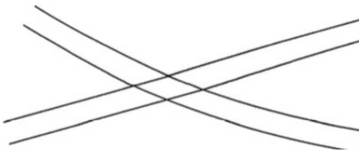


Figure 1.12 - A non-standard diamond crossing

1.2.6 Diamond crossing with slips

A diamond crossing with slips is the layout permitting the passage of rolling stock between two intersecting tracks as well as over such tracks. It may be single or double with variants as follows.

A diamond crossing is with single slip when only one connection is made between the intersecting tracks. These are designated SS (single slip; or diamond crossing with single slip).

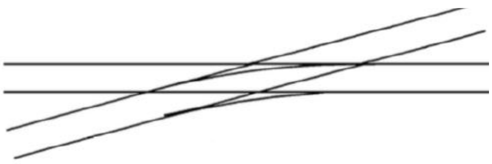


Figure 1.13 - A diamond crossing with inside single slip

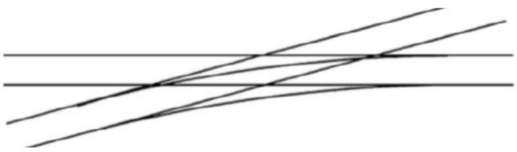


Figure 1.14 - A diamond crossing with outside single slip

A diamond crossing is with double slip when both intersecting tracks are connected. These are designated DS (double slip; or diamond crossing with double slip).

Figure 1.15 - A diamond crossing with inside double slip

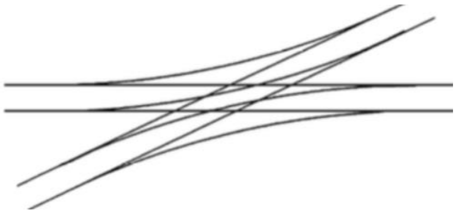


Figure 1.16 - A diamond crossing with outside double slip

1.3 Literature review of S&C failures

1.3.1 Failure occurrence in railway switches and crossings components

In general, failure means the termination of the ability of an item to perform a required function: for example, a train is unable to run over a switch rail with the intended speed (Kassa, 2017). A rail is defined as failed when it's broken, cracked or otherwise damaged and can no longer fulfil its design function. In recent years a number of railways, principally but not always passenger railways, have adopted the goal of zero rail breaks. This may not be practically possible, but it represents a goal that drives reduction of rail breaks through the development of inspection and monitoring systems and the wheel-rail technology (Cannon et al., 2003).

Having the objective for this project to apply wear and rolling contact fatigue (RCF) resistant coating material on vulnerable and on high risk of damage S&C rail parts, a distinction between the failures occurring on these rail parts and the failures concerning the surrounding infrastructure (bearers, joints, etc.) needs to be made. Furthermore, another distinction applies between failures that are caused by wear and rolling contact fatigue and those that are caused by other factors. A third substantial distinction is about the possible positions of the relative failure modes (wear, fatigue, cracks) on S&C rail components: for example, either on the head, web or foot regions of the rail.

Compared to plain track, i.e. straight or curved track, only made up of ballast, sleepers and rails, rigidly connected to each other, an S&C structure contains several special features:

- It has distinguishing components, e.g. switch tongues, frogs and slide plates, which are, due to their specific geometry (and irregularities), exposed to higher static and dynamic forces, thus showing specific deterioration, higher wear and failure rates (Zwanenburg, 2007; Cornish, 2014);

- The moving parts of S&C, can lead, in case of malfunctioning (or worse: breaking), to direct derailment, thus requiring immediate action in case problems are detected – whereas plain track sometimes sustains its function due to built-in redundancy (Zwanenburg, 2007).

These characteristics lead to special inspection and maintenance requirements for S&Cs.

1.3.2 Failure modes classification

An understanding of the degradation mechanisms associated with S&C units is essential for the optimization of design and maintenance procedures to eliminate or minimize the impact of the causes of the life limiting degradation (Capacity for Rail, 2015).

Wear, plastic deformation, cracking, corrosion and rolling contact fatigue have been identified as common failure mechanisms for rails (Cannon et al., 2003; Capacity for Rail, 2015). Rolling contact fatigue of rails has increased in severity and extent over the last 30 years for several reasons, including the following (Cannon et al., 2003):

- Demands for higher speed, increasing traffic density and axle loads – and, in particular, the combination of all these three factors in heavy-haul railways.

- Improved lubrication and harder rails result to lower wear rates. However, this has a twofold effect. First, if the installed rail profile does not match well with the wheels passing over, high stresses are produced until the rail wears to a more suitable shape. Hence, low wear rates imply longer periods of high stress. Second, high wear rates can remove embryonic cracks before they can propagate to significant depths whereas low wear rates prevent this.

- The introduction of more powerful locomotives, particularly those with traction control systems that are able to use the available friction between wheel and rail without wheel slip. The higher shear forces that these locomotives apply to the rail surface may lead to increased rolling contact fatigue.

- In some rail systems there has been increasing deployment of passenger vehicles, designed more for high-speed stability than good curving performance. Accordingly, there has been a tendency of increased tangential forces (generated in curves).

- When railway companies are no longer vertically integrated, i.e. when there is no longer exclusive control of both the track and the vehicles running over the track, not well maintained wheel profiles are a potential risk factor: poorly maintained transverse profiles cause high contact stresses and deterioration in curving performance; poor circumferential profiles (wheelflats and out-of-roundness) generate high dynamic loads on the rail.

Today's rail failures can be divided, in general, in the following three categories (Cannon et al., 2003):

- Defects originating from manufacturing process – a classic example is the 'kidney' defect that usually originates from a hydrogen shatter crack in the rail head. Therefore, great care has to be taken to minimise the occurrence of atomic hydrogen in the hot bloom of the oxygen steelmaking process.

- Damage caused by inappropriate handling, installation and use; for example, the wheelburn defect is caused by spinning wheels.

- Failures caused by the exhaustion of the rail: many failure modes caused by rolling contact fatigue are within this group, for example, head checking (s. figure 1) and squats.

Over the last 30 years, rail failures of the third category have been increasing, especially failures relevant to rolling contact fatigue.

From table 1.2 – Network Rail statistical data observed nationwide in UK – it can be seen that the number of S&C components classified as heavy or severe fatigued increases within the period of 2009 to 2015.

	Classification	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15
England & Wales	heavy	1,560	1,566	1,884	2,296	2,418	2,519
	severe	1,112	1,481	2,231	3,159	3,810	4,424
Scotland	heavy	247	271	280	323	350	372
	severe	151	187	220	252	262	316
Network Total	**heavy**	1,807	1,837	2,164	2,619	2,768	**2,891**
	severe	1,263	1,668	2,451	3,411	4,072	**4,740**

Table 1.2 - Number of S&C components classified as heavy or severe fatigued from 2009/10 to 2014/15 in the UK railway network (Network Rail).

Failure may be classified by the failing components (see table 1.3). If, for example the failure cause is in the switching system, one or more of the different switching system components may have caused the failure. A broken stretcher bar, broken bolts, dry slide chair or baseplate and a switch anchor loosing are possible sources for failure (Kassa, 2017).

Components	Failure causes/mechanisms
Rail	Wear, rolling contact fatigue, plastic deformation, rail head cracks, rail foot fractures, rail web cracks
Stretcher bar	Stretcher bar bracket breakage
Switching machine	Too much or too little power, unable to close the switch rail against the stock rail
Sliding chair and rollers	Dry slide chair, rusty slide table or fully contaminated lubrication which blocks the movement of switch rail from sliding
Fastening system	Missing bolts, damaged rail pad, broken base plate
Sleeper	Rail seat deterioration, flexural cracking at the sleeper centre, and transverse cracking at the fastening bolt

Table 1.3 - Failure mechanisms classification by components (Kassa, 2017).

A failure data analysis done by (Hassankiadeh, 2011) based on failed turnout components data (the actual P-Way failure modes data which were recorded in 2009) of the UK railway network is shown in the following figures. Permanent way failures are attributed to the rails, sleepers, ballast and subgrade. The total number of failure modes was 2458. The project aim of (Hassankiadeh, 2011) was the identification of the different modes of failure in S&C components and the determination of their occurrence rate within a year.

Turnouts are probably the most important infrastructure elements of the railway system. They are subjected to high risk owing to many potential failure modes. The assessment of failure risk in turnouts in order to ensure high availability and safe operation can be based on historical data and occurrence of failures (Hassankiadeh, 2011).

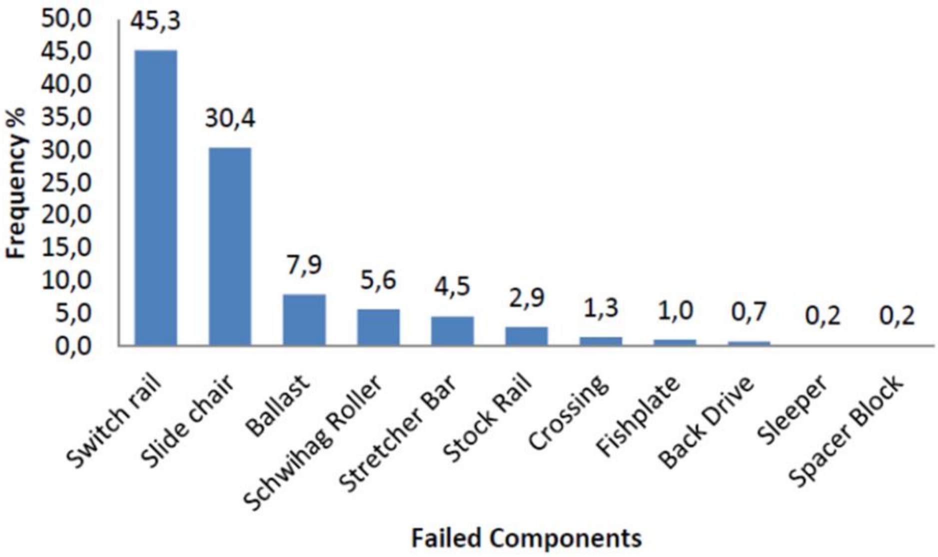


Figure 1.17 - Failure frequencies of turnout components (Hassankiadeh, 2011).

Figure 1 shows that switch rail and slide chair were the most common failed components, which made up more than 75% of failed components in 2009 for UK railway network. In contrast, ballast, Schwihag roller, stretcher bar and stock rail made up about 20.9% of failed components. Finally, some components like crossing, fishplate, back drive, sleeper and spacer block comprised less than 4% of failed components (Hassankiadeh, 2011).

Figure 2 shows the importance of obstructed and dry chairs failures among the failure modes with an occurrence of 58%. An obstruction appears if ballast particles are thrown on the switch component due to high train speeds or a switch becomes iced. Cracking or breaking, ballast voiding, getting out of adjustment, contamination and plastic deformation make up to 40.9 % of failures, whereas squat, rolling contact fatigue, creep, widening track and wet bet failures constitute the lowest portion of occurrence with only 1 % (Hassankiadeh, 2011).

In order to find out how failure frequency varies with weather conditions, an additional attention has been given by (Hassankiadeh, 2011) to the determination of weather effects on the occurrence of failure. The failure occurrence on UK turnouts for the different seasons of the year 2009 is shown in figure 3.

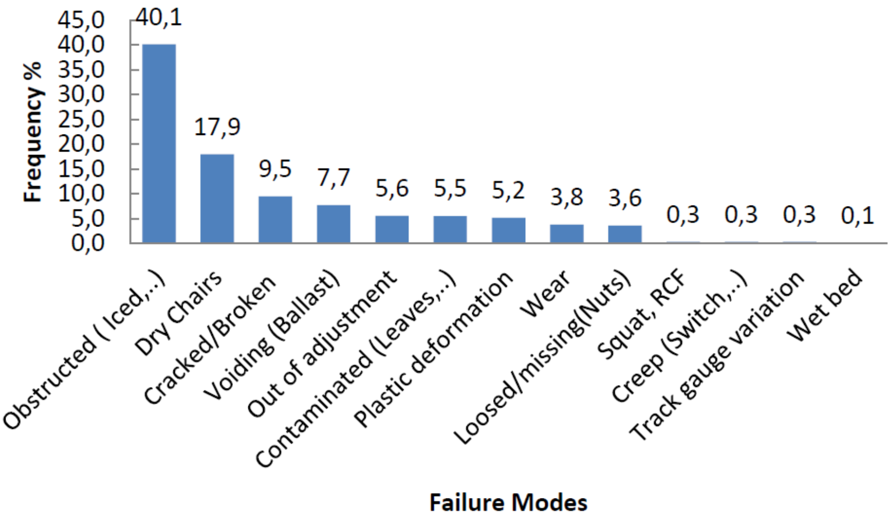


Figure 1.18 - Frequencies of failure causes/modes for turnouts in UK (Hassankiadeh, 2011).

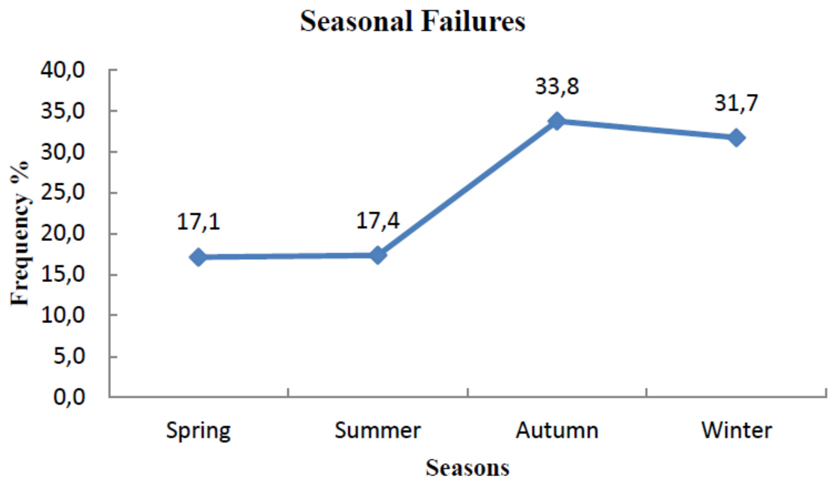


Figure 1.19 - Failure occurrence for the different seasons (of the year 2009) (Hassankiadeh, 2011).

Figure 3 reveals a relationship between the seasons of a year and failed components. It is clearly shown that weather plays a significant role. A larger number of failures occurred in the seasons of autumn and winter. This means that cold weather represents a significant factor. Indeed, much attention should be given to inspection during cold weather periods. The small difference between autumn and winter failures frequencies might be the result of leaves falling during autumn (Hassankiadeh, 2011).

The designation of possible rectification gains a great importance. Actions that are available or can be taken by an operator to negate or mitigate the effect of a failure on a system are called rectification. The different types of rectification for turnout components are listed in table 1.4 (Hassankiadeh, 2011). The frequencies of the rectifications (repairs or enhancements) for the failed components provide another insight for how often the failure modes of wear and rolling contact fatigue occur on switch and crossing rail components. It is noticeable that the switch rail is one of the most sensitive turnout components and that it needs specific attention and maintenance.

Rectification	Total Number	Failed Components
De-Iced	559	Switch rail, slide chairs, Schiwag Roller, Back drive, Stretcher bar
Lubricated	445	Slide chairs, Schiwag Roller
Remove Obstacle	427	Switch rail, slide chairs, Stretcher bar, Back drive
Renewed	243	Stretcher bar, Slide chair, Crossing (nose crack), Fishplate, Switch rail, Stock rail, Sleeper, Space block, Ballast
Lift &Pack	190	Ballast
Grind	167	Switch rail, Stock rail, Fish plate
Adjusted	143	Schiwag Roller, Switch rail, Stretcher bar, Back drive, slide chairs, Ballast
Cleaned	136	Slide chairs, Switch rail, Schiwag Roller
Weld repair	71	Switch rail, Crossing, Fishplate
Tightened	70	Slide chairs, Stretcher bar(nuts), Back drive, Fish plate
Gauged	7	Switch rail, Stock rail
Total	2458	-

Table 1.4 - Rectification actions taken for failed turnout components (Hassankiadeh, 2011).

The consequences of individual failure modes on the performance of a railway network are important to be determined. Upon this a failure classification by severity provides a method to categorise the criticality of the effects on the function of an item or component (Kassa, 2017), s. Table 1.5.

Severity level	Criticality nature
Category I - Catastrophic	A failure which may cause death or total system loss
Category II - Critical	A failure which may cause severe injury, major property damage, or major system damage
Category III - Marginal	A failure which may cause minor injury, minor property damage, or minor system damage which will result in delay or loss of availability or speed restriction
Category IV - Minor	A failure not serious enough to cause injury, property damage, or system damage, but which will result in unscheduled maintenance or repair

Table 1.5 - Failure classification by severity (Kassa, 2017).

The derailment at Hatfield (UK) in 2000, resulted by head checking (s. Figure 5), provides an example of the fatal consequences of rail fatigue.

Figure 1.20 - Head checks at the surface of a rail gauge corner (Cannon et al., 2003).

(Kassa, 2017) states that over 30% of the failure modes are related to rail mechanical and track geometry failures. Furthermore, for rail components associated with the failure mechanisms of cracking, wear and plastic deformation it is necessary to take preventive actions, design new or improved components (Kassa, 2017). The S&C key components and damages have been put together by (Bezin, 2016), s. Figure 6:

Component	Failures
Cast manganese Casting	transverse fatigue crack (foot or nose)
Crossing nose	wear, plastic deformation, shelling and spalling
Wing rail	wear, plastic deformation, shelling and spalling
bearers	fatigue cracking, voids
switch rails	lipping, head checks, squats, wear
points	all the above + fracture by fatigue
stock rails	lipping, head checks, squats, wear, spalling
slide plates	poor movement (high friction) and ceisure
bearers	fatigue cracking, voids

Figure 1.21 - S&C key components and damages (Bezin, 2016).

Root causes for failure, categorised in broader source areas (s. table 1.6), are reported in (Capacity for Rail, 2015):

Source areas	Root causes for failure
Design	*Track design, rail and vehicle geometries (and their compliance)*
Enviromental	*Extreme weather conditions*
Installation/set-up	*Human factor, tolerances*
Maintenance	*Mechanised/manual*
Manufacturing	*Processes, tolerances*
Operational	*Speed, loading regime, traffic mix, bearing capacities*

Table 1.6 - Failure root causes categorised in broad source areas (Capacity for Rail, 2015).

(Capacity for Rail, 2015) assembled a failure matrix (s. table 1.7) associating the S&C components with the occurring failure modes (defect types) and their root causes.

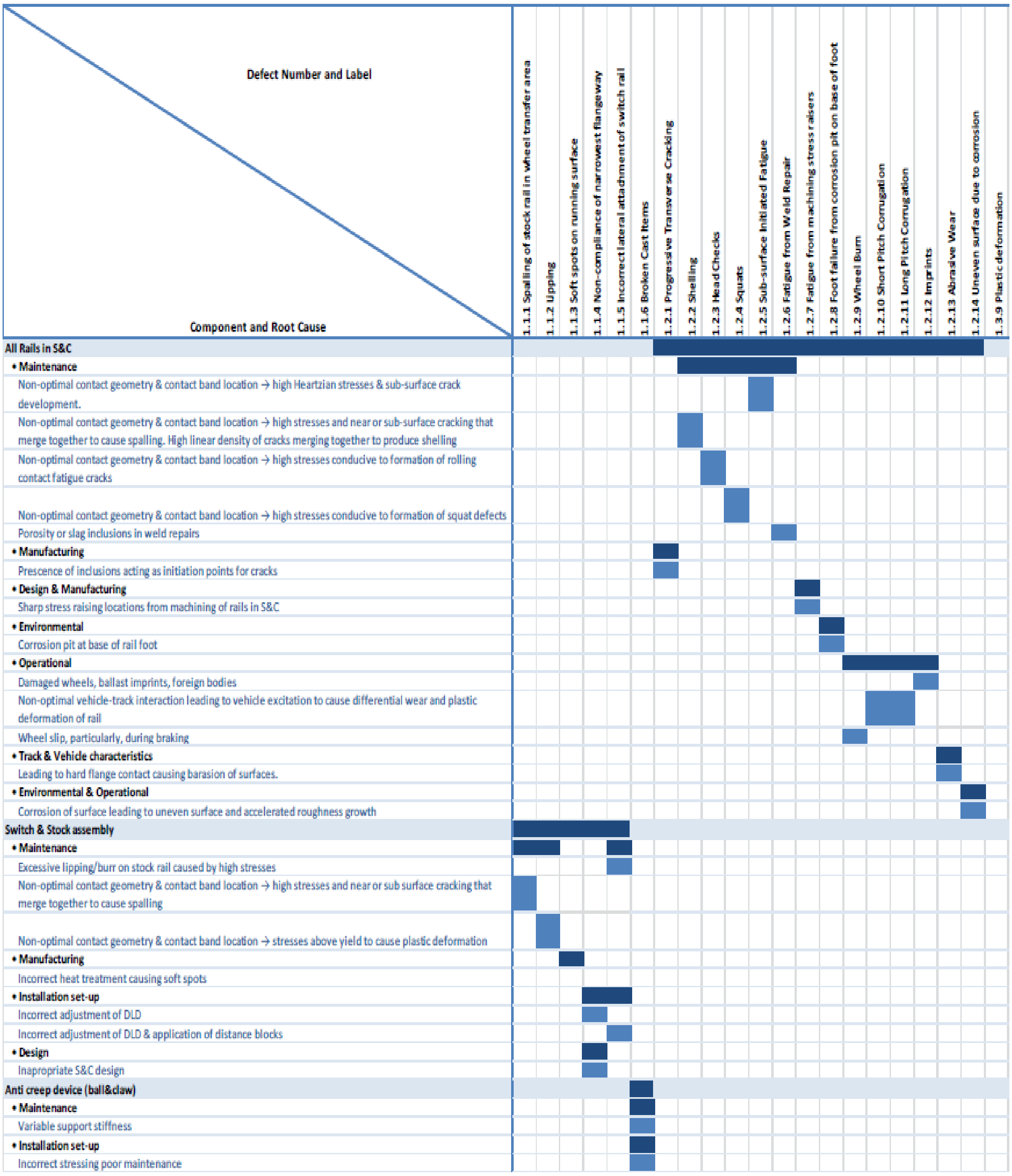
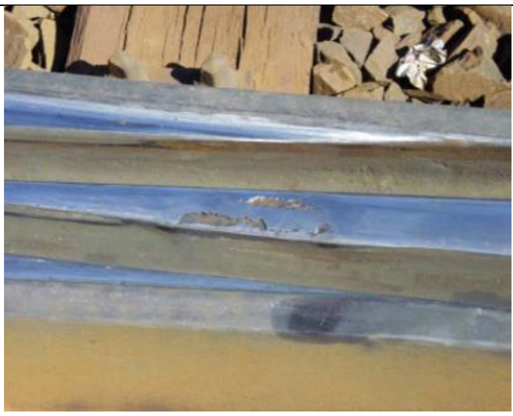


Table 1.7 - Failure modes classification for S&C components (Capacity for Rail, 2015).

Furthermore, a very comprehensive and illustrated catalogue providing valuable information on S&C component failures has been brought off by (Capacity for Rail, 2015). In particular, information about the location of the failure on the components geometry, detailed description of the characteristics and appearance of the failure modes as well as on potential failure causes can be retrieved from this study. Moreover, the study lists which corrective/preventative measures can be taken in order to correct (or prevent) the failure modes as well as how to detect these. The following table presents pictures of (Capacity for Rail, 2015) which show characteristic failure modes of S&C rail components:

	Spalling of stock rail
	Lipping of switch/stock rails
	Fatigue initiated in rail subsurface

	Plastic deformation of wing rails
	Spalling of crossings
	Spalling & plastic deformation of crossing nose

	Progressive transverse cracking of rail

Table 1.8 - Characteristic failure modes of S&C rail components (Capacity for Rail, 2015).

According to (Cornish, 2014) there are three main failure modes within an S&C unit: wear, plastic deformation and fatigue; these are the failure modes also found on railway plain line infrastructure. Within S&C components, 53% of failure concern the switch blade. The switch rail has a significant influence on the S&C unit, as it is a moveable railway section and varied rail profiles allowing for a transition from the through route to the turnout. Statistical analysis (of Network Rail failure statistics from 2011 – 2013) has shown that the common failure mode of degradation depends on the length of the switch. The shorter switches (slower speed) are generating higher percentage of plastic deformation failures, whereas the longer switches (higher speed) are developing more wear failures. This is due to the variation, with freight vehicles tending to generate plastic deformation from high loading less likely to traverse higher speed switches (Cornish, 2014).

The transfer from the switch rail to the stock rail generates a larger vertical loading, which generates a much larger cumulative strain over time / under tonnage. This is shown by an increase of 85% in the strain under the same tonnage between the stock and transferred section. The turnout route often experiences larger vertical strains through laden freight, but is traversed less often. This leads to larger amounts of plastic deformation rather than abrasive wear and removal of material or fatigue as the plastic flow of the material occurs before the abrasive wear removes the material (Cornish, 2014).

Moreover, the stock rail with the switch blade closed had higher strain than the open switch stock rail. The increased strain is due to the transition of the wheel from the switch rail onto the stock rail and the generation of increased dynamic loading, including multi point contact. The maximum increase in mean strain of 150με shows that the stock rail with the closed switch blade deteriorates quicker, including the below rail conditions, and then continues to degrade at an accelerated rate (Cornish, 2014).

Trains running over railway tracks cause degradation of these tracks and its components (rail, rail fastenings, railpads, sleepers, ballast etc.). (Zwanenburg, 2007) reports some main parameters that effect the speed of this degradation:

- The track geometry: train tracks in bad geometrical condition will cause "rollercoaster"-behaviour of the train, which results in higher dynamic loads applied by the train to the track;
-

- The state of the track material: bad condition of sleepers or worn rails provide an unsmooth running path, which due to the resulting vibrations, results to faster degradation of other track components.

In addition, the relation of train loads vs. track geometry and the state of the track material, there is also a relation between track geometry and the state of the material: bad material causes more track geometry degradation. This relation is also valid in the opposite way: bad track geometry will in the same negative way affect the state of the track material (Zwanenburg, 2007).

Track parameters influencing the degradation rate (besides geometrical state of the track and the state of the materials) are e.g. the sub-base condition or the quality of initial installation (Zwanenburg, 2007).

Table 1.9 records the total number of S&C units that have been renewed and table 1.10 the rails abandoned. The numbers of full renewals of table 1.10 include the numbers of full renewals, the number of units removed or recovered and the number where asset life has been extended through partial renewal or re-ballasting (Network Rail).

Table 4.10: S&C full renewals

	Actual 2005/06 (units)	*Actual 2006/07 (units)*	*Actual 2007/08 (units)*	*Actual 2008/09 (units)*	*Delivery Plan 2009/10 (units)*	*Actual 2009/10 (units)*
Non-WCRM:						
London North Eastern	75	47	73	93	67	71
London North Western	95	129	109	90	76	61
Anglia	21	17	43	*	*	*
Kent	9	3	2	*	*	*
Sussex	7	9	3	77	36	39
Wessex	69	75	34	*	*	*
Western	80	82	70	50	31	35
England & Wales	356	362	334	310	210	206
Scotland	13	58	39	35	30	25
WCRM:	151	22	63	74	n/a	n/a
Network Total	**520**	**442**	**436**	**419**	**240**	**231**

Note: *Data for all four South East Routes are combined into Sussex

Table 1.9 - Switches and crossings renewed (Network Rail, UK).

Table 4.11: S&C abandonment

	Actual 2005/06 (units)	Actual 2006/07 (units)	Actual 2007/08 (units)	Actual 2008/09 (units)	Delivery Plan 2009/10 (units)	Actual 2009/10 (units)
Non-WCRM:						
London North Eastern	11	48	11	34	16	12
London North Western	0	20	10	33	16	18
Anglia	0	*	8	*	*	*
Kent	0	*	0	*	*	*
Sussex	0	2	2	1	13	11
Wessex	2	*	8	*	*	*
Western	24	29	18	8	5	20
England & Wales	26	62	94	76	50	61
Scotland	0	0	14	6	6	5
WCRM:	0	0	0	0	n/a	n/a
Network Total	**26**	**62**	**108**	**82**	**56**	**66**

Note: *Data for all four South East Routes are combined into Sussex

Table 1.10 - Switches and crossings abandoned (Network Rail, UK).

A typical S&C unit will be replaced after 25 to 60 years, with the period of renewal dependent on the speed and tonnage of the route. For routes with high speeds, above 128mph, 13 or 25EMGTPA (Equivalent Million Gross Tonnes Per Annum), which represents 2.1% of the total S&C population in the UK, the expected lifetime is 25 years. The typical lifetime increases incrementally up to 60 years for routes with speeds below 25mph and 6EMGTPA, which make up 23% of the UK S&C population (Cornish, 2014).

(Zwanenburg, 2006) completed a statistical study of S&C units on the Swiss rail network. It shows that geometrical degradation increases renewal rates due to the increased deflection. The S&C unit experiences increased deflections through larger stresses and the rail material is degraded to a state that the unit needs replacement in a short duration. From the statistical analysis completed by Zwanenburg, the ages of replaced S&C fluctuated between 10 years in service in 1993 to 21 years in 2005. The explanation for the increase in duration in service is due to higher quality components, such as hard wood and concrete sleepers instead of using timber sleepers.

1.3.3 Comparison with railway networks in Europe

On the UK railway infrastructure, there are 20,327 sets of switches and crossings, with over 200 variations in design due to design parameters, such as switch lengths and angle of the diversion route (turnout route).

S&C have historically taken 24% of maintenance and 23% renewal budgets against 5% of representative track miles. This is due to complex wheel to rail interaction, design and operation of switches and crossings. The required percentage of budget shows the significance of the asset within the rail infrastructure (Cornish, 2014).

The total track length in the European Union is about 0.5 million kilometres (Cannon, 2003). The density of switches and crossings in most railway networks is estimated to be one every kilometre which equates to over 300,000 units within the networks of EU27 countries and the cost of maintenance of an S&C unit is believed to be equivalent to that for about 0.3 km of plain line track.

Further costs are incurred at renewals which, even at very modest rates of renewal, mount up to a very large figure. Thus, the economic impact of S&C units on the maintenance and renewal budgets of railway authorities is very apparent and hence any increase in the life span of this important infrastructure asset through better design or maintenance practices is considered highly desirable (Capacity for Rail, 2014).

In (ERRI, 2000) figures that were derived from rail systems throughout the world provide some indication of the scale of the rail failure problem (Cannon et al., 2003): for the ratio of defective to broken rails per track kilometre/year a value of about 0.1 is reported. Furthermore, according to (ERRI, 2000) rolling contact fatigue cracking is a major cause of premature rail removal in some of Europe's most modern railway systems. The ICON (Integrated Study of Rolling Contact Fatigue) project was designed to increase knowledge of rolling contact fatigue damage and wear mechanisms. It was estimated that RCF defects alone cost European railway networks within the European Union around €300 million annually and as these defects account for about 15%, the emerging cost of all defects is about €2 billion per year (ERRI, 2000).

Approximately 25.000 S&C allow the trains to operate on the Swiss railway network and 20 to 40 percent of the track maintenance budget is spent on inspection, maintenance and renewal of S&C (Zwanenburg, 2007).

Countries	Track (km)	S&C population	S&C units per track kilometre
Belgium	6,500	12,200	1.88
Italy	27,100	42,700	1.58
Netherlands	6,500	7,800	1.20
UK	31,100	25,800	0.83
Sweden	**14,900**	**12,000**	**0.81**
France	65,100	25,600	0.40

Table 1.11 - Turnout population of European railway networks (Kassa, 2017).

In the Swedish railway network there are about 12000 units of track switches and crossings, which at 13000 km, make up about 5.5 % of the total track length. However, more than 13 % of the total maintenance costs and 25% of track renewals are spent on S&C. In comparison, Network Rail (UK) is using about 17% of the track maintenance budget and ca. 25 % of the track renewal budget in S&C. Furthermore, costs for train operation disruption and delays have to be added. This shows that switches and crossings are a major rail infrastructure aspect and require a disproportionate amount of the budget (25% of the track maintenance budget for 5% of track). In addition, it has to be considered that implementation of S&C into the track system is increasing (Hassankiadeh, 2011; Kassa, 2017).

Proactive monitoring and safety management for the prevention of incidents (which could lead to an accident) has led to the determination of accident precursors (see figure 7). Broken rails are the most common type of common accident precursors and account for almost half of all reported precursors. A relatively high number of broken rails were reported by Greece, Poland and Romania in 2014, confirming the same findings from previous years (European Union Agency for Railways, 2016). Track buckles were reported as the second most prevalent type of precursors.

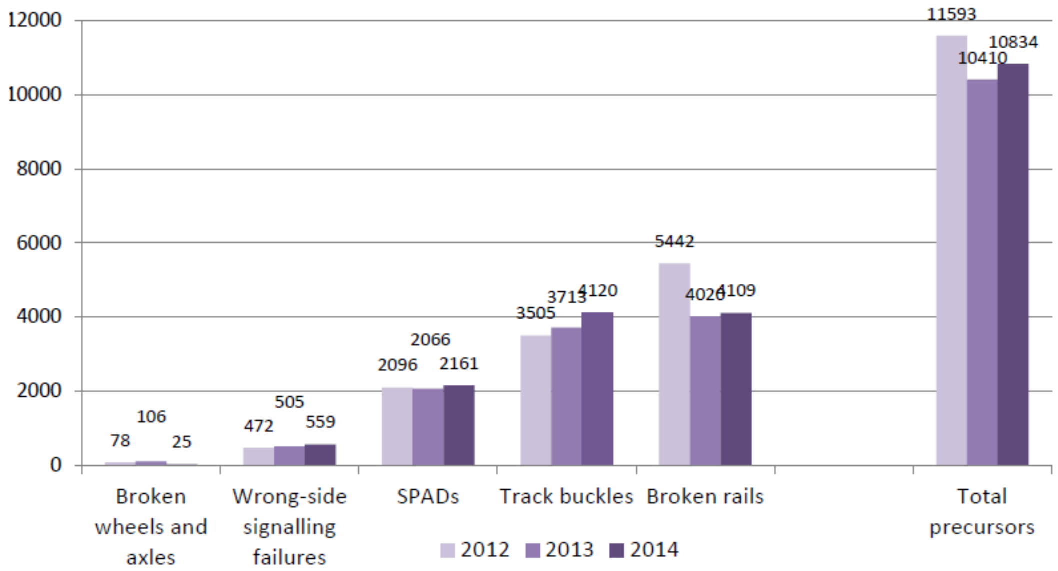


Figure 1.22 - Accident precursors (EU-28: 2012-2014) (European Union Agency for Railways, 2016).

However, railway safety standards in Europe are among the highest in the world and accidents are notably rare. According to EU statistics, the number of train accidents per year in the 28 countries of the European Union is declining steadily: from 2004 to 2011 a decrease of train accidents of about 70 percent was registered (Diernhofer).

1.3.4 Discussion

The importance of reliable infrastructure systems is undoubted. One needs only to be reminded of 10 May 2002 in the UK. Seven people lost their lives and 76 were injured. Within an hour, the poor condition of the turnouts was identified as the cause. Railway turnouts consist of switches and crossings with specific and complex layout, which are exposed to several defects. In fact, a high percentage of railways infrastructure component failures occur in turnouts. Their safe and reliable operation must be assured by systematic prevention and maintenance measures (Hassankiadeh, 2011).

The identification of the possible failure modes and the detection of the most critical components as well as the determination of the corresponding rectifications represent the main aspects of rail failure (Zwanenburg, 2007; Hassankiadeh, 2011). However, several years and a wide range of data are required for the determination of the failure frequency situation at S&C with satisfactory accuracy levels (Kassa, 2017).

Although some appointed reports associated to financial matters or safety performance in the European Union exist – for example the biennial report issued by the European Union Agency for Railways on the development of railway safety performance in the European Union – comprehensive data and statistics of European networks concerning railway track failure are not readily available.
It would be of major interest to have data on the mean operational life time of switches and crossings components (or the life time between failures and actions of replacement or repair) in order to assess the usefulness of repair actions from an economical point of view.

It can be concluded that if nowadays concerns regarding rail failure modes are compared with the literature review on rail defects done by Cannon et al. in 2003, little differences are observed. Rolling contact fatigue is an ongoing challenge as increased demands for higher speeds and higher traffic density result in higher axle loads and contact stresses. However, an improvement of the inspection, prevention and maintenance processes becomes eminent.

1.3.5 Summary of S&C failure analysis

In this section, we classify S&C failures and give several examples of the main failures related to S&Cs.

Classification of S&C failures

Here we recall that S&Cs consist of the following major components:

1. Rail

- Set of switches

- Two switch blades
- Two stock rails

- Closure rail

- Common crossing
  - Through rail
  - Check rail
  - Wing rail
  - Nose

2. Sleepers (bearers)

3. Ballast

4. Substructure (subgrade)

Therefore, classification of S&C failures can be performed based on components' failure as follows:

- **Failure Classification based on components' Failure**
  - Rail Failure
  - Sleeper Failure
  - Ballast Failure

- Subgrade Failure

On the other hand, the classification of S&C failures can be also performed based on the nature of Failure:

- **Failure Classification based on Nature of Failure**
  - Fatigue cracks failure
  - Rolling contact fatigue cracks
  - Wear failure
  - Material deformation failure
  - Shear failure

In the following content, various examples of main failures of S&C are given in terms of RAMS analysis.

Cases of main failures related to S&Cs

Here, various main failures that can affect S&Cs are given. In the following tables we indicate the related component, characteristics, the cause of failure and related solutions for each failure (C4R, 2013).

Failure	Component
Spalling of stock rail	Stock rail

Characteristics

This defect mainly occurs in the wheel transfer area of the switch and shows cavities left by material having spalled out.

Cause

- High contact stresses leading to near surface crack initiation and subsequent merger to cause spalling. High stress can result from worn wheels (false flange) or non-optimal wheel transfer zone and narrow running bands.
- Wheel flange not matching together with design of wheel transfer zone
- Incorrect profile of wheel flange

Appearance

- In the wheel transfer area of the switch

Corrective/Preventative Measures

- Deburring
- Grinding
- Replacement of switch and stock rail assembly
- (improved wheel profile management)

Failure detection

- by visual inspection

Failure	Component
Lipping	Switch and stock rail assembly

Characteristics

This defect mainly occurs in the wheel transfer area of the switch and crossing nose/wing rail and appears as a plastically deformed lip. This defect can lead to material breakouts from the stock and switch rail and the crossing nose.

Possible Causes:

- Non-optimal wheel rail contact leading to high stresses that exceed the yield strength of the material and result in localised plastic deformation
- Wheel flange not matching together with design of wheel transfer zone
- Incorrect profile of wheel flange
- Poor maintenance (prevention of lip development through early deburring)

Appearance:

- Switch and stock rail assembly
- (Also moveable crossings)

Corrective/Preventative Measures:

- Deburring
- Replacement of switch and stock rail assembly (resp. moveable crossing)
- (Improved control of wheel profile & track geometry)

Failure detection:

- by visual inspection

Failure	Component
Soft spots in the running surface	Switch Rail

Characteristics:

This defect occurs mainly in the forged area of switch rails or in close proximity of welds of fixed or moveable crossings. It is characterised by a depression in the running surface caused by localised loss of hardness and strength as a result of the heating and cooling stages during forging.

Possible Causes

- Incorrect heat treatment of material during forging
- Incorrect welding procedure involving high preheat

Appearance

- Switch Rail (also fixed crossing and moveable crossings)

Corrective/Preventative Measures:

- Replacement of switch rail (resp. crossing)

Failure detection

- by visual inspection

Failure	Component
Non-compliance of narrowest flange way (residual switch opening)	Switch & stock rail assembly

Characteristics

Going below the limit of the narrowest flange way can cause a touching of the switch rail by the wheel flange during passage of the vehicles. This defect can lead to whipping of the switch rail and hence (in worst case) to a break of the switch rail.

Possible Causes

- Incorrect adjustment of the driving and locking device
- Inadequate maintenance

Appearance

- Switch & stock rail assembly

Corrective/Preventative Measures:

- Correct adjustment of Driving and locking device (DLD) system (if more than one DLD)
- Regular inspection & maintenance

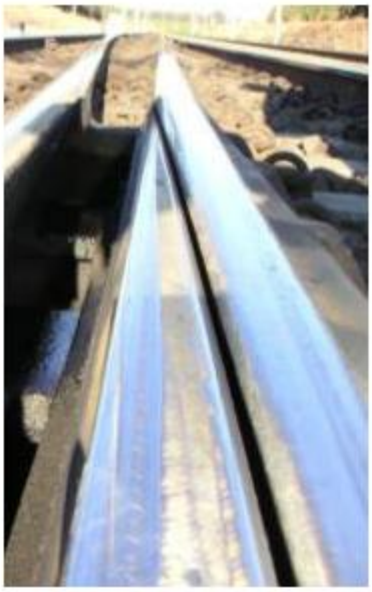
Failure detection

- by measurement of the narrowest flange way

Failure	Component
Incorrect lateral attachment of switch rail	Switch & stock rail assembly

Characteristics

This defect is characterised by a small gap (incorrect lateral attachment) between switch and stock rail and respectively between the crossing nose and wing rail. The defect can cause high dynamic loads that lead to accelerated damage of S & C components.



Possible Causes:

- Incorrect adjustment of the driving and locking device
- Incorrect application of distance blocks
- Excessive lipping/burr on rails
- Incorrect switch rail straightening process

Appearance:

- Switch & stock rail assembly

Corrective/Preventative Measures:

- Correct adjustment of DLD system
- Correct adaptation of distance blocks
- Deburring of rails

Failure detection:

- by visual inspection

Failure	Component
Broken cast items	Anti-Creep Device (Ball & Claw)

Characteristics:

This defect is characterised by a broken (normally the ball section) of a ball and claw type anti-creep device within switches.

This can lead to obstruction of rail vehicles, movement of the switch, incorrect alignment of the switch toes and subsequent point operation that in turn can cause detection failures.

Possible Causes

- Incorrect stressing methodology
- Poor Track Maintenance and incorrect setting upon installation

Appearance

- Broken component

Corrective/Preventative Measures

- Set switches correctly and replace broken component.

Failure detection

- by visual inspection

1.4 Main features of RAMS analysis of S&C

In this section, we firstly indicate the parameters involved in the RAMS analysis of S&C. Then, we introduce the main RAMS activities during the life cycle of S&C.

1.4.1 RAMS parameters

In order to perform RAMS analysis of S&C, the following parameters are needed:

- Reliability parameters

PARAMETER	SYMBOL	DIMENSION
Failure Rate	Z(t), λ	failures / time, distance, cycle
Mean Up Time	MUT	time, distance, cycle
Mean Time To Failure Mean Distance To Failure (for non-repairable items)	MTTF MDTF	time, distance, cycle
Mean Time Between Failure Mean Distance Between Failure (for repairable items)	MTBF MDBF	time, distance, cycle
Failure Probability	F(t)	dimensionless
Reliability (Success Probability)	R(t)	dimensionless

- Availability Parameters

PARAMETER	SYMBOL	DIMENSION
Availability inherent achieved operational	A (.) = MUT/(MUT+MDT) A i A a A o	dimensionless
Fleet Availability	FA (=available vehicles/fleet)	dimensionless
Schedule Adherence	SA	dimensionless

- Maintainability Parameters

PARAMETER	SYMBOL	DIMENSION
Mean Down Time	MDT	time, distance, cycle
Mean Time/Distance Between Maintenance	MTBM/MDBM	time, distance, cycles
MTBM/MDBM, Corrective or Preventive	MTBM(c)/MDBM(c), MTBM(p)/MDBM(p)	time, distance, cycles
Mean Time To Maintain	MTTM	time
MTTM, Corrective or Preventive	MTTM(c), MTTM(p)	time
Mean Time To Restore	MTTR	time
False Alarm Rate	FAR	time-1
Fault Coverage	FC	dimensionless
Repair Coverage	RC	dimensionless

- Safety Performance Parameters

PARAMETER	SYMBOL	DIMENSION
Mean Time Between Hazardous Failure	MTBF(H)	time, distance, cycle
Mean Time Between "Safety System Failure"	MTBSF	time, distance, cycle
Hazard Rate	H(t)	failures/time, distance, cycle
Safety Related Failure Probability	Fs(t)	dimensionless
Probability of Safe Functionality	Ss(t)	dimensionless
Time to Return to Safety	TTRS	time

1.4.2 RAMS analysis activities

Various main RAMS activities during the life cycle of S&C need to be performed. Here we will introduce these activities as follows:

Set RAM and safety targets

Firstly, we need to set RAM and safety targets. In details, in this phase, RAM plan and Safety assurance plan need to be prepared for setting MTBF target and SIL target.

RAM allocation, deriving RAM requirements

Secondly, after setting RAM and safety targets, RAM allocation needs to be performed to allocate the global MTBF target to each component of the system. Methods, such as FMEA, FTA, Markov Chains, can be adopted to achieve the above activities.

Hazard identification and analysis, deriving safety requirements

In this stage, we need to perform hazard analysis so as to derive safety requirements. There are three following main activities for derive safety requirements.

– **Preliminary hazard analysis (PHA)**

PHA is used for identifying preliminary hazards according to European Preliminary Hazard List (Subset-088), user requirements or some other involved documents/standards;

The outputs of PHA are SIL allocation to each preliminary function to meet the SIL target and safety requirements. The FMEA is adopted to implement the PHA.

– **System hazard analysis (SHA)**

SHA is used for identifying hazards of system functions according to System Design Requirement Specifications or some other involved documents/standards;

The outputs of SHA is SIL allocation to each system function to meet the SIL target and safety requirements. The FMEA is also adopted to implement the SHA.

– **Interface hazard analysis (IHA)**

SHA is used for identifying hazards about vital I/O and data according to System Architecture Specifications, System Interface Specifications and Module Communication Protocol;

The outputs of IHA is SIL allocation to meet the SIL target and safety requirements. The FMEA is also adopted to implement the SHA.

– **Safety Integrity Level derivation and assessment**

This activity is performed based on the PHA, SHA, and IHA.

LCC

The lifetime of S&Cs on the main track is in general 40 years and, therefore it is necessary to calculate for more than 200 new S&Cs per year in the reinvestment plan. A cost-benefit analysis based on life cycle costs could be a good tool for finding which S&Cs need to be replaced. Life cycle costs can also be used in the design stage or when decisions between different types of S&Cs have to be taken.

The life cycle of an asset can be subdivided into 6 phases according to (IEC 60300-3-3):

- Concept and definition
- Design and development
- Manufacturing
- Installation
- Operation and maintenance
- Disposal

The owner of an asset can consider 3 stages for LCC-analysis:

- Development
- Operation
- Phase-out

For the asset owner, the cost connected with the development stage is the acquisition and installation cost, while the development is carried out by the vendor. These costs are normally fixed.

The S&Cs can be described by different levels. Level I is the superstructure carrying the load, and level II is the superstructure and the mechanical parts with the driving and locking devices. Level III is the total system with the signaling and interlocking system, as shown in the following figure. Only level II is used in the operation phase of the LCC assessment.

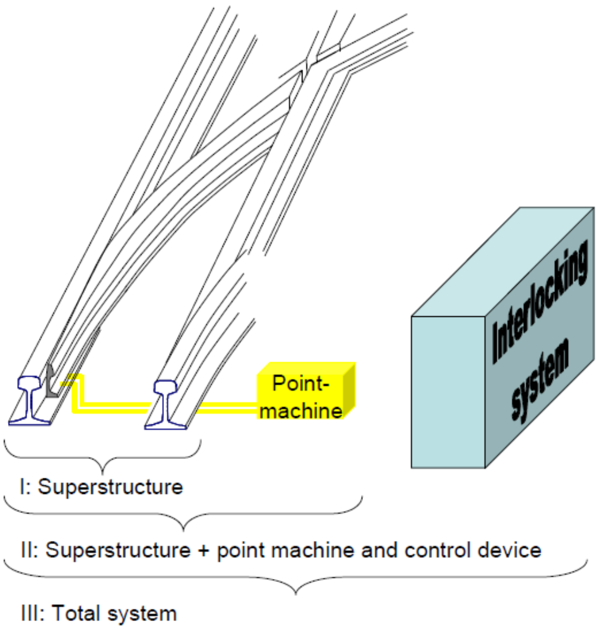


Figure 1.23 – Three levels of S&C

1.4.3 Implementation of RAMS analysis on S&C

Provided that sufficient and reliable field data are obtained, RAMS analysis on S&C can be implemented in terms of RAM analysis and safety analysis, shown as follows:

- RAM analysis (cf. section 1.4.2)

  As for the RAM analysis, the following steps need to be implemented:

  1) Setting RAM and safety targets according to user requirements or related standards;
  2) Performing RAM plan and allocation, in details:
     - Identifying the RAMS parameters indicated in section 1.4.1;
     - The methods given in section 1.1 can be used to calculate the indicators of RAM;
  3) Proposing RAM requirements;
  4) Assessing LCC based on RAM analysis;

- Safety analysis (cf. section 1.4.2)
  As for the safety analysis, the following steps need to be implemented:
  1) Performing hazard identification and analysis through FMEA, based on the failures (cf. section1.3), if it is appropriate:
     - PHA
     - SHA
     - IHA
  2) Assessing SIL ;
  3) Proposing safety requirements.

1.5 Maintenance

Switches must be kept in good condition in order to guarantee an adequate running of the train through them, and thus, to minimize its degradation by dynamic loads. If not properly maintained, the wheel-rail interface will be negatively affected, which could eventually derive in derailments (e.g. as a result of the wheel impacting a blade that is not correctly coupled to the stock rail or suffers excessive wear). Because of safety and operational issues, switches are intensively inspected and maintained.

Roughly speaking, inspection costs account for about 50% of all maintenance costs for switches. In spite of the high investment on maintenance, switches have a lesser lifespan than plain track given that they suffer higher stress. As an example, the service life of a wooden sleepers S&C is about 20 years in average, while when using concrete sleepers the expected life increases up to 30 years. In the subsequent sections, we go through a list of the main maintenance operations for S&Cs, while considering both systematic corrective operations and renewal/replacement operations.

1.5.1 S&C lubrication

As in general lubrication, the basic purpose of S&C lubrication is to reduce the friction and wear between movable components and supporting surfaces (Liu et al. 2017). Consequently, it directly reduces switching force, i.e., the load of switch machine. The choice of the lubricant is crucial for the lubrication quality. A good S&C lubricant should satisfy the following requirements (Liu et al. 2017):

- The ability to prevent rust or corrosion.
- The ability to repel and flush outside contaminants, such as water, dirt, mud, sand, grit, and any matter that can break the lubrication film and reproduce friction.
- Long and constant lubrication intervals independent of climatic conditions (temperature, humidity, precipitation, etc.).
- Non-toxic and safe for both human and environment.

S&C lubricants are generally recommended by their manufacturers to be applied by spraying, wiping, brushing or even pouring. Among them, spraying is the easiest and the most efficient method. Traditional S&C lubrication is performed manually. On-site lubrication operators often have to carry a knapsack or handheld tank of lubricant and apply it with the help of a sprayer. There are problems with manual work, namely cost, quality, efficiency, accessibility and safety. In order to cope with these issues, automatic lubrication techniques have been developed. Some techniques replace manual lubrication work by automatic lubricators installed with switches, as shown in the following figure.

Figure 1.24 - An automatic lubricator

Such unmanned techniques can release track workers from heavy work and perform remote lubrication (particularly in the least accessible areas). In addition, a computer/PLC can exactly control lubricant consumption to avoid over application and lubricate both switch rails at the same time. Moreover, this "computerized" procedure obviously allows for a better traceability of the operations.

1.5.2 Replacement

This phase of S&C renewal covers the extensive work activities needed to commission the replacement of S&C panels, including installation of:

- Geotextiles and ballast
- Bearers
- Fastenings, rails and frogs, plus:
- Welding and grinding
- Initial track geometry restoration
- Control system commissioning
- Final commissioning and testing
- Removal of plant and personnel from site

The total duration of this phase is taken to be two shifts, which together with the removal of the old S&C work activities, roughly gives a total time of 32 hours needed on site for the major renewal work. This is consistent with the 30 hours quoted by BV and 37 hours quoted by Network Rail in (INNOTRACK D5.4.1, 2009).

The following sections define the resources needed for the major work activities to be undertaken during the renewal phase. There is again significant potential for savings in time, labour and plant to be accrued through the use of modular S&C renewal techniques during this phase. The nature and potential of these are described where appropriate in the following parts. Deliverable D2.3 of NeTIRail-INFRA is used as a main reference for the description below.

- Installation and assembly of panel

The bulk of the labour and plant requirements for conventional renewals are accounted for in this work activity, and it is acknowledged that these resources will also be used to some extent to deliver the other work activities. The installation and assembly phase of the S&C renewal also utilises the same resources used for removal of the old S&C panel. Hence labour requirements are taken as being a total of 16 persons for two shifts, consisting of 10 track workers, 4 safety personnel and 2 signalling interface operators. Engine requirements are taken as being one specialised road/rail excavator, with two additional tools, plus two items of small engines such as a dumper truck for removal of spoil.

These assumptions should be considered as average figures and may be different from one IM to another, depending on the available machinery, labour cost, location, etc. The reader can refer to the report of the TCDD visit carried out in the framework of this task which has involved partners from IFSTTAR, USFD, TCDD and INTADER who have attended an S&C whole replacement operation in Kayseri-Turkey (Kayseri, 2017).

The work undertaken during the renewal procedure covers installation of the new ballast sub layer, deposit of bearers, installation of chairs and sliders followed by the crossing itself and the stock, switch and check rails and tie bars. Also included is the installation of the additional ballast needed in the sleeper cribs and shoulders (Kayseri, 2017).

There are significant savings that may be made in this work activity through the adoption of the modular S&C renewal technique, mainly through the ability to install the S&C panel much more quickly than for conventional renewals (Paragreen et al., 2017). All of the work that would otherwise be needed to lay the bearers, slide chairs, rails, fastenings and drive mechanism can be achieved in one operation. According to the information given by the IMs there is the potential for the whole renewal to be achieved in 8 hours. There is also significant potential for a reduction in the labour needed, as much of the renewal is mechanised using specialised rail wagons with tilting beds. These aspects will be further discussed in the second chapter of the present report pertaining to lean techniques.

- **Welding**

This work activity covers the welding activity required to connect the S&C panel to the adjacent plain line including rail re-stressing and rail grinding once the panel has been installed, with resources taken as being four welders for one shift, plus four items of specialist welding equipment.

- **Initial track geometry restoration**

Restoration of the track geometry to allow safe resumption of services following installation requires one tamper plus crew for one shift.

Even with geometry restoration, conventional renewals usually require application of significant temporary speed restrictions (TSRs) to reduce the impact of settlement of the ballast and panel under traffic conditions. Modular S&C renewals can drastically reduce this as a result of the higher installed quality and integrity of the panel, even to the point where immediate restoration of line-speed operation is possible.

- Control system commissioning

This work activity covers the commissioning of the S&C drive and its reconnection and interfacing with the signalling system. Lubrication of the slide chairs and rollers and adjustment of the switch rail throw and locking mechanisms must be undertaken during this work activity. It is assumed that the bulk of the labour and plant needed for this will be supplied from the resource already accounted for in the work activity covering installation and assembly of the S&C panel. However, there will also be a requirement for the services of specialised signalling engineers. This work activity therefore covers the resource needed for these, this being two signalling engineers for two shifts.

- Final commissioning and testing

Upon completion of the S&C panel renewal and commissioning, this work activity covers the testing, inspection and acceptance required. The additional resource needed for this work activity is assumed to be two permanent way engineers for one half shift.

- Removal of plant and personnel from site

This work activity covers the removal of plant and personnel that were needed for the S&C removal activities upon acceptance and hand back. Labour resources are shown as being null for this work activity, as these would be accounted for as part of the unproductive time per shift and thus included in the estimate given under the resources needed for the installation and assembly of the S&C panel.

The machine cost included in this work activity covers provision of a train used for the component, ballast and spoil removal for the two shifts required for the installation and assembly of the S&C panel. This is assumed to be the same train used in the phase where the old S&C panel is dismantled and removed.

1.5.3 Post-renewal activities

After a period of ballast and panel settlement under traffic following renewal, it is usual for track geometry to be restored and the S&C panel to be inspected and maintained to ensure correct operation of the switch rail and locking mechanisms. This phase covers the resource and labour needed for these activities, which are assumed to be performed overnight or outside track possession, ideally without disruption to train operations.

- Final track geometry restoration

The resources needed for restoring the track geometry to allow safe resumption of line speed operation requires one tamping unit plus crew for one shift.

- Final inspection and acceptance

This work activity covers the drive adjustment, testing, inspection and acceptance required following final track geometry restoration. The additional resource needed for this work activity is assumed to be two permanent way engineers for one half shift.

1.6 Conclusions

In this chapter we went through the main features pertaining to safety of S&Cs and we discussed both the methodological and operational aspects in relation with RAMS analysis of S&Cs. One of the major issues for RAMS analysis is the availability of data. In the case of S&Cs, the required data to perform detailed RAMS analysis are related to the whole life cycle of the S&C, starting from the installation, through all the operations undertaken regarding preventive and corrective maintenance and renewal.

It should be noted here that the research undertaken within NeTIRail-INFRA project in relation with the IMs which are partners of the project but also outside the project lead to the same observation: these data are not reported in a sufficient way. Our investigations showed that the main reasons are twofold.

1) A major part of relevant data is not reported. Namely, various operations are achieved during systematic inspection as necessary, such as lubrication, inspection of component fixation, welding, etc. These data are not reported (or not appropriately). Ideally, details regarding the exact operations performed, the applied products, the weather conditions, etc. need be reported. Moreover, precise details regarding the railway traffic along the involved section are needed to assess the load/solicitation the S&Cs are subjected to. Besides, roughly speaking in most cases only the major operations such as renewal/replacement are recorded and traced.

2) The relevant available data are spread over various systems/databases (engineering, maintenance, etc.). Moreover, in general interoperability is not guaranteed among the storing systems. This is namely due to the data formats chosen and the lack of common standards. In the framework of NeTIRail-INFRA project, this issue is addressed in the framework of task T4.5 (WP4).

For this current project, there is a lack of detailed data to perform detailed RAMS analysis: precise description of failures, traffic density type, weather conditions, maintenance operations, etc. Further data collection will be carried out to obtain enough and reliable field data.

2. Application of lean and automotive techniques

The purpose of this task was to apply lean and automotive techniques to the installation or renewal of switches and crossings, to identify inefficiencies and potential cost and time savings. This task has concentrated on mapping and observing the actual installation tasks and renewal tasks of switches and crossings. However, it is expected that the planning stage could also offer as much benefit, if not more benefit from Lean optimisation, and may provide the greatest benefits. The planning process was outside of the scope of the study in NeTIRail-INFRA, but the planning process for a tamping operation was studied within the AUTOMAIN FP7 project[1]. For the tamping planning process the process was mapped, steps and loops identified and in the AUTOMAIN case studies a very large number of interfaces identified due to the number of stakeholder involved including the train operators, maintenance contractors, infrastructure managers, equipment suppliers and timetable planners. Within the AUTOMAIN project social network diagrams were developed to demonstrate these interactions and make recommendations for improvement.

2.1 Lean Case Studies

Two case studies were carried out studying the implementation of lean techniques in the installation of new switches and crossings. The first case study was carried out in Kayseri, Turkey near to the railway station, where an old switch was being replaced. This was a straight forward swap and the new switch sections were constructed by the lineside and then lifted into place.

The second case study took place at Celje, Slovenia. Here the two new S&Cs were observed being installed as part of a new layout of track just outside of Celje station. In this case old track had been removed, the new ballast and subgrade had been prepared and the observations were of the two new switches being constructed in-situ.

The two different case studies presented quite different scenarios, the new switches being constructed in Celje in-situ as part of a major upgrade project was a much busier site, but had the possibilities for redeploying more resources to other tasks rather than waiting at certain stages in the process.

First case study – Kayseri, Turkey

Monday 15th May 2017

Timing	Meeting before the visit:	from 08:39 to 09:28
	Site visit:	from 09:28 to 16:55
Location	Approximately 300m east by north east of Kayseri Railway Station, Kayseri, Turkey	

[1] AUTOMAIN Deliverable D2.2 – Lean Analysis of Track Maintenance Process 2012

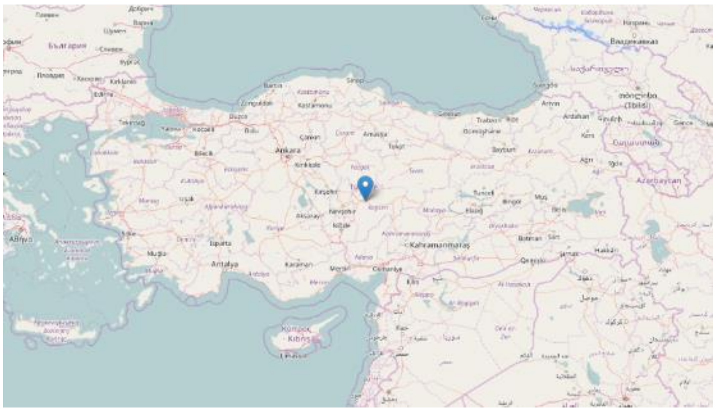


Figure 2.1 - First case study – Kayseri, Turkey

Second case study – Celje, Slovenia

Date – Monday 16th October 2017-Tuesday 17th October

Location – Approximately 100m NNE of Celje Railway Station in Slovenia

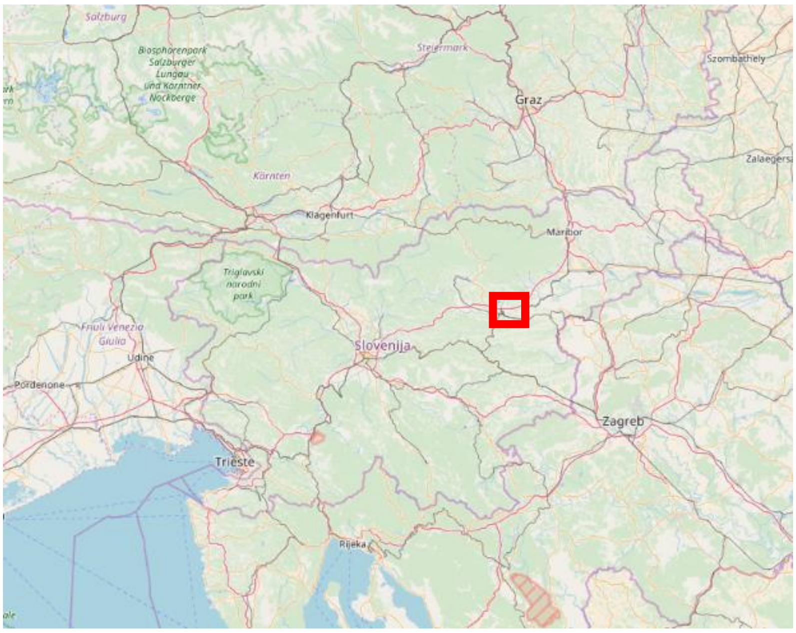


Figure 2.2 - Second case study – Celje, Slovenia

2.2 Methodology

The methodology used in the lean assessments was to visit each site and observe the switch installation activity. Prior to the observations beginning the key tasks were identified. For each task the resources used were noted, as well as the start and end time of the task. Each task was also photographed and for the observations in Celje, Slovenia a timelapse video was taken of the whole process for referring to later.

Figure 2.3 - Video capture for S&C installation

Following on from the observations, each task was classified as either:

- Value adding task – task that directly adds value
- Non-value adding necessary task – task that is necessary but in itself does not add any value
- Waste - task with some element of waste as defined in "seven types of waste", see below

The seven types of waste identified in the lean methodology are:

1. Transport (moving products that are not actually required to perform the processing);
2. Inventory (all components, work in process, and finished product not being processed);
3. Motion (people or equipment moving or walking more than is required to perform the processing);
4. Waiting (waiting for the next production step, interruptions of production during shift change);
5. Overproduction (production ahead of demand);
6. Over Processing (resulting from poor tool or product design creating activity);
7. Defects (the effort involved in inspecting for and fixing defects).

In addition to classifying the tasks, the tasks were presented in a Gantt chart form and the wastes were identified on the Gantt chart in an amber coloured bar, to highlight the waste processes and where improvements could be obtained. Also, the resource use over time were plotted.

From these results, it was possible to analyse the extent of the waste and to make recommendations to reduce or eliminate these waste in future operations and also to suggest optimisations for different track types.

2.3 Key results from observations

The complete analysis and reports of the lean analysis can be found in the Annexes of this report: Annex 1 - Lean optimisation of S&C renewal Kayseri, Turkey; and Annex 2 – Lean optimisation of S&C installation Celje, Slovenia.

2.3.1 Kayseri, Turkey

Key types of waste identified in the S&C replacement process in Kayseri:

- Motion (people or equipment moving or walking more than is required to perform the processing);
- Waiting (waiting for the next production step, interruptions of production during shift change);
- Overproduction (production ahead of demand);
- Over Processing (resulting from poor tool or product design creating activity);
- Defects (the effort involved in inspecting for and fixing defects).

Motion

The switch section and crossing sections were possibly moved more than necessary, by transferring them on to the adjacent track before they were moved into their final place. However, with the plant machinery that was being used for this operation the method used in this case was perhaps optimal, as cranes that would lift the sections directly into place were not available.

Discussions with the TCDD team indicated they do have rail cranes which are used in some S&C replacement operations and can therefore be used to lift the S&C directly in place rather than having to slide it from on top of existing rails. However, due to the overhead lines this type of crane was not practical for the observed case.

Figure 2.4 - Example of a rail crane similar to what is available to TCDD.

However, other designs of cranes could make the direct placement of the S&C sections whilst still being under overhead lines (see below an example from Sweden). However, it is expected that the machinery hire costs would be significantly greater. The analysis also shows that the time required to move the sections is relatively small with durations of 4-7mins and therefore there is unlikely to be any economic benefit to the use of improved lifting equipment, unless it can be shown to reduce the risk of damage to components as they are being installed or provides other benefits such as improved safety.

Figure 2.5 - Example of crane able to lift S&C sections whilst under overhead lines.[2]

[2] https://www.globalrailwayreview.com/article/34001/new-investment-highs-existing-swedish-rail-infrastructure/

Waiting

Waiting is one of the major waste identified during that analysis of the switch replacement in Kayseri. Considerable resource was wasted as track workers were underemployed whilst waiting for backhoe loader in some activities during the morning as that particular item of machinery was over employed on many parallel tasks.

Figure 2.6 - Illustration of waiting time

Waiting was also caused by some tasks taking long times but being critical tasks which prevented other tasks from proceeding until that particular task was completed. In many cases these long tasks used only a small proportion of the total resources available, so the others were left waiting. This is particularly true for the longest tasks of clearing and levelling the old ballast, distributing the new ballast, and the installation of the switch motor. In the tasks associated with clearing, levelling and distributing ballast, the task occupied the whole work site and therefore the new sections could not be installed. Similarly, the switch motor needed to be installed before the engineering train could run through and distribute the fresh ballast.

There was also a lunch break during which all work stopped, the key resources at this time was the backhoe loader for levelling the ballast. Around the same time the excavator was underutilised. Thus, if the two machine operators could operate both machines, it would be possible to stagger their lunch breaks and therefore reduce the total time for this renewal operation.

Figure 2.7 - Illustration of old S&C section being removed.

Overproduction

Overproduction relates to a component being produced ahead of when it is required. This could relate to the switch sections being pre-built during the previous day. The time and resources to build the switch components should be assessed regarding the time and resources required to build these sections, and whether this would fit within the gap around midday when the ballast clearing and levelling operations were being carried out, as there was a very low usage of track workers during this period.

Conversely, the installation of the switch motor could potentially be better prepared, as this task took 56 min. and prevented progress as this need to be completed to allow the ballast train to run through the S&C.

Over Processing

Potentially, there was over processing carried out during the tasks of levelling the old ballast layer task which took 51 min. and was a significant portion of the total time of the S&C replacement operation, whilst it is important to ensure the gradient between the ends of the old track is maintained, the quality of the levelling should be proportional to any benefits. The old ballast is then covered by a layer of fresh ballast which was again levelled.

Defects

There were several “defects” where tasks had not been performed perfectly correctly and therefore required rework. In many cases the additional work required unfastening the rail from the sleepers to allow adjustment of the rail or sleeper position or replacing a fishplate for an insulated block joint. This work could be avoided with either better planning or systems in place to prevent such rework having to be carried out.

Conclusions and recommendations from Kayseri, Turkey

The appropriate optimisation of this S&C replacement task should be dependent upon what is the primary objective. We understood that the operation, we saw was not typical and usually a switch could be replaced in 6 hours with less track workers. This seems entirely possible if faults weren't made which needed correcting and if some tasks didn't require as much time, for example if less time was required to install and setup the switch motor and the levelling of old ballast didn't take so much time. The total stop of work for a lunch break could also be eliminated with better planning of resources, if the excavator operator could operate the backhoe loader and they staggered lunch breaks.

By eliminating these types of waste and reducing the installation time for the switch motor to 15 min., it is expected to finish the whole operation approximately two hours earlier and is therefore approximately aligned with expectations.

ID		Task Mode	Task Name	Duration	Start	Finish	15 May, 10 / 15 May, 11 / 15 May, 12 / 15 May, 13 / 15 May, 14 / 15 May, 15
1			Unfasten joints for intermediate section	26 mins	15/05/17 10:06	15/05/17 10:32	Excavator + operator[0],Backhoe loader + operator[0],Track worker
2			Lift new crossing section on top of adjascent track	8 mins	15/05/17 10:14	15/05/17 10:22	Track worker inc engineers and supervisors[2],Backhoe loader + opera
3			Clear old ballast from switch section	38 mins	15/05/17 10:08	15/05/17 10:46	Track worker inc engineers and supervisors[3],Backhoe loader +
4			Unfasten joints for crossing section	26 mins	15/05/17 10:06	15/05/17 10:32	Track worker inc engineers and supervisors[4]
5			Lift and remove crossing section	12 mins	15/05/17 10:32	15/05/17 10:44	Backhoe loader + operator,Excavator + operator,Track worker inc
6			Lift and remove old intermediate section	7 mins	15/05/17 10:37	15/05/17 10:44	Track worker inc engineers and supervisors[4],Backhoe loader + c
7			Clear old ballast from whole section	24 mins	15/05/17 10:46	15/05/17 11:10	Track worker inc engineers and supervisors[4],Backhoe load
8			Move new switch section on top of adjacent track	4 mins	15/05/17 10:44	15/05/17 10:48	Backhoe loader + operator,Track worker inc engineers and super
9			Levelling of old ballast	51 mins	15/05/17 11:10	15/05/17 12:01	Backhoe loader + operator,Excavator + operato
10			Apply fresh ballast	7 mins	15/05/17 12:	15/05/17 12:08	Engineering train + driver,Track worker inc en
11			Distribute clean ballast	30 mins	15/05/17 12:08	15/05/17 12:38	Backhoe loader + operator,Track worke
12			Level ballast	8 mins	15/05/17 12:	15/05/17 12:46	Backhoe loader + operator,Track worl
13			Slide crossing section into place	12 mins	15/05/17 12:46	15/05/17 12:58	Excavator + operator,Track worker
14			Slide switch section into place	2 mins	15/05/17 12:58	15/05/17 13:00	Excavator + operator,Track worker
15			Connect fish plates - Switch end	36 mins	15/05/17 13:00	15/05/17 13:36	Track worker inc engineers
16			Lift intermediate section into place	8 mins	15/05/17 13:00	15/05/17 13:08	Excavator + operator,Track work
17			Connect fish plates for intermediate section and align	15 mins	15/05/17 13:08	15/05/17 13:23	Track worker inc engineers ar
18			Manually ballast at the end of sleepers	21 mins	15/05/17 13:23	15/05/17 13:44	Track worker inc enginee
19			Add ballast and manually tamp at switch end	9 mins	15/05/17 13:44	15/05/17 13:53	Track worker inc engin
20			Install switch motor, attach to sleepers and adjust bars as well as electrical connections	15 mins	15/05/17 13:53	15/05/17 14:08	Welding staff[2],Si
21			Run ballast train to drop fresh ballast around sleepers	8 mins	15/05/17 14:08	15/05/17 14:16	Engineering train

Table 2.1 - Description of tasks timing

In addition, potential actions to reduce reworking should include measures to get things right first time.

The resources also show a better utilisation, however, there is still the period during the middle of the operation where there is a low utilisation of the track workers, as shown in the figure below.

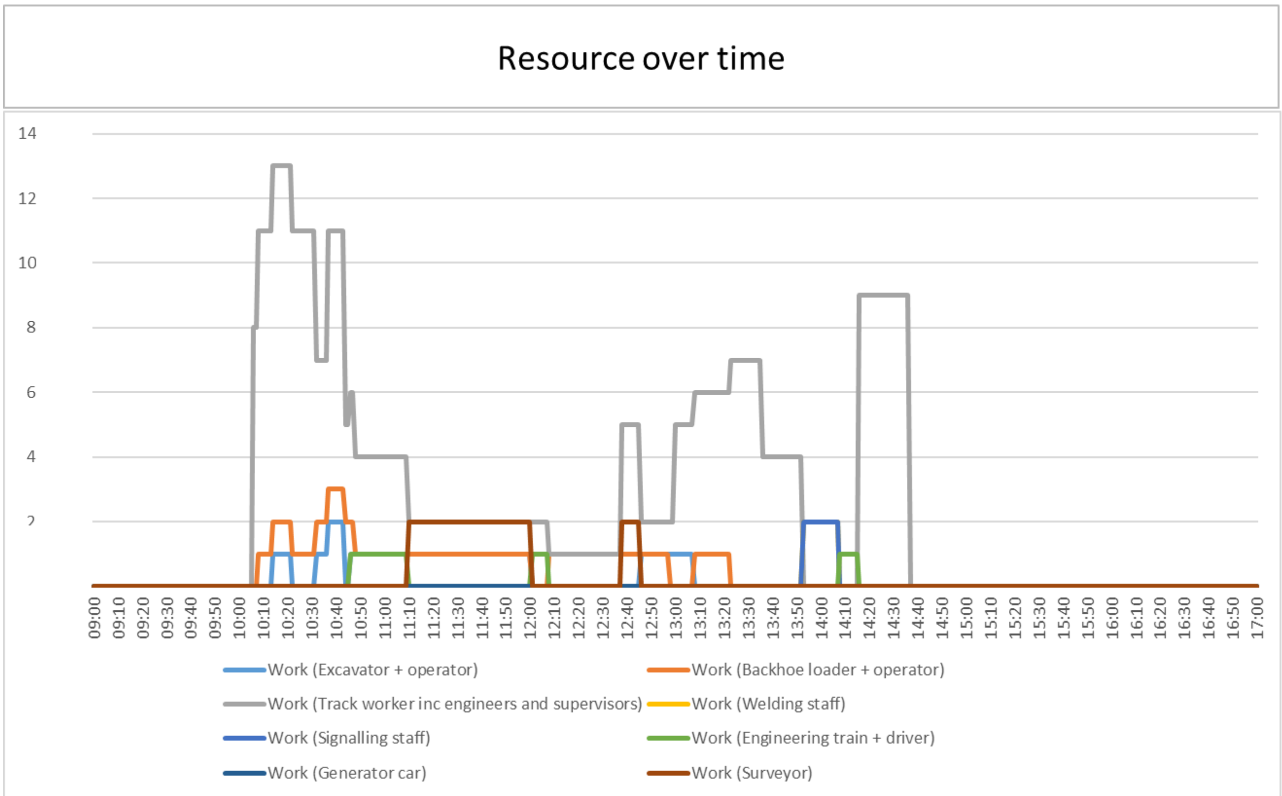


Figure 2.8 - Resource use over time

Key optimisation parameters and potential actions

The operation of the replacement of the S&C could either be optimised for cost, or for minimum possession time, or a compromise between these two items. In all optimisation scenarios, the defect wastes should be eliminated, and the longest tasks analysed in greater detail and studied to understand if the work could be planned in such a manner that it prevents too much waiting.

Examples of potential actions to optimise individual tasks are given in the following.

Tasks related to clearing old ballast, levelling old ballast and distributing fresh ballast

Check what are required levels of quality, is the task being carried out to levels of quality higher than necessary and will post installation tamping correct some of the deviations. It would also be worth considering whether additional equipment could improve and speed up the process, such as a simple rake attachment which could be dragged behind the backhoe loader or excavator. Also consider the excavator and backhoe loader operators taking it in turns to carry out this operation, so that work can carry on continuously without the need for all work stopping for a lunch break.

Installation of switch motor and the switch motor fixings to sleepers

Nearly an hour was spent waiting for the switch motor to be installed and adjusted whilst no other work could continue until after these tasks were completed. Consider making the adjustments to the sleepers for the switch motor mountings before the switch is installed. Perhaps the first task should be to remove the switch motor from the old switch and install it including modifying the sleepers and adjust it to the new switch section. Then remove the motor again whilst the switch is moved and then as soon as the new switch is in place, the motor can be reinstalled but would require little additional adjustment and therefore would not hold up the final operations.

Defects

Defects can be minimised though better planning and processes to ensure errors are not made. Most of the defects in this operation were either due to mistakes (such as fish plates being installed and then later replaced with insulated block joints) or inaccurate positioning of the sleepers relative to the ends of the rails, or due to sections being dragged into place the final positioning was not very accurate and therefore the rails needed to be released from the sleepers to allow the fine adjustment to connect the rail joints.

Mistakes such as fish plates being installed rather than insulated block joints can be mitigated with the rail ends being clearly marked with the appropriate joint type. Marking could include marking the ends with different coloured paints for different joint types for example. Or a Poke Yoke solution may be applied to prevent mistakes from happening. A Poke Yoke solution only has one way of fitting together, so it is impossible to assemble incorrectly. In this example the bolt holes locations for insulated block joint (IBJ) could have different spacings to those for the fish plate, so if the holes at the end the rail have been drilled to the spacing for an IBJ, it would therefore be impossible to fit a fish plate in this location. However, it would be even more important in this case to ensure the correct joint type is planned for as the holes are drilled in the rail section and this solution may also cause issues with the compatibility with existing infrastructure.

The issues related to task 3.3 “Crossing section” where the end sleeper and fishplates had to be removed to manoeuvre ends into place. This could be mitigated by either greater precision in measuring the end sleeper location on the existing old crossing section and ensuring that these positions were aligned on the new crossing section. Or it may be beneficial to install the end sleeper separately to the rest of the panel. The rest of the panel could be constructed except the end sleeper. The new end sleeper is installed first in the correct location closely aligned and at the same level as the end sleeper for the plain line track. The crossing panel could then be installed over the top and the ends of the crossing rails then fastened down to the end sleeper after the fish plate are in place.

Figure 2.9 - Installation of insulated block joints

Numerous times the rails had to be released from the sleepers to allow adjustment and alignment of the rails, and then required refastening. These operations were time consuming and required large amounts of man power. More accurate placement of panel sections could help to prevent this rework from taking place, however, this may require additional equipment. As previously mentioned improved lifting equipment such as the crane shown below may help the operation and improve the accuracy of positioning as it entirely lifted and can therefore be positioned and rotated more easily as it is lowered into place. Whereas, using the excavator and backhoe loader to drag, partially lift and push the sections into place makes such accurate locating more difficult and hence the need for the adjustment work. However, investment in such equipment would be very expensive and the additional cost is likely to be higher than the value of time saved through adjustment.

Figure 2.10 - Overview of the working location

Despite this other lifting options should be considered, jacks were used extensively in this process to align the rail ends and options such as several sets of “A” frame lifting equipment such as those shown below could be considered to suspend the whole section again after it has been roughly positioned by the excavator and backhoe loader for the accurate positioning and manoeuvring. This would also free up the excavator and backhoe loader for other tasks.

Figure 2.11 - "A" frame lifting equipment

Optimising for minimum possession time

The whole operation could either be optimised for minimum possession time and consider that cost is less important than the time that the line is closed for. In this particular example that we saw, the traffic was very low through Kayseri station and therefore it is unlikely that possession time was a large constraint. However, if it was, there are considerations that could be made in addition to those mentioned above. Firstly, it was obvious in the morning that the backhoe loader was over utilised and in several cases, tasks were being delayed whilst workers waited for the backhoe loader to return to their task from another operation. If cost was not important, it may be worthwhile to hire a second backhoe loader just for the morning, this would also help to stagger the lunch break so that work did not stop when the backhoe loader operator took his lunch break. Also, more specialised lifting equipment as discussed above may help to reduce the overall possession time, but is likely to be very costly.

Optimisation for minimum cost

If the operation was optimised for minimum costs but allowed longer possession times, it may be worth considering to reduce the number of track workers.At various times of the day they were very poorly utilised and by halving the number of track workers could save cost, but only extend the time required for certain tasks. The other option would be to retain the same level of staffing, but rather than build up the new sections the day before the S&C replacement, these could be made up throughout the day by the track workers during phases with low work load. This would need to be carefully assessed to ensure that with the time and resources available they could build up the three sections in the time available. However, but doing this the workforce would be better utilised throughout the shift and it would not require a separate shift of workers to build up the sections in advance. During conversations with TCDD colleagues it seems that during the demonstration at Kayseri station, there was a higher number of track workers than normal, which indicates that this first recommendation is already normal practice.

2.3.2 Celje, Slovenia

Regarding the Celje use case, the various tasks have been analysed for wastes and the key wastes identified were – motion, waiting, over production, over processing and correcting defects. Details are discussed in what follows.

Motion

Motion refers to the unnecessary movement of products, machinery or people. In the case switch installation at Celje there was not excessive amounts of motion waste. However, due to the constraints of the site and to ease working, sleepers and rail were unloaded from engineering trains and then moved away from the working site for storage until they were needed. This created an excess of movement of these products, but it is understandable that this was done to help keep the site clear. Nevertheless, modifying the process so that sleepers and rail are unloaded and moved directly to the location where they will be used later would avoid some of the waste.

There was also a large amount of movement of people, due to the nature of the site. Staff were deployed between tasks at different locations as the need for labour spiked (eg. for manually moving rail) and fell, this helped to minimise the amount of waiting, so on balance the motion waste is optimal.

Waiting

Waiting wastes were minimal on the Celje site due to resources being redeployed as necessary. However, in some cases there were periods of waiting, for example whilst waiting for the loader to bring crossing section for the first S&C. There were also periods of waiting for the engineering train and the tamper and ballast smoothing vehicle. The engineering train occasionally had to wait for access to the site to lay new ballast, and the train also had to wait whilst sleepers were being unloaded.

However, there is little that could be improved in this unless additional loaders were to be deployed. The tamper and ballast smoothing vehicle also faced considerable waits in accessing the site and also their deployment on site. The ballast smoothing vehicle helps to distribute and level the ballast after the tamper has passed. Nevertheless, due to the constraints of the site it has to enter the site first and then wait for the tamper to complete its task before it was deployed, which resulted in it waiting for several hours.

There were also periods of waiting around tasks such as cutting and drilling the rail ends and fastening the fish plates where the wait was short enough that it was not worth redeploying staff to another part of site, but did leave labour waiting.

Over production

Over production relates where a component is produced before it is required and relates to the cost and issues of holding excessive stock. Although sections of switch were produced ahead of when they were required, this did not cause any large waste.

Over processing

Over processing is when something is produced to a higher than required quality using excessive resources. This was not a large problem for this site either. However, there were elements of the process where a large amount of time was spent in realigning sleepers for example, which took excessive amounts of time and may not provide much difference in the quality of the track to justify the time spent.

Defects

Correcting defects was one of the largest wastes identified in this analysis. Examples of correcting defects included tasks such as lifting the track, removing and then replacing sleepers and cutting the ends of sleepers. These are tasks which if carried out correctly first time would not be required, and could be eliminated with better planning or processes.

Recommendations

The table below demonstrates the potential resource savings by the elimination of the waste identified within this report. However, only the resources which were active in each task are included here. Thus, this does not include the waste due to waiting times. Consequently, the additional potential improvement gained by eliminating waiting is not demonstrated here.

Name	Start	Finish	Total Work observed	Total Work after removal of wastes	Saving
Loader	16/10/17 07:27	17/10/17 13:04	282 mins	244 mins	38 mins
Track worker inc engineers and supervisors	16/10/17 07:50	17/10/17 14:13	4,206 mins	3,023 mins	1,183 mins
Engineering train + driver	16/10/17 07:32	17/10/17 10:50	48 mins	48 mins	0 mins
Tamping train + driver	17/10/17 10:50	17/10/17 13:38	85 mins	85 mins	0 mins
Ballast smoother	17/10/17 11:57	17/10/17 13:36	37 mins	37 mins	0 mins

Table 2.2 - Overview of machinery use

The use of resources was poorly balanced with numerous peaks and lows and regular phases of requiring high quantities of staff for moving particular components and then them waiting until the next task which required a similarly high amount.

Potentially the use of specialised lifting equipment could be used for modular installation. There were areas near to the site where such installation could have taken place, although not adjacent to this site. Therefore, specialised lifting equipment such as that recommended also for the Kayseri case study could have to be used to transfer completed modules to site. Constructing off-site or near to the site could allow for better use of resources. Such lifting equipment could negate the need to have such high peaks of workers which were required for tasks such as manual movement and lifting of rail sections. However, the cost of such specialised lifting equipment is expensive to hire or purchase, and depending upon the labour rates for Slovenia, it may be more cost effective to construct with higher use of labour.

However, the use of other manual lifting equipment could also be deployed to help the lifting of rails and track without needing to use the loader. For example, the loader was regularly deployed for lifting the track, to help with alignment and connection of the fish plates, such as manual lifts, which would help to free up the heavily used loader for other tasks.

The greatest improvement however could be in reducing the rework and motion waste. Much of the waste related to the defects and motion could be avoided with improved planning and simple marking of components. For example, the motion of sleepers being unloaded from the engineering train and then moved away from the work site before being brought back and laid in order could be avoided or minimised by grouping sleepers together as they are loaded on the engineering train. With good marking on the sleeper ends the loader driver could deploy the sleepers directly to the correct location. Improved planning and marking of the sleepers, could also avoid the need for sleeper adjustment, removal and replacement of long sleepers and the need to cut the sleeper ends once in situ. Such planning would not have any large financial costs to implement either.

Optimisation for minimum costs

The site was very well organised and with the elimination of waste, as described above, the construction could easily be optimised for minimum costs, with the potential savings of resources, described in the table above.

Optimisation for the minimum installation time

To optimise the installation for minimum time the removal of the identified waste and off site construction should be implemented. Also, if cost was less of a constraint shift working could be considered, or better use of the periods when most of the staff take breaks, (eg. some of the lifting and tamping work to take place during these periods where less staff are on site, improving safety and reducing task time). However, to implement the offsite construction, more expensive lifting equipment would be required which is likely to significantly increase costs.

3. Conclusions

This deliverable has presented reports on lean optimisation of S&C installation. The first case study was on a lesser used line and in the second case study the installation was part of a large remodelling of the layout around a station. In both cases the installation was not constrained by time and there was no issue of penalty payments for delaying vehicles. Therefore, it was obvious that in both of these activities the installation was planned for minimal costs. Also, in Turkey the labour rates are relatively low, so again the use of high numbers of staff, but use low cost generic backhoe loaders makes economic sense. However, in both cases recommendations have been made to reduce waste and make further savings by implementing some simple planning and marking techniques to ensure that task was completed right first time, and eliminate rework.

The lean optimisation also makes recommendations for reducing the time taken to complete the installation as would be applicable on a heavily used passenger line. Primarily the same steps should be adopted to minimise waste, but also with the use of more expensive lifting equipment, which would significantly increase the installation cost, but reduce the possession time required.

The impact of the lean improvements in this report will vary widely for different line types, traffic densities and types and different countries and that a lean optimisation study should be carried out for each situation to identify the most appropriate measures.

It is also expected that wastes could be eliminated from the planning process, these wastes could be as large or if not larger than those identified within this study. It is therefore recommended that the planning process should be studied further in the future and build upon the work carried out in the AUTOMAIN FP7 project for tamping operations. AUTOMAIN identified the complex interfaces and decision loops in the planning process, leading to significant waste, as well as the very long time periods over which the planning took place.

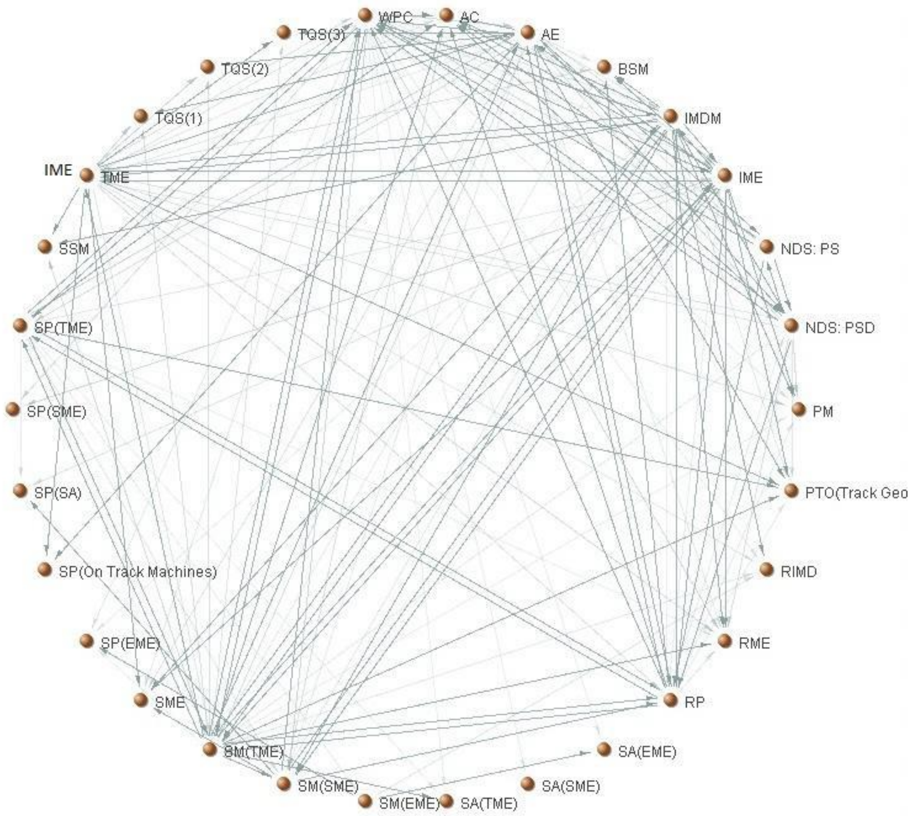


Figure 3.1 – Example social network from the AUTOMAIN project, demonstrating the complex interfaces in planning a tamping operation.

The deliverable also presents the main features related to RAMS aspects and the key considerations to be made. The literature review also details the main failure modes, while considering various factors. Roughly, the optimal switch design and maintenance will depend upon the location of the switch, the line type and environmental conditions, this is also described in deliverable D2.3 which describes some of the different switch technologies.

As well as the line type and environmental conditions, technology decisions for optimum life cycle costs will depend upon where the current switch is in its life cycle. Many of the key switch failure modes depend upon visual inspection to detect, such as lipping to the switch blade or damage to the crossings. Other key maintenance tasks include the lubrication of the switch slide plate.

In the same way, many of the maintenance tasks for S&C relate to visual inspection and regular maintenance activities such as lubrication. It is relatively more efficient to do these tasks, in priority, in locations with high density of switches and therefore the waste of motion (time walking to and between switches is minimal) compared to carrying out the tasks at a remote location. This is especially true as over time local signal boxes have been replaced with centralised control systems and therefore less staff is regularly working in such remote locations.

The table below gives a summary of the aspects referred to above.

Technology	Environment	Location	Line type	Failure types impacted
Inspection train high speed image capture inspection/laser 3D imaging of switch and crossing	All environments	Largest benefits are for remote locations where manual visual inspections are difficult and take a long time access the S&C	Benefits busy lines also as there is less access for manual inspections.	Spalling of stock rail, Lipping, Soft spots in the running surface, Non- compliance of narrowest flange way, Incorrect lateral attachment of switch rail, Broken cast items
Remote condition monitoring of switch motor and interlocking	All environments	Benefits all switch locations, but largest benefits are to remote locations where the overhead of visiting a switch for diagnosing issues is high.	Benefits busy lines also as there is less access for manual inspections. Remote condition monitoring will also lead to preventative maintenance and any failure will have a larger impact on the traffic on busy lines.	Poorly lubricated slide chairs, interlocking failures, switch motor failures.

Technology	Environment	Location	Line type	Failure types impacted
Hardened switch blades and crossings	All environments	All locations	Hardened switch blades and crossings will extend the lift S&C based upon the traffic loads. Therefore, hardened switch blades and crossings will provide the most benefits on the busiest lines with the heaviest traffic.	Spalling of stock rail, Lipping, Soft spots in the running surface, Non- compliance of narrowest flange way, Incorrect lateral attachment of switch rail, Broken cast items
Snow guards	High altitude or other cold climates with high snow fall	Snow guards can provide benefits in all locations. But remote locations are likely to have the highest benefits due to their accessibility.	Switch failures on busy lines will have the largest impact, due to the amount of traffic affected.	Snow and ice blocking switch blade movements
Switch heaters	High altitude or other cold climates with high snow fall	Snow guards can provide benefits in all locations. But remote locations are likely to have the highest benefits due to their accessibility.	Switch failures on busy lines will have the largest impact, due to the amount of traffic affected.	Snow and ice blocking switch blade movements
Automatic slide chair lubricators	All environments	Largest benefits are for remote locations where S&C take long time access and of a low density.	Benefits busy lines also as there is less access required.	Manual lubrication
Lubrication free slide chairs	All environments	Largest benefits are for remote locations where S&C take long time access and of a low density.	Benefits busy lines also as there is less access required.	Manual lubrication

Technology	Environment	Location	Line type	Failure types impacted
Low cost switch vibration condition monitoring as developed in the NeTIRail-INFRA projects	All environments	Benefits all switch locations, but largest benefits are to remote locations where the overhead of visiting a switch for diagnosing issues is high.	Benefits busy lines also as there is less access for manual inspections. Remote condition monitoring will also lead to preventative maintenance and any failure will have a larger impact on the traffic on busy lines.	Spalling of stock rail, Lipping, Soft spots in the running surface,

Table 2.3 - Maintenance operations and monitoring means for S&Cs

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