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D2.1 High Level Architecture Design Document

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PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Revision control / involved partners

The following table gives an overview on elaboration and processed changes to the document:

Revision	Date	Name / Company short name	Changes
1	21/09/2017	UoB/COMSA/L'Boro/DTVS/RRC	First version
2	27/09/2017	UoB	Initial review edits
3	30/09/2017	UoB	Final review edits
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The following project partners have been involved in the elaboration of this document:

Partner No.	Company short name	Involved experts
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Table of contents

List of figures

List of tables

1 Introduction

This document follows on from the work conducted in WP1. As a starting point, the research group investigated the standards and best practices found in current systems in operation. Then, as part of the backcasting method, the partners performed a horizon scanning study to analyse the future trends in the different rail modes. Finally, as shown in section 1.1, researchers collected various concepts from literature and joined them to ideas raised during workshops.

This stage of the project, as illustrated in Figure 1, focuses on establishing overall high-level designs and system architecture principles to be further developed in the subsequent work packages. To do so, we have analysed the concepts collected from literature and identified the necessary technical steps and technological developments to achieve the desired solutions.

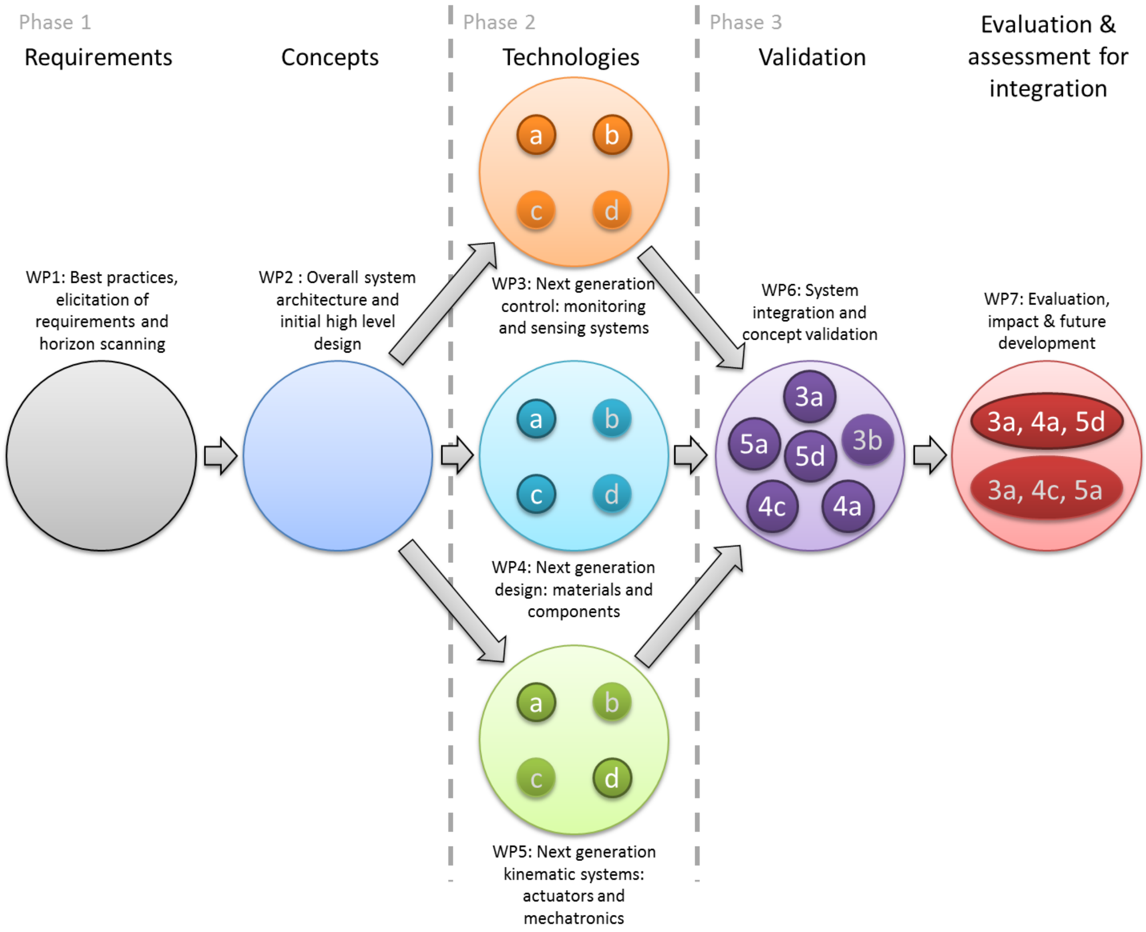
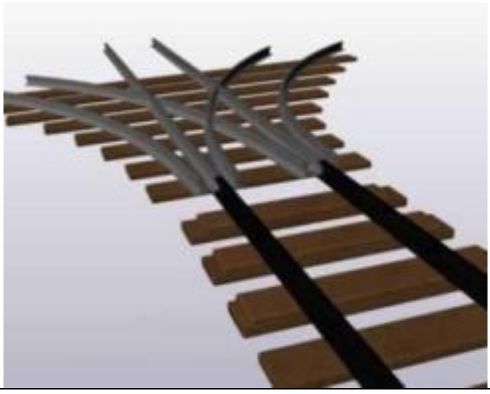


Figure 1. S-CODE work package process

This document is divided into four parts, exploring from general design principles and system architecture to a more in-depth outlook of subsystems and components for S&C concepts. Chapters 2 and 3 focus on the general principles of design and operation of S&C systems and explain the high level concepts of systems architecture. Chapters 4 and 5 will introduce the methodology used for the evaluation and further refinement of concepts, as well as act as quantifiable guidance for the process of identification for the necessary technologies to be investigated. Chapters 6, 7, and 8 will draw from the results of the concept refinement and identify the technological needs and high-level design principles for condition monitoring and sensors. Finally, Chapter 9 will assess high level requirements and parameters for S&C installation to be taken into account when selecting concepts and their respective technologies.

1.1 List of concepts from D1.1

Following the collection of concepts from the literature, from other industrial sectors and from brainstorming sessions during meetings with the S-CODE partners and during the Focus Group with external experts, a selection of concepts was carried out, comprising one or more of the ideas generated. These ideas (concepts) are the ones considered for subsequent evaluation at this stage. They are described by the functionality in the following pages (each concept is on a separate page).

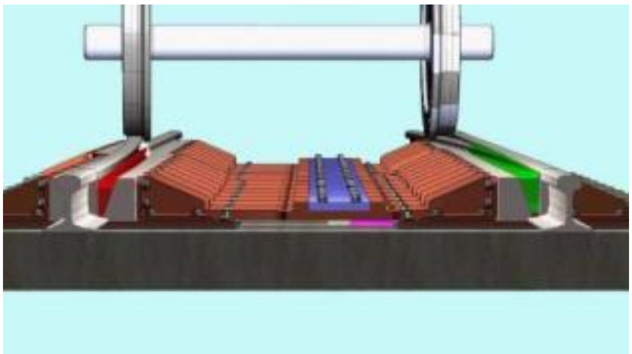
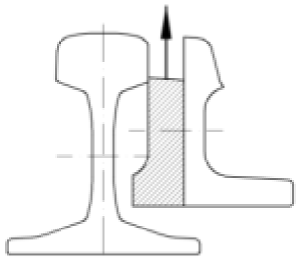
Bending of stock rail	Concept **A**
Description The track is bent to switch between possible routes. Both rails move together.	
Principle of Operation Both stock rails are moved together either by lifting-moving-dropping or by sliding across laterally. The stock rails can either be moved by a small amount as shown in the photo below from the REPOINT project or bent fully to meet a new track (Dolderbahn). Appropriate rollers can be used to lower the friction during lateral movement.	
Example(s)	
REPOINT 	Dolderbahn 

Vertical movement of track parts/inserts	Concept **B**

Description
Components move vertically to change track direction or eliminate discontinuities on the tracks

Principle of Operation
A segment (or insert) is lifted upwards or dropped in the gap to create or fill the gap. This mechanism can be used in switches and crossings, both alike.

Example(s)

Winterproof railway turnout	Illustration
	

Moving the switch section laterally	Concept **C**

Description

The whole switch section is moved laterally. Both rails move together.

Principle of Operation

Unlike concept A, a pre-set section is created to match the profile of the possible routes. This whole section is moved laterally along with the sleepers.

Example(s)

Washington Cog Railway	Pilatus Railways
	

Rotating the switch section	Concept **D**

Description

The whole switch section rotates around a horizontal axle to switch between different directions.

Principle of Operation

A pre-set section is created to match the profile of the possible routes. This whole section is rotated around an axis (in-line with the primary path).

Example(s)

Pilatus railways

Flange bearing frogs	Concept **E**

Description

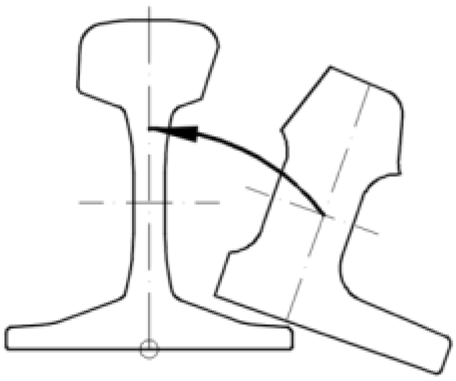
Frogs without discontinuity on which the flanges support the train.

Principle of Operation

Rather than having large vertical gap in the crossing, it can be filled partially to allow the train to ride on the flanges of the wheel on the corresponding side of the wheel.

Example(s)

Liberec tram, CZ	Voestalpine Nortrak
	

Rotation of tongue about the longitudinal axis	Concept **F**
Description Tongue rotates instead of moving horizontally.	
Principle of Operation Rather than moving the tongue (or switch blade) rail laterally, it can be rotated around a longitudinal axis (in-line with the ground), to create or remove the gap. This can be applicable to both, the switch and crossing.	
Example(s)	
Illustration 	

Actuated nose for crossings	Concept **G**

Description

The nose of the frog is also actuated to eliminate track discontinuity.

Principle of Operation

The nose (frog) can be a movable component which can be actuated to move closer to the wing rail to remove the gap. The movement can be lateral, rotational or any other.

Example(s)

Swingnose at Bonn Hauptbanhof	Voestalpine moveable frog
	

# Moving wing rail	Concept **H**

Description

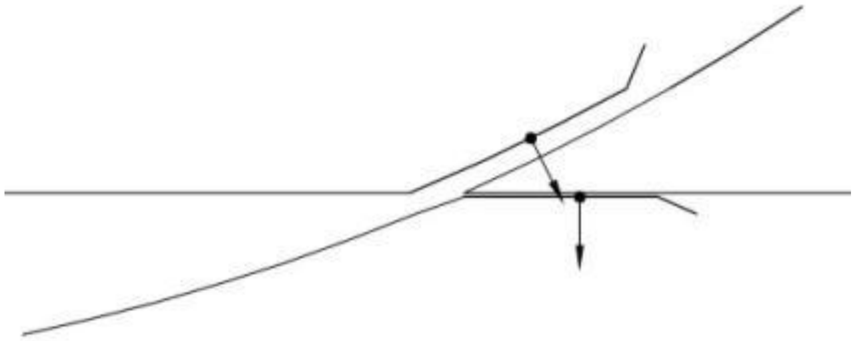
The wing rails move to fill the discontinuity in the crossing.

Principle of Operation

The wing rails can be movable components which can be actuated to bring closer to the nose to remove/fill the gap. The movement can be lateral or rotated or any other.

Example(s)

Illustration



Guiding the trains from the tracks

Concept **I**

Description

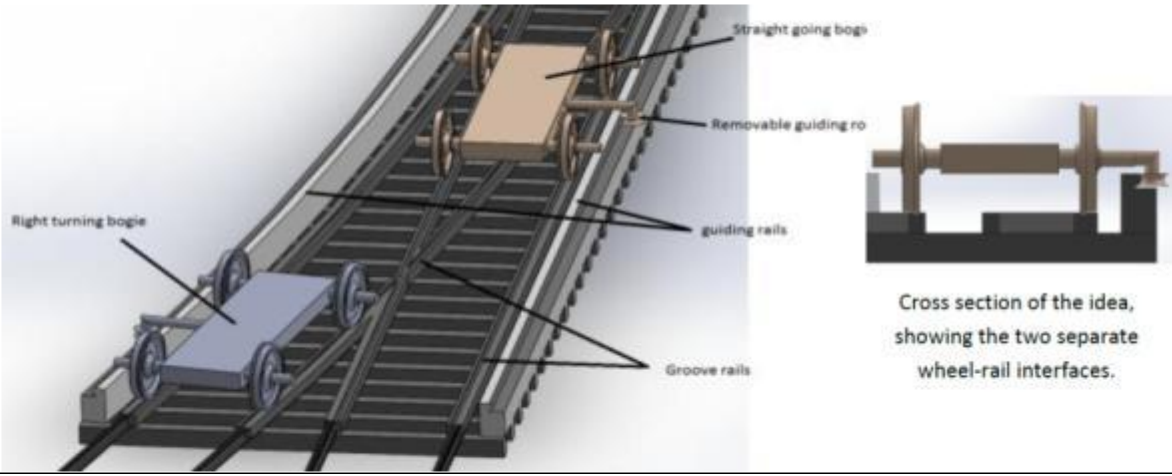
Additional track parts support the train while guiding the wheels to the desired direction.

Principle of Operation

The train can be guided using the track and components from the bogies which can be retractable. The guiding rail can be on the side of the track or in the middle of the track. It may be possible to use the mechanisms that Funiculars use to steer/direct the carriage towards its desired path.

Example(s)

Passive infrastructure with guiding rail



Cairngorn Funicular

Sliding panels for crossings

Concept **J**

Description

Panels move to fill the flangeway gaps with inserts

Principle of Operation The crossing part can have a pre-set route on a sliding panels which can be slid appropriately to create the desired route.
Example(s)

Illustration	
	

Rotation of stock rail or part of it	Concept **K**

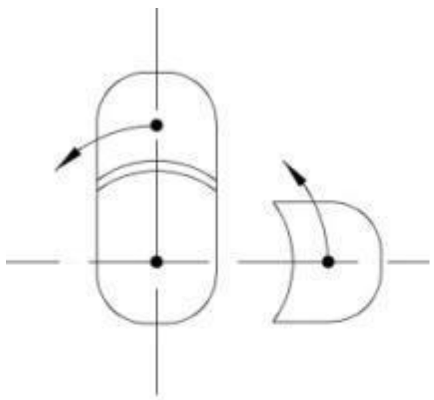
Description

The stock rail rotates around its longitudinal axis, independently from the other stock rail

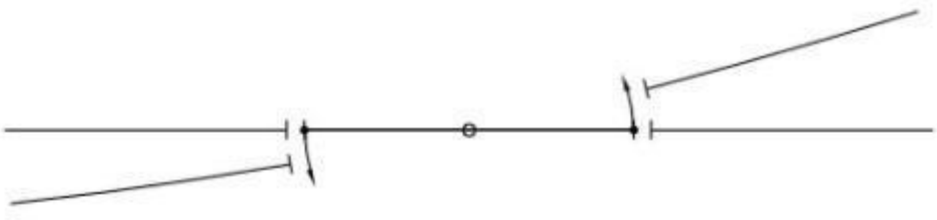
Principle of Operation

The figure below shows cross-section of the cross rail. A component can be brought on top of the fixed stock rail to create a different route.

Example(s)

Illustration	
	

Pivotable rail for crossings	Concept **L**
Description Substitution of the crossing with a pivotable rail.	
Principle of Operation A section of the rail can be placed into the crossing. This rail can be rotated around an axis that is in perpendicular direction to the ground as shown in the figure below (Top view).	
Example(s)	
Illustration	

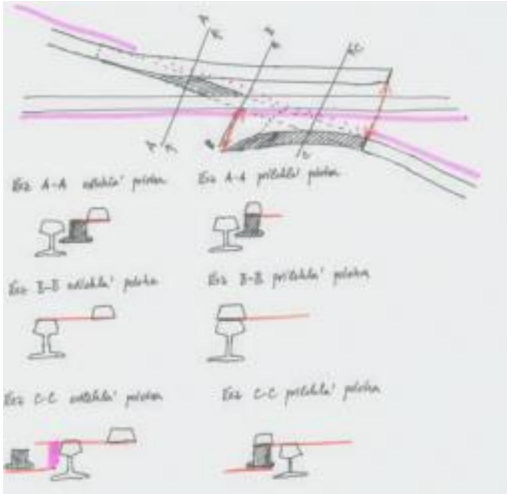


Overrunning of crossings	Concept **M**

Description
Crossing rails in two different levels, creating a 'bridge' instead of a flangeway gap.

Principle of Operation
A section of rail can be brought on top of another rail to create a different route as shown in the photograph and drawing below.

Example(s)

DT	Illustration
	

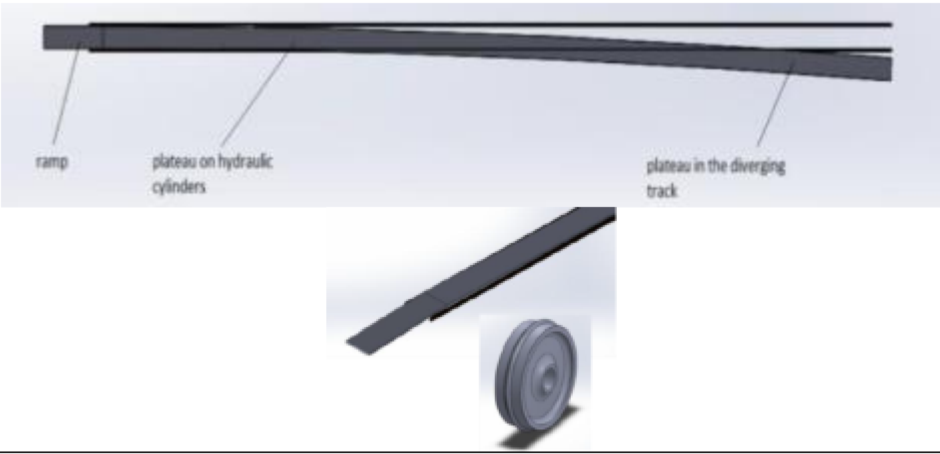
# Diverging bridge	Concept **N**

Description
Diverging bridge to divert the train from one rail route to another.

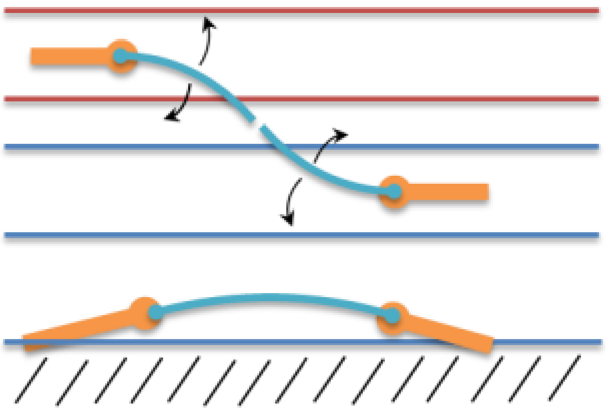
Principle of Operation
Diverging tracks are connected by a 'bridge' that guarantees the track continuity. The first example proposes changes in wheel flanges, while the second a guidance from inside the tracks. The bridge itself needs to be actuated so that they merge together allowing the train to hop from one track to another.

Example(s)

Illustration



Illustration



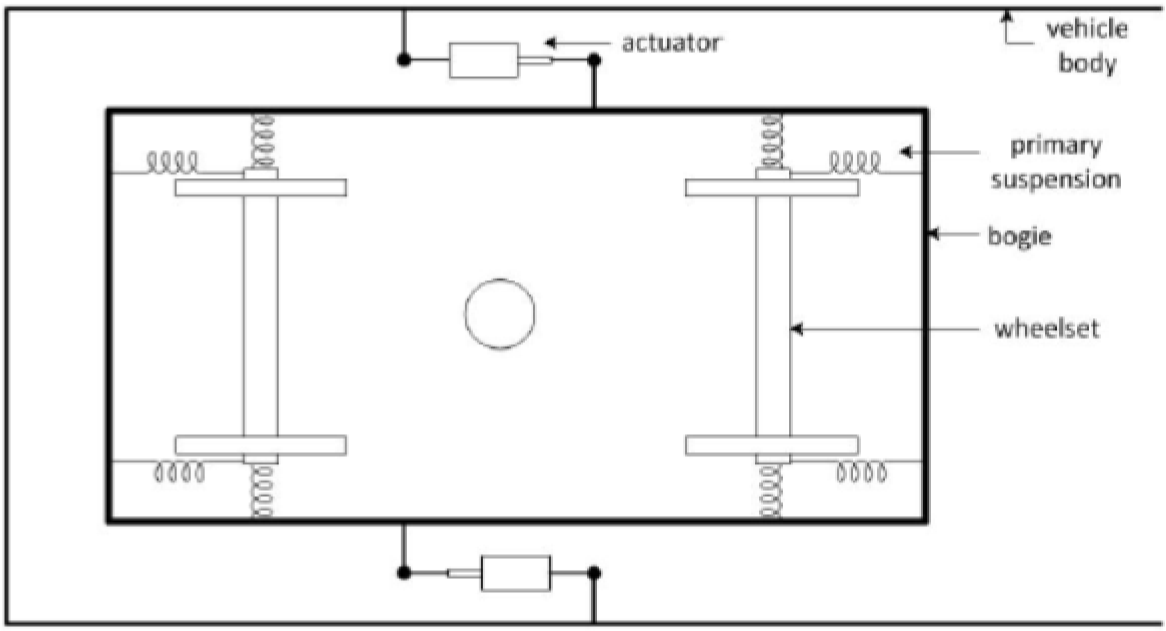
Active steering	Concept **O**

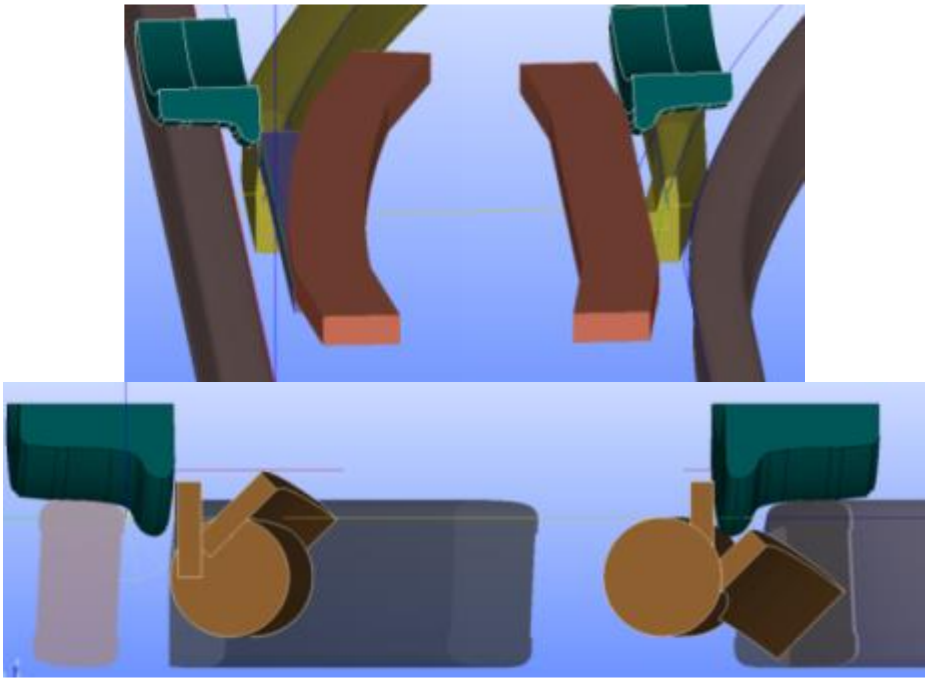
Description
Bogies are actuated in order to steer in one of the directions. In a later stage, track equipment is no longer necessary.

Principle of Operation
The bogie can be actively steered to choose the desired path from pre-set passively laid out paths.

Example(s)

Illustration



Flange-back steering	Concept **P**
Description Equipment on tracks guide the back of the flange instead of guiding the front.	
Principle of Operation A component in the switch that can be brought about to guide the wheels from the back of the flange.	
Example(s)	
Illustration 	

Single-flange steering

Concept
Q

Description

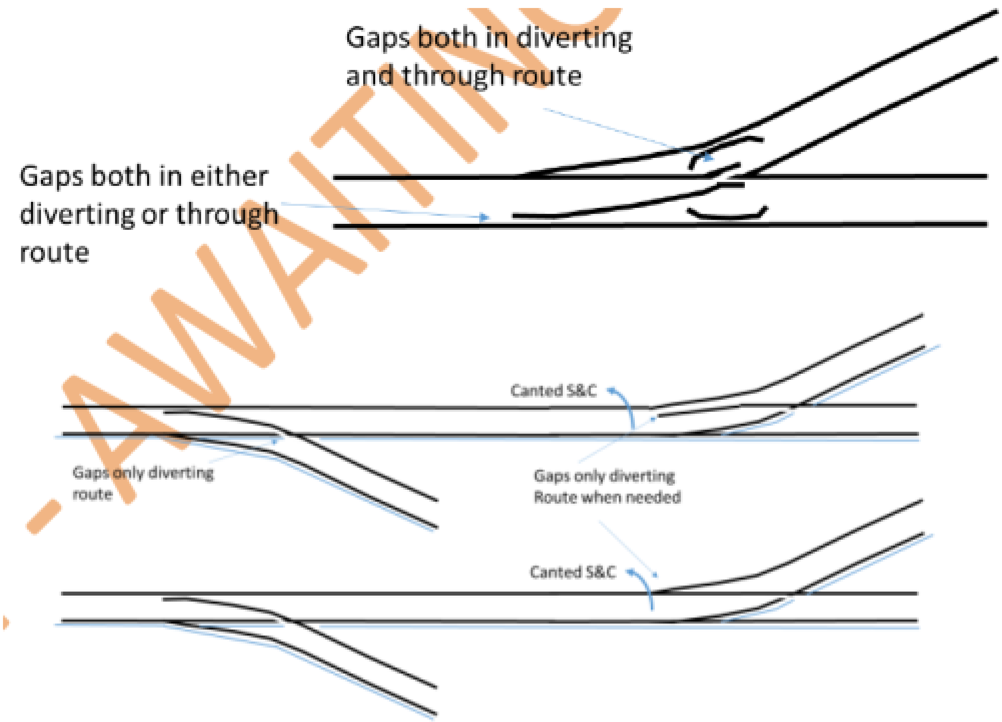
Guiding the train using flanges on wheels on one side of the bogie but opposite wheel flange to be removed.

Principle of Operation

By removing the flange from one side of the vehicle there is no longer a requirement for both switch and crossing gaps on the opposite rail; the 'flat' wheel can be directed in either direction. All of the guidance is carried out by the remaining flanged wheel and correct cant for the diverging route.

Example(s)

Illustration

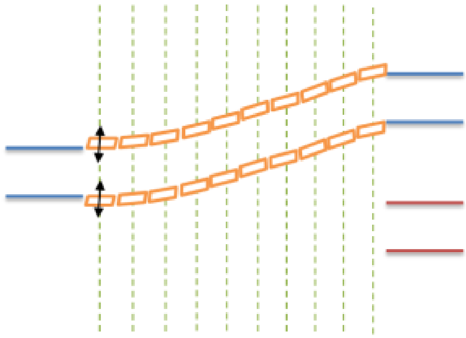


# Multiple section switch	Concept **R**

Description
Switch tracks are composed of multiple small parts that arrange together to design one of the possible directions.

Principle of Operation
The track can be composed of independently movable segments. These can have their own actuators and supervisory controller unit to check their relative positions and align themselves in a continuous path.

Example(s)

Osaka Monorail	Illustration
	

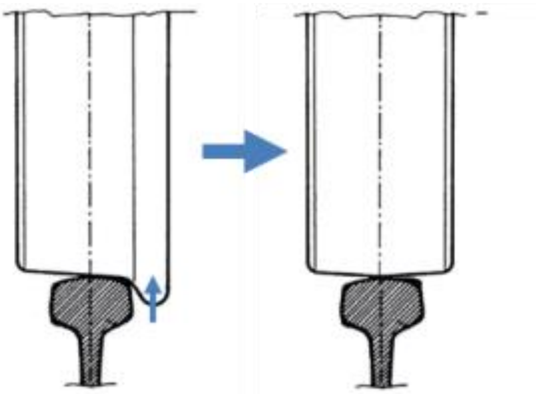
Dynamic flanges	Concept **S**

Description
Retractable ‘active’ wheel flange to move freely to one of the directions on tracks.

Principle of Operation
The flange of the wheel can be retracted to miss the part of the switch and crossing that is adjacent to the stock rail and extended afterwards. This can be done on one side of the wheel while the other side of the wheel can be used to guide the bogie.

Example(s)

Illustration



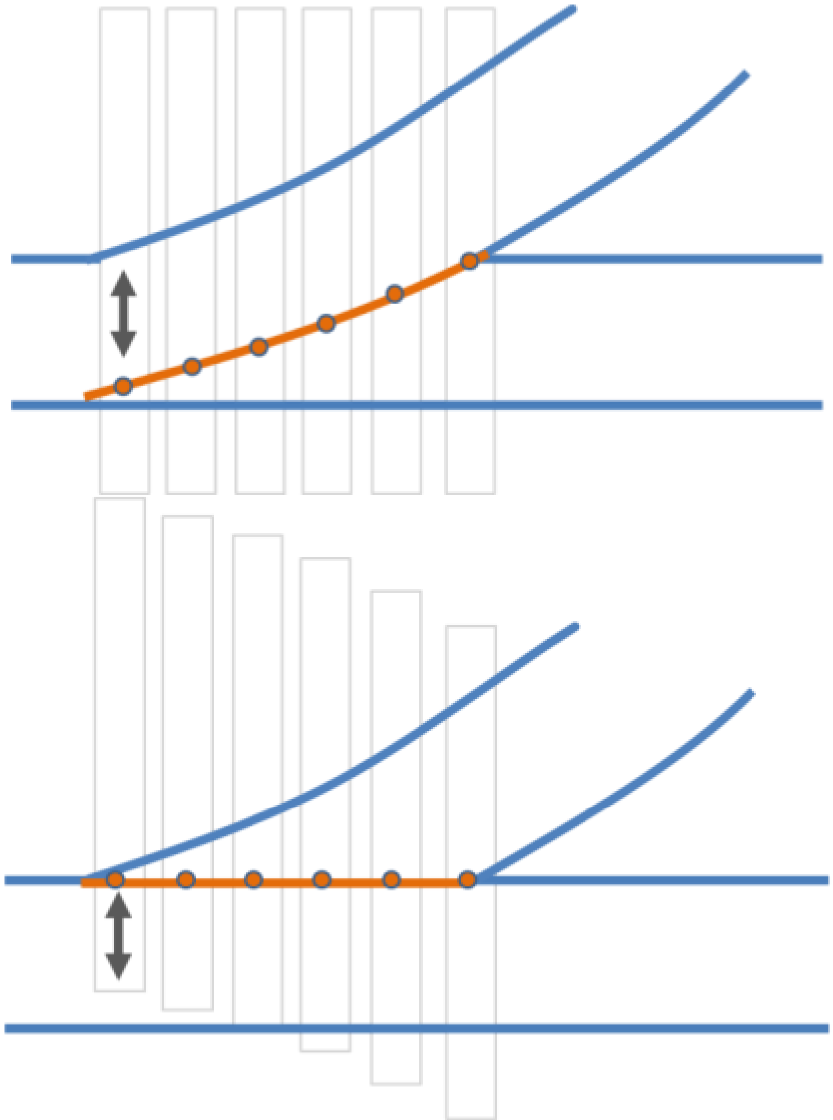
Single switch rail	Concept **T**

Description
Using a single section of switch rail to guide the bogie to the appropriate path.

Principle of Operation
A single section of the switch rail can be moved from one rail to the other, to create appropriate routes as shown in the figure below.

Example(s)

Illustration



Filling the gaps between tracks

Concept

U

Description

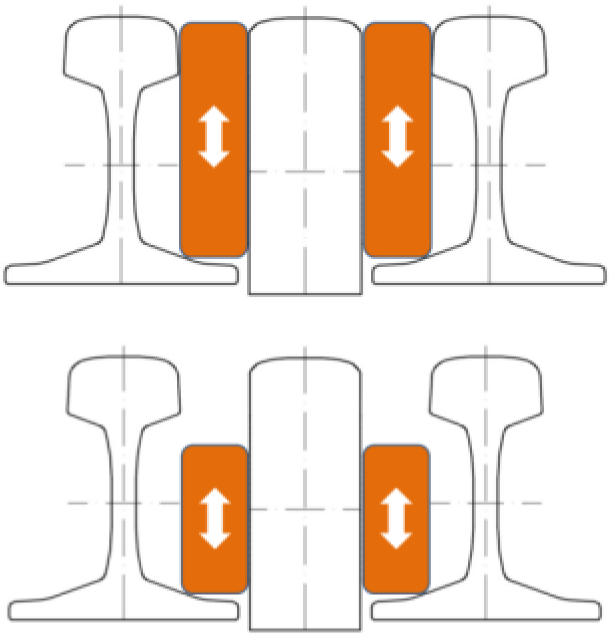
Dynamically filling the gaps using deformable materials.

Principle of Operation

The gap in the crossings can be filled in using inflatable materials or "Dilatant" materials such as "D2O". This can be done dynamically to create or remove the gap. Similar principle may also be applicable to the switching of the railways.

Example(s)

Illustration



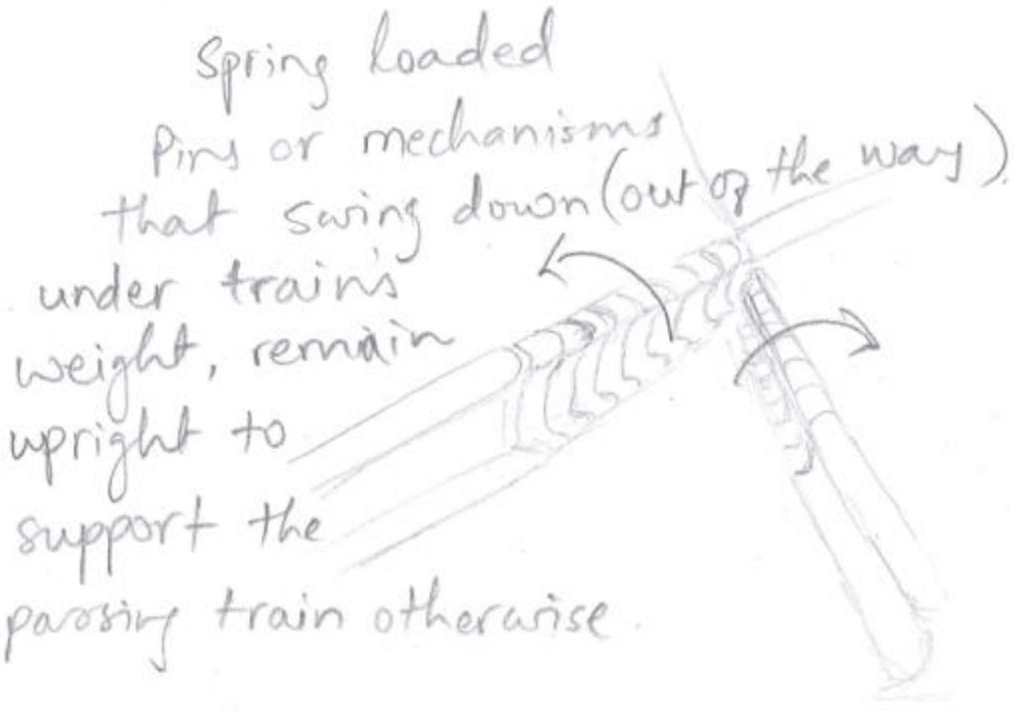
# Spring loaded pins	Concept **V**

Description
Spring loaded pins or mechanisms that swing down (out of the way) in one direction tracks under the train's weight, and remain upright to support the train on the other direction

Principle of Operation
Inside the crossings, the gap can be filled in using smaller segments of rail or pin-like structures that can be moved passively upon a passing train such that the segments move downwards or bend back to give way to train in the traversing direction. These segments should support the train's weight that is traversing in any other direction than the pin's natural movements.

Example(s)

Illustration



2 Design principles and system architecture

2.1 Introduction

The new design concepts for S&C will have to take into account aspects related to installation, renewal and maintenance. The designs should also address the causes of failure of most present types of S&C, which are related to:

- Moving parts.

- High loading at fairly small cross-sections, e.g. in switch-blades.

- Impact loads due to traversals of gaps.

- Complicated geometry that gives rise to high contact pressures due to contact point transitions, contact close to free edges, etc.

- Stiffness of S&C greater than that of open track.

- High frictional loads and creep due to sharp curving in diverting mode.

- Close interaction of S&C with the signalling system.

Based on the features of the machinery which is usually employed to install and renew S&C, it is recommended that certain limits on weight and measurements are respected for the different elements and modules of S&C.

In a railway network, the S&C are the devices that allow the railway vehicle to leave one route and to take another one (facing move) or, in the opposite sense (trailing move), to incorporate from one route to another. It is the function of switches and crossings to allow these movements in current designs of turnouts. To do this, the switches introduce "longitudinal" joints in the rolling surface, as a result of the coupling of their head with that of the stock rail. The crossings introduce gaps (diamond gap) in the rolling surface, which is partially resolved by the wing rails that offer some support to the wheels when their flange crosses the diamond gap [1].

High speed crossings are a variant of conventional line crossings for high speed, which have a movable frog point, moving as appropriate to the through or diverging route, thereby eliminating the gap and offering a complete rolling surface to the wheel. In this case, the behaviour of the crossing resembles that of a "short" switch, engaging the corresponding rail along a longitudinal joint.

There is also another variant of crossing for low speed running, which resolves the support of the wheel as it passes through the diamond gap by rolling with the wheel flange over the (raised) bottom of the gap itself.

In the past, S&C designs were conditioned by the limitations of manual operation of the moving parts. Hence the movements were horizontal, or sideways. For the train speeds of the first half of the twentieth century, track with (transverse) joints between rails was acceptable.

Technological advancements in mechatronics enables the development of new and radical S&C designs. However, welded track is an essential component for the safety and comfort of traffic, and rail joints are a critical point to be solved in these new designs. Couplings through transverse joints can imply points that are very sensitive to thermal variations, as well as being generators of impact forces to wheel sets and bogies, with consequent maintenance costs.

The design of moving parts is critical for maintaining and monitoring the closure gaps.

2.2 Innovative designs minimizing S&C loads and material deterioration

One of the main goals for new S&C designs should be reducing material deterioration (wear, plastic deformation, rolling contact fatigue), including the prediction of rail wear deterioration (rail wear margin). It has been proved that track and rail degradation can be reduced by optimization of geometry and stiffness properties of the turnout, leading to reduced life cycle costs [2].

2.2.1 Switch panel

The solutions for reducing loads and rail profile degradation in the switch panel include suitable selection of rail profile and rail inclination, rail grade and application of friction management.

A design with inclined rails (e.g. 1:20, 1:30, 1:40) are generally considered to be better to designs with completely vertical rails. Furthermore, the selection of an appropriate rail grade may lead to a reduction in wear.

In a facing move, the maximum rolling contact fatigue damage occurs on the switch rail after the full wheel transition from the stock rail. In a trailing move, the damage occurs on the stock rail after the full wheel transition from the switch rail [3].

The ongoing work on solutions will have to focus on prescribed track gauge variation in the switch panel, accounting for traffic in facing and trailing moves in both through and diverging routes.

2.2.2 Crossing panel

Crossing panels also suffer from discontinuity in both support and kinematic guidance of the vehicle’s axles, leading to a large range of damage from rail materials, cast crossing structural fatigue, ballast support deterioration (voids) and fatigue of components (pads and bearers).

Whilst traversing a crossing the wheelset experiences rapid changes in contact conditions. The point of contact on the wheel running on the crossing is moving outwards as the wheel passes the throat of the crossing and the wing rail diverges at the crossing angle. The wheel therefore rolls onto a decreasing rolling radius and its centre of gravity moves down, until a second point of contact appears between the root of the wheel flange and the crossing nose; this is what is called the load transfer (from wing to nose and vice versa in facing and trailing moves respectively). This sudden upward motion of the wheel on the nose is directly related to the magnitude of the vertical dynamic impact force induced by this load transfer. The same behaviour occurs in the reverse direction of movement. The dynamic impact force contains a very high frequency peak value (P1) and a medium frequency oscillatory response (P2). The P1 force, due to the high magnitude of stress generated, may arguably be a key driver for damage within the rail material. The P2 force is associated with the movement of the wheel mass coupled with the rail against the sleeper and its support.

It therefore leads to damage of the support in crossing panels, and it is especially linked to ballast deterioration.

In addition to the vertical dynamic impact load, the rolling radius difference generated between left and right wheels induces sudden lateral dynamic forces also impacting on rail damage as well as support and lateral geometry degradations. The magnitude of the wheel force, although lower than the vertical impact, can typically be in the order of 20 to 30 kN. Spalling on crossing noses, and plastic deformation or localized crushing on wing rails, are examples of damage related to the P1 force. Voided sleeper or fatigue of cast crossings are examples of damage related to the P2 force. These can occur some distance away from the load transfer area due to the longer wavelength of the P2 force.

The geometry of the wing rail significantly influences the magnitude of the dynamic forces that occur when the wheel load is transferred from wing rail to the nose, or vice versa. It should be stated that cant deficiency improves bogie steering due to the increase in lateral forces with a consequent reduction in relative centrifugal force. The researches [4] on two different wing rail geometries (half and full cant) show that the full cant leads to lower vertical movement of the wheel and therefore lower vertical peak forces. This has implications on the damage made to support elements and ballast, as well as potentially to casting fatigue. On the other hand, half cant appears to be less affected than full cant by both rolling contact fatigue and wear.

Crossing panels for high speed lines have shallower crossing angles and movable crossings to make damage more controllable. Thus, in medium speed lines with mixed traffic, with no movable crossing and wider angles, the damage is higher. Worn wheel profiles also lead to very different dynamic behaviour and damage and, therefore, need to be considered in the design and optimization of a crossing. Key areas to optimize crossing geometry are the nose shape and its topping angle: how fast it rises, as well as the wing rail slope and its height with respect to the nose.
Track support stiffness is a key driver for the P2 impact force. The overall resilient stiffness of the crossing panel governs the load spreading capabilities along the panel and therefore the peak load in the load transfer area. The quality of the ballast support underneath sleepers, mass/bending properties of the long bearers, their connection with the rest of the panel, the rail pad stiffness used between the cast crossing and the sleepers, the bending properties of the cast crossing and mass are all governing parameters in terms of track stiffness reaction and damage level.

Results show that reducing the track stiffness from 500 to 85 kN/mm leads to significantly lower normal contact forces [4]. This reduction increases further with increasing speed.

At the same time, the maximum reductions in terms of ballast pressure, rolling contact fatigue and forces in the rail-pads are obtained by using soft pads (50-150 kN/mm), and the maximum reductions in terms of rail stresses (both on the foot and in the head) are obtained by using stiff pads (520-700 kN/mm). Considering medium quality support (150 MN/m^3), the optimized solution for a crossing panel corresponds to a soft pad (100 kN/mm).

The use of under sleeper pads (USPs) can lead to reasonably continuous track stiffness all along the crossing panel, counterbalancing the effect of increased rail inertia. This fact may be beneficial to drastically reduce the formation of voids in the sleeper-ballast interface and, consequently, the differential settlement.

Using USPs it is possible to achieve decreases in ballast pressure, thus acting as a protection layer. Nevertheless, there is a critical increase of stresses at the rail foot, which can cause transversal cracks in the casting, drastically reducing the Life Cycle. Therefore, it is necessary to critically analyse the choice of using USPs in relation to each case considered and particularly the available ballast quality and stiffness.

In order to achieve even better results, it is necessary to go in the direction of a uniform support as in a ballastless track system. A solution consists in linking longitudinally the sleepers below the load transfer area in order to achieve a more continuously supported track system [5]. Potential benefits may include reduction of sleeper vertical and lateral accelerations as well as forces transmitted to the ballast layer with potential reductions in differential settlement. Another beneficial effect may be a reduction in sleeper roll limiting uneven loading between the left and right side on turnout with wide bearers.

A significant proportion of S&C for railway systems are currently manufactured from cast austenitic-manganese steel (AMS). AMS has traditionally been used owing to its good resistance to abrasion, high work hardening capacity on impact and excellent toughness following solution treatment and water quenching. However, there are a number of drawbacks with the use of AMS, which has prompted S&C suppliers to explore the use of alternative materials. AMS relies on work hardening to achieve optimum resistance to wear. The time taken to reach optimum hardness depends on axle load and for light rail applications the time to reach optimum hardness is inevitably considerably longer than that for heavy axle load applications. An alternative solution consists in pre-hardening the frog through explosion (Explosive Depth Hardened -EDH-); however, this solution means extra costs.

AMS is not an easy material to cast or machine into the complex shapes needed for switches and crossings. The narrow freezing range of AMS results in many cavity type defects. Casting defects are common and are often the starting point of cracking seen in service. The presence of sub-surface casting cavities also increases the difficulty of weld restoration. Thus, the presence of such cavities restricts the permissible magnitude of vertical wear.

A further problem with AMS is the thermal instability of the austenitic structure, which renders it difficult to weld repairs in track should material break-outs occur. Another major disadvantage of AMS crossings is that they cannot be inspected by ultrasonic or eddy current techniques [6].

The direct weld connection between manganese steel crossings and carbon steel rails cannot be carried out with the usual welding processes (e.g. thermal welding, shielded manual arc welding, etc.) nor directly with processes such as flash-butt welding. This is due to the metallurgical incompatibility of the two steels. The crossing to rail connection is made possible by using a stainless steel insert that is flash-butt welded, first to the frog and then to the carbon-steel rail. However, this process of double welding, if not carried out correctly, can lead to failures in track or can lead to a 'soft-spot' around the adaptor casting being created.

As an answer to the defects identified, Vossloh Cogifer has developed special bainitic steel that provides a higher surface hardness and limits the initiation of such defects.

The new material and its implementation is different from existing steel grades and will offer significant benefits over traditional cast manganese crossings in terms of improved internal quality and the resulting extension of component life at the same time as reduced maintenance cost.

2.2.3 Long-term design solutions

The next generation of radical S&C designs will have to be based on new methodologies of switching trains between tracks in a manner that improves capacity, performance and reduces costs whilst maintaining safety.

Thus, the next generation of S&C design will have to incorporate:

- optimised wheel-rail interface;
- new mechanisms for switching a train;
- novel kinematic elements;
- significantly reduced electrical failure modes;
- intelligent self-diagnostic, self-adjusting and self-correcting systems;
- guaranteed correct support conditions.

2.3 S&C resilience to extreme weather conditions

A cold climate produces rail breakage due to low temperatures and, in switches, problems with moving the switch blade due to snow and ice.

Heating by electrical or gas systems is generally the implemented solution. The energy flow is higher with gas solutions and therefore such systems can remove large amounts of snow more quickly. Heating with an electrical heater is more reliable and does not require as much maintenance. The heating elements are placed on the inside foot of the stock rail and on the foot or in the web of the switch rail. Most of the heat from a heating element is radiated out in the air. The solution can guarantee removal up to 20 cm of snow per hour. The life of a heating element is about 10 years.

New solutions can make the heating system more efficient, more reliable and able to cope with more snow than older systems. One solution is based on heating cables which are restricted in power output (to about 150 W/m per cable). The energy to heat up the rail is not radiated to the air and most of the power is used to heat up the rail. The cables are protected by an insulating cover which reduces the heat loss to the air.

Other new solutions are based on heating plates that can heat up the air between the switch rail and stock rail by using from 100 W up to 900 W per sleeper gap. This power is enough to heat more than 80 cm snow/hour. The most challenging problem is how to control the system. As the power output is so high it is important to limit the use to situations when there is heavy snow fall or drifting snow and high winds. In certain countries, other systems are used: warm air or water, spraying anti-freeze liquid and geothermal heat pumps.

An extreme warm climate also causes problems. These are associated with track buckling and deterioration of track geometry. Temperature extremes and temperature variability are the most frequently seen weather-related causes of derailments. On

railway switches, the point machine protects itself due to deformation/temperature sensors and the signal turns to red.
Rail vehicles may derail when extreme heat causes a switch to open up. High stresses increase the risk of buckling due to solar heating close to the S&C, but also give longitudinal and lateral displacements within the switch panel. These displacements cause failures due to "S&C not in control".
The turnout section becomes a fixed point in the track where all forces join, creating a particular stress condition which is potentially unstable. S&C with timber bearers are at the greatest risk, because these S&C are lighter than those with concrete bearers, but the stresses which produce displacements are the same.
Beyond visual inspections, the measures to mitigate those risks are lubricating moveable parts where possible and painting the points with a reflective paint (see Capacity4Rail project).
Painting critically operative switches and diamond cross switches with heat-reflecting white paint, to absorb less heat, reduces rail temperatures and, therefore, risks. A painted rail will be five to ten degrees cooler than an unpainted rail.

2.4 Optimized S&C sensor strategies to minimize traffic disruptions

The point machine always controls the position of the S&C. During the movement of the switch rail, time for movement, force, motor current, hydraulic pressure and/or the distance can be measured. The Roadmaster from Voestalpine [4] is a system that includes both point machine measurements and track measurements in the S&C.

In digitalised interlocking systems, current, voltage and energy can be measured and time variant control signals can be registered. Even in relay based interlocking systems, it is possible to record the occurrence and time of different events.

To be able to perform an analysis for S&C, it is necessary to identify the different panels of the S&C and use different parameters for each panel. The geometry at the crossing and the point machine are not normally within the tolerances of newly laid track (+/- 2 mm) and should therefore be identified and monitored separately, while the rest of the S&C can be treated as normal track. For the diverging route, a special analysis of gauge, side wear and alignment also can be made. In the analysis, prediction models for each parameter are needed and these models need the input of traffic volume in straight and diverging routes.

2.5 Weight and measurements for the different elements and modules of S&C

Based on the features of the machinery which is usually employed to install and renew S&C, it is recommended that certain limits on weight and measurements are respected for the different elements and modules of S&C. The construction works to install or renew a turnout in railway lines usually use one of the following three systems: mobile railway cranes, caterpillar beam-gantries, or a set of gantries with motor bogies, as represented in the following figures.

Figure 2. Mobile railway crane

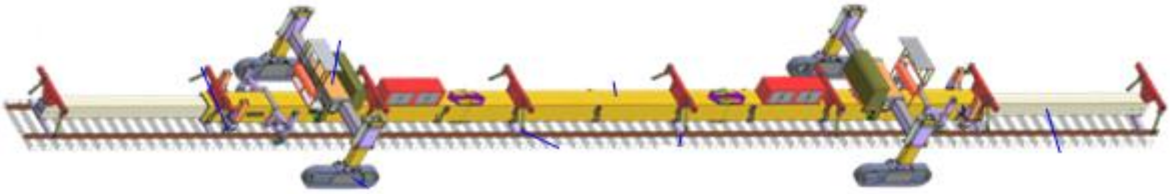


Figure 3. Caterpillar beam-gantries

Figure 4. Set of gantries with motor bogies

When manipulating the different panels of a turnout, their weight is decisive, as is the maximum allowable bending deformation. Therefore, it is important to have machinery to suspend the panel at as many points as necessary to avoid maximum deformations. Table 1 shows the length and weight of each panel and the required distance between suspension points (during their handling) for two types of high speed turnout in Spain, according to the maximum permissible deformation considered.

Table 1. Maximum distance between suspension points in Spain

TURNOUT (tangent)	PANEL	LENGTH (m)	WEIGHT (kp/m)	MAX. BENDING DEFORMATION		
				3 cm	6 cm	10 cm
0.02	Switch	63	1.013	10,991	13,070	14,851
	Closure	62	1.407	12,040	14,318	16,268
	Crossing	49	1.609	11,643	13,845	15,731
0.03125	Switch	54,6	1.006	11,010	13,093	14,876
	Closure	54	1.331	12,208	14,518	16,495
	Crossing	21,3	1.724	11,443	13,608	15,462

In view of these requirements, the performance of different types of machinery is available, as shown in Table 2 and in Figure 5.

Table 2. Performance of different types of machinery in Spain

Machinery	Components	Length (m)	Load (t)
TLPS-6500 de VAIA CAR	2 Caterpillar Gantries + 1 Beam	56,5	62
TL-70 de DESEC	2 Caterpillar Gantries + 1 Beam	38,3	40
GEISMAR-FASSETTA	8 Gantries + 8 motor Bogies	63,0	78

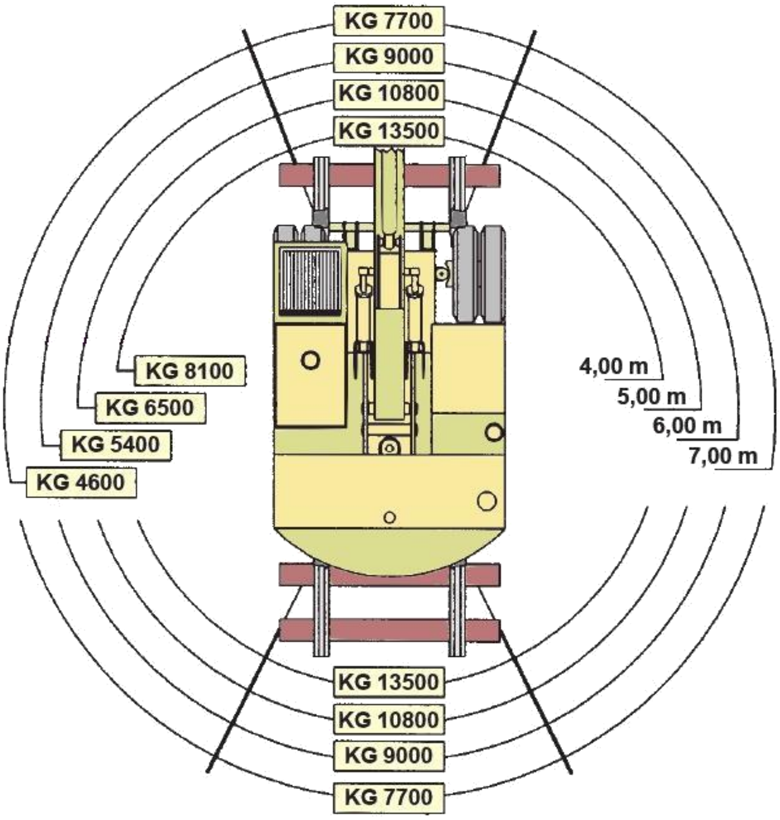


Figure 5. Performance of different types of machinery in Spain

Suitable machinery has to be chosen depending on necessities, which may include coupling several identical machines if the panel weight or length requires it.
As an example,
Table 3 shows the equipment used to install some high-speed turnouts in Spain.

Table 3. Equipment used to install some high-speed turnout in Spain

PANEL (tan 0,02)	Quantity of gantries	Length (m)	
		between gantries	cantilever
Switch	**8**	8,2	2,7
Closure	**7**	9,4	2,7
Crossing	**6**	8,7	2,7

In view of this, the new S&C designs should take into account suitable modularity so that the requirements derived from the weights and dimensions of the different panels can be manipulated as much as possible by the machinery available today.

3 High level system architecture

3.1 High level system architecture requirements

Work conducted at Loughborough University by Bemment et al. [7] has drawn on industry Standards and requirements to derive a list of top level requirements for track switch systems. This splits the requirements into 4 broad categories:

1. Support vehicles and guide vehicles;

2. Direct vehicles along the route set by the interlocking;

3. Confirm the route to the interlocking;

4. Communicate back to a maintenance organisation the future ability to perform requirements 1, 2 and 3.

Existing designs adequately provide for requirement categories 1, 2 and 3. More detailed requirements for these categories should be available from infrastructure owners and managers. Category 4 has some overlap with the requirement for self-inspecting, correcting and adjusting S&C.

Current S&C require significant inspection and adjustment intervention. In order to automate this process self-inspecting, correcting and adjusting S&C would, in the first instance, require instrumentation, and then the necessary actuation to make adjustments where necessary [8].

To this end, the S&C systems must be constructed from multiple capture and use points.

Capture Points are collocated with the monitored parameter, which, depending on the sensor type, could be physically on the S&C asset. These locations are geographically dispersed and often hostile. Sensors require accompanying hardware to sample, process, package, and transmit the data. This, to some extent, must be physically attached to the sensor.
Use Points are located where the captured data is integrated into another system or process. This could be human orientated at a data presentation terminal, or automatic by integrating into a computational model or control loop. These locations could be anywhere across a rail network, company or wider industry.

The systems must be capable of performing the following functions [9]:

- Interface to numerous sensors distributed across the S&C asset;
- Interface to numerous types of sensor depending on the monitored parameter;
- Carry out different levels of signal processing depending on sensor type;
- Transmit different types of data depending on sensor type;
- Provide data to different stakeholders depending on purpose;
- Provide data at different frequencies depending on purpose;
- Generate trusted information for trusted decisions depending on purpose;
- Be scalable across different types of S&C across different networks.

Regarding scalability, it should be noted that the criticality of a S&C asset should be determined by both the level of traffic that crosses it, including speed, weight and quantity, as well as the number of operation cycles it undergoes. Those situated on high traffic mainlines may experience the most loading and potential for damage and wear, whereas those positioned close to multi-platform stations and junctions may experience higher operation cycles and are therefore prone to other failure modes; both of these installations are considered high criticality. There are then also low criticality assets, such as those which are infrequently crossed or operated. The impact asset failures have on the network differs vastly based on criticality. Failures on high

criticality assets may quickly affect the entire network, whereas lower criticality may not affect the service at all.
It is therefore logical for the system to be able to scale to suit different S&C installations. High criticality assets may justify much more expensive monitoring equipment as the potential benefit of avoiding failure is far greater.

3.2 Horizontal system architecture

The above requirements call for a highly flexible, scalable system, enabling multiple capture points to be connected with relevant use points. This can be achieved with a horizontal, open interface, system architecture.

3.2.1 Local networks

Capture points in close proximity, on the same or adjacent assets for instance, can be integrated into a local system, reducing the number of connections required to the horizontal bus. This also facilitates the addition of further compliant sensors for larger or more complex assets.

3.2.2 Wireless communications

Wired connections between sensors, their associated hardware and the rest of the system present numerous challenges in terms of robustness, scalability, cost, range and maintenance. Wireless communication technologies can overcome these challenges whilst adding two more; power supply and connection reliability.

Power supply problems may limit the number and type of sensor which can be deployed; fibre optic systems and those with a high sample frequency, for example, have a higher energy demand. Some improved battery technologies combined with power management strategies can offer many years life for low power applications. Many energy harvesting technologies are available including solar, wind, radio wave and kinetic. Solar and wind approaches are not guaranteed to have equivalent performance for all S&C installations, and are not likely to eliminate many wires due to size and installation location requirements. Kinetic harnessing may offer a solution when considering kinetic energy transferred by passing trains into the S&C, as modules could be small enough to be integrated directly into a sensor node. Lastly, radio wave harnessing technologies, such as those deployed in RFID may offer a solution whereby a main powered interrogator device can emit radio waves to energise and sample sensors distributed within a range around the asset.

Many wireless communication technologies built on principles such as mesh networking and handshaking can offer high connection reliability, however this is not guaranteed in the scenario of passing vehicles, considering their metallic structure and numerous electromagnetic emissions. This could be a particular challenge for dynamic data requiring collection during the passing of a train; some on sensor buffering, for example, could solve this issue.

3.2.3 Processing at the edge

Readily available, low cost, high performance processing systems allow more intelligence to be deployed into the local system, at the edge of the network. Computation of relevant information can be executed locally using potentially advanced techniques such as pattern recognition, Fourier transformation and model based analysis. This reduces the bandwidth demand of the local systems connection to the network, reducing transmission costs as well as remote data storage costs. Algorithms can be used to minimize the size of data so that old data is compressed. For instance, fresh data is stored with an interval of one second and after one month this is recalculated into a value per hour.

3.2.4 Many to many communications

With data being processed and stored on the network it may be necessary for particular use points to access capture points directly to obtain the required information. A robust and highly available capture point access management policy must be in place to support implementation of this sort of structure. Internet Protocol and message queuing protocol (such as AMQP) are examples of this approach.

If highly available direct access to the capture point cannot be supported for whatever reason, then strategies should be considered for the capture point to deliver relevant data to a high availability point of presence elsewhere on the network.

Allowing access between capture points and capture systems may lead to discovery of greater insight through data fusion techniques; sensors may even become available for multi-use applications [10].

3.2.5 Open interface protocol

Communication between capture points, local networks and use points must be carried out with open interface protocol. This determines the manner and format in which data is exchanged. An open interface allows systems developed elsewhere to integrate into the wider system. In S&C monitoring this might mean additional sensor types or even adapters for existing systems such as maintenance and traffic management systems.

3.3 Reliable monitoring systems

In order for an automatic monitoring system to be introduced into an operational business, it must be seen as reliable and trusted. Since the key aim of automatic information capture is to achieve efficiencies, it is essential that the capture system does not decrease efficiency through unreliability. Examples include false alarms, where incorrect analysis requests additional unnecessary maintenance visits, or system failure, where the monitoring system fails more often than the asset it is monitoring.

3.3.1 Trusted decisions

To realise the highest efficiencies and benefits, monitoring systems must be trusted to operate largely unsupervised. Potentially huge volumes of data are generated, making review and assessment by a human impossible. Together with having a clear understanding of the intended purpose of the system, Verification and Validation activities must be completed in order to gain trust in the output.

This area poses the biggest implementation challenge to automatic monitoring systems as the intent of the system must be well defined, understood and accepted by stakeholders, and proven to deliverable by the system design. Until systems can be trusted they will not be adopted, until they are adopted they will not bring benefits.

3.3.2 Reliable by design

The design of the system is essential to achieving reliable performance; consideration for well-tried design principles should be made [11]:

- Appropriate redundancy: Multiple sensors, signal routes and independent signal evaluation;

- Adequate noise immunisation: Screened cables and vibration isolation;

- Mechanical environment consideration: Multi frequency vibration, high accelerations, falling objects, heavy duty maintenance processes, passing workers, extreme weather and animals.

Many of these issues can be eliminated by mounting equipment adjacent to the track whilst also increasing maintenance access. Stand-off monitoring techniques such as optical and acoustic methods may therefore be of benefit.

3.3.3 Safety Integrity Levels

When safety critical decisions are made with the data then the Safety Integrity Level (SIL) of the system must be evaluated. Detection of the switch blade in either the normal or reverse position is a clear safety critical decision; attaining the necessary SIL typically adds cost and complexity to the system. The use of collected information to automatically assess the condition of the asset and replace existing inspection regimes could also be considered a safety critical decision.

3.4 S&C and Interlocking Systems

3.4.1 Interlocking high level description

In the railway signalling sector, computer-based interlocking is an arrangement of signal apparatus that prevents conflicting movements through a combination of tracks such as junctions or crossings. An interlocking is designed so that it is impossible to display a signal to proceed unless the route to be used is proven safe. The typical architecture of the interlocking is characterized by:

1. A central post, which implements the safe management of the railway traffic;

2. A peripheral post, which manages the interface with the field devices. The peripheral post/module is equipped with a module that does not perform interlocking functions but:

a. Dispatches the commands received from the central post to the field devices distributed in stations and along the lines;

b. Collects the state of these devices and sends the extracted information to the central post.

Computer-based interlocking is currently in use all around the world, including the most demanding high speed networks on main lines and also in metros. Existing interlocking systems are mainly focused on safety/vital related information and, in some cases, could also manage non safety/non vital information which are in any case related to the diagnosis of the interlocking components.

The diagram below aims to visually describe how the interlocking system works and how it needs to interface with its respective automatic control system.

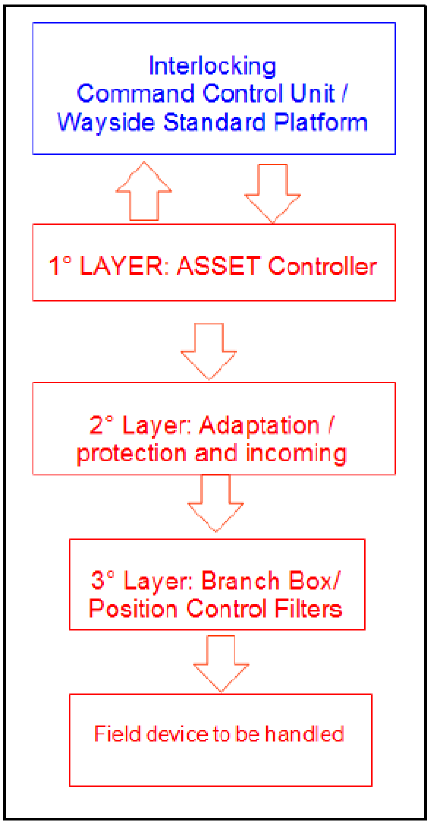


Figure 6. Simple diagram showing how interlocking system works

3.4.2 Link between interlocking and Switches

With an interlocking system it is possible to control the field devices (i.e. switch or light signal) through a peripheral module that monitors the status and availability of the devices. In particular, in relationship with the switches, the peripheral module allows:

- Provision of the required power supply to the electric motor when it has to make the switch operation;
- Generation of and sending to the field device a FSK signal (square wave with 166Hz and 250Hz frequencies) used to detect the status of the switch between an operation and another one;
- Provision of galvanic isolation of the supply voltage from the outputs;
- Limitations of the output current in the case of faults;
- Provision of diagnostic information by visualising signals (LED) on the module and using the diagnostic tool;
- Measurement of the voltage and current absorption;
- Checking of the position control of the switch.

Meanwhile the peripheral module provides the following information:

- the ID of the device;

- the status of the switch operation, i.e. whether it is in progress and the routing position (normal or reverse);
- if the switch is in control or not;
- Vital errors: in case of vital errors the switch becomes unavailable because the fault involves an inside component of the peripheral module;
- Non-vital errors: in case of non–vital errors the fault is linked to external components not directly linked with the peripheral module.

In particular, the errors can be:

- operator errors;
- reversed cables;
- control loss;
- serial bus communication error;
- interior warning;
- warning on communications.

3.4.3 Possible developments of Interlocking, linking with future self-inspecting/self-adjusting S&C

On the subject of possible future self-inspecting/adjusting switches, it is considered beneficial from an interlocking perspective if these new switch designs are able to automatically detect and adjust at least some of the vital errors introduced above in a certified way. This solution will provide to the next generation of interlocking the possibility to automatically re-acquire the control of switches, after becoming unavailable due to the occurrence of vital-errors, without having to wait for an intervention in the field by the maintenance teams. It must be noted that, taking into account all the possible different type of switches actually installed, it is difficult to identify a "standardised" list of vital-errors but the list below contains the most common/relevant parameters to be checked/adjusted to avoid vital errors:

- Switch points must be within 4 mm of tolerance;
- Lubrication status of the components;
- Electrical isolation of the switches;
- Geometrical parameters (gauge, linear expansion etc).

3.5 Basic Principles of Control Systems

3.5.1 Aims

If a self-inspecting/self-adjusting capability was introduced to existing S&C, there would be a need to take measurements, and then to take action should those measurements differ from the target situation. The system which would need to be put in place would:

- Interface with the sensors that take those measurements;
- compare those measurements to a target situation;
- report any difference between the measured and target;
- make changes to adjust the measured situation towards the target.

Once such a system is in place additional benefits can be introduced:

- Redundancy: Introduction of multiple sensors, actuators, drive mechanisms, etc. to allow continued operation in the case of single mode failure. These must also be independent and not dependent on common components, power source and weather conditions;
- Condition monitoring: Examining the measured parameters for unusual trends, or differences between similar equipment, in order to detect problems before they progress to failure [12].

3.5.2 Basic Control Systems Design

Open Loop

The simplest form of control is defined as "open loop". It has a *command* or required situation, a *controller* that converts that requirement to an *input* to the system. The *system* then responds and there is an *output*, which, if the controller is functioning well should correspond to the command.

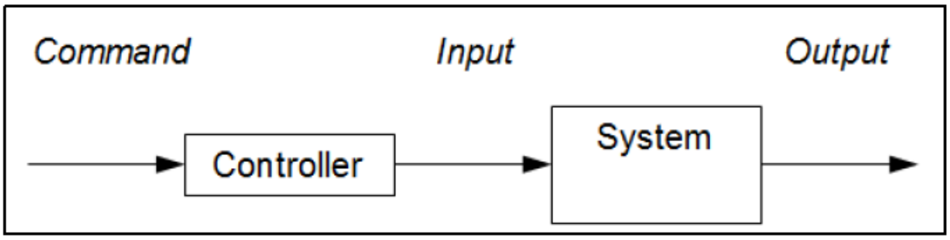


Figure 7. Simple control – Open loop

A comparable example would be a car's speed control. The command is the speed required, (for example 50mph). The controller takes this command and converts it to an input to the system, in this case throttle angle. This may be achieved using a lookup table of throttle angle for a given speed as defined by experiment during development. With the throttle set to an angle known to correspond to 50 km/h, then the car accelerates to 50 km/h.

One problem with open loop control is that it is susceptible to *disturbance* and *uncertainty*. Disturbance is an unknown or unmeasured factor outside the system that can affect the output. Uncertainty is a factor within the system that can affect its operation.

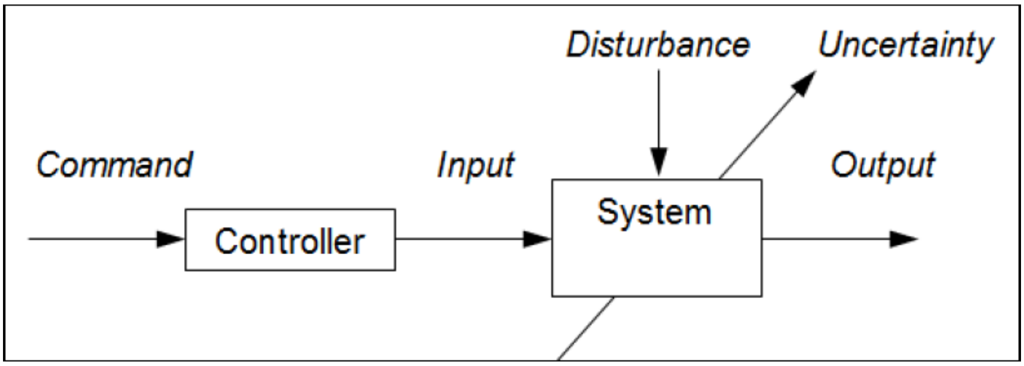


Figure 8. Open loop showing disturbance and uncertainty

In the car example, when the car begins to descend a hill, a disturbance is introduced. The car may accelerate, despite the control system maintaining a constant throttle angle. The open loop control system is unable to take the effect of the disturbance into account when controlling the system.

Uncertainty is an unknown or unmeasured variation in parameters (and/or the structure of the dynamics) describing the system to be controlled. Returning to the car example, ageing of the transmission may increase friction, introducing uncertainty to the throttle angle required to maintain a given speed and also what gear you are in. Again, the open loop control system is unable to take the effect of the uncertainty into account when controlling the system.

Considering existing S&C, the control of critical positions in the system requires manual inspection and adjustment to maintain the required tolerances. The switch control system cannot directly quantify the gaps between the switch blade and stock rail and must rely instead on driving until a limit switch is closed or the drive system stalls. This is similar to open loop control, although one could consider the manual intervention to be a slow feedback loop.

Closed Loop

In closed loop control, we aim to reduce the effect of disturbance and uncertainty by taking the output from the system as *feedback*, comparing it to the command to give an *error*. This error is then fed back into the controller and the controller aims to adjust the input to reduce the error to zero.

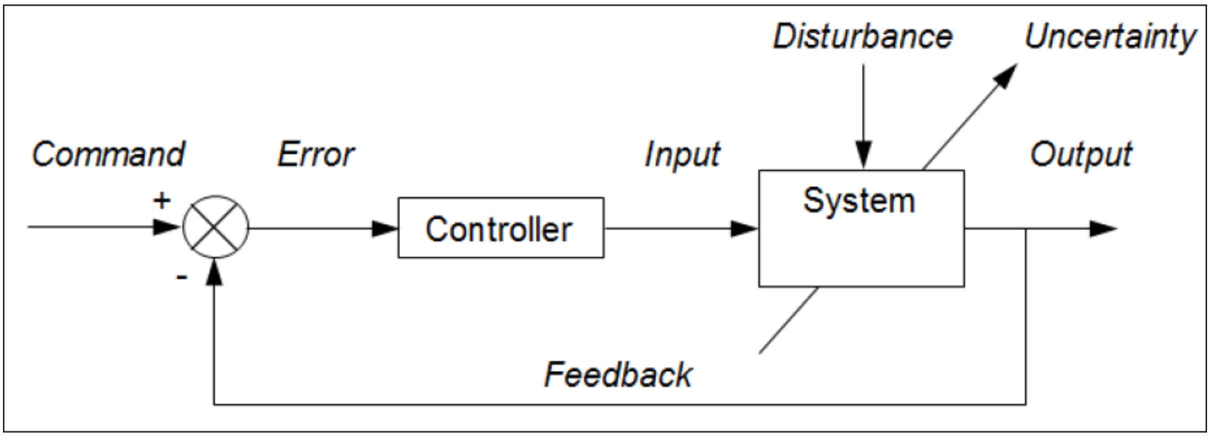


Figure 9. Closed loop

In the case of the car, if the car slows down as it begins to climb a hill, the output speed, say 45 mph, and the command speed (50mph) will differ. The difference between the output and the command are used to create an error. The controller can increase the input (throttle angle) to increase speed and reduce the error towards zero. The design aims for the controller are to ensure that the output follows or *tracks* the command as closely as possible, even in the event of disturbances or uncertainty. The controller reacts in a timely manner to *regulation*, i.e. a change in the command. Closed loop control has the following benefits over open loop control:

- improved command tracking performance;
- disturbance rejection (such as unmeasured external loads);
- reduced sensitivity to system changes (parameter variations);
- unstable processes can be stabilized.

However, careful design is needed to ensure that the system is stable.

3.5.3 Outline Control System Design Process

In order to design the control system, the first step is to understand the system and develop a design model. This is usually a mathematical model of the system, including disturbances and uncertainty. Ideally, this model should be validated against engineering and/or test data.

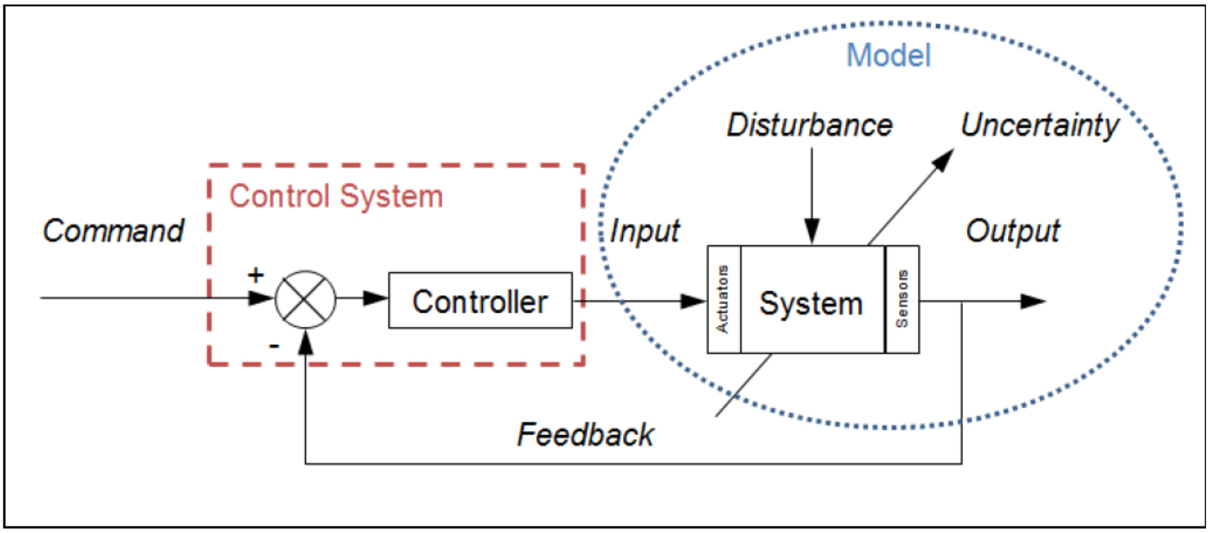


Figure 10. Control system design process

Analysis of the design model in the time and frequency domains provides data for the initial design of the controller. Assessment of the design is accomplished with reference to a number of key performance parameters as described below:

- Steady State Error – difference between command and output in a steady state, i.e. unchanging, situation;
- Rise time – time taken for the response to move from 10% to 90% of the command following a step change in command;
- Settling time – time taken to become within 2% of the new steady state value following a step change;
- Overshoot – expressed as a percentage of the final value over the steady state value;

- Stability.

A final design will depend on the system requirements. From example, overshoot may not be acceptable, therefore the project may have to accept a slow rise time.
Once a suitable controller design is achieved, testing is undertaken using a (usually complex and non-linear) simulation model. Dependant on the application, some Hardware in the Loop (HiL) testing of key sub-systems may be necessary before implementation on the real system.

3.5.4 Hardware Redundancy

Current S&C installations have no built in redundancy. Should any part of the mechanism fail, the system fails. Traffic must then be stopped and a maintenance team will need to attend the site before service can be restored. However, redundancy of sensing and actuation is used in many similar safety-critical applications in other industries and may be of benefit to S&C. There are a number of options to consider when determining which form of redundancy to apply.

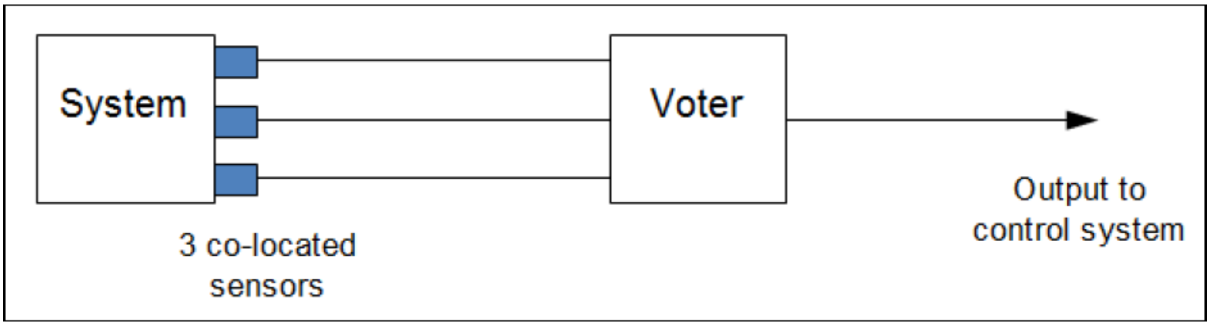


Figure 11. Hardware redundancy

Static redundancy requires three or more sensors, see the schematic in Figure 11. Should the state of any one disagree with the other two, the voter disregards the sensor(s) in the minority. Three sensors allow one fault to be tolerated. In general, a voting system with n sensors can tolerate m faults, where m = n – 2.

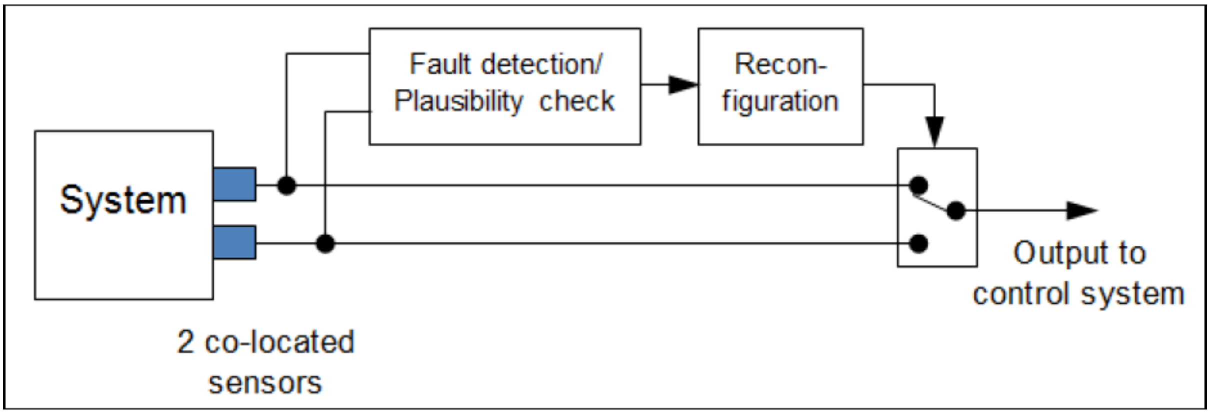


Figure 12. Dynamic redundancy

For dynamic redundancy, it is possible to reduce the number of sensors to two, however, we need the capability to run some form of self-test or diagnostic, see Figure 12. Dynamic redundancy using 2 sensors allows 1 fault to be tolerated. In general a dynamic system with n sensors can tolerate m faults, where m = n -1.
A further step would be to introduce analytical redundancy, in which one sensor is used. In order to understand whether the sensor is functioning correctly, analysis of other available data is done in real time to check the plausibility of the output from that one sensor. The work of Grewal et al. [13] at Loughborough University has been published in this field.

Actuator redundancy functions in a similar manner. Using several actuators in a given situation will allow for continued operation despite the failure of any one. There are however some difficulties with redundant actuation. All of the actuators must be powerful enough to drive the system individually and back drive the failed actuator(s). For redundancy to work, a failed or jammed actuator must not be able to lock the system in position. Some of these points may require careful consideration if the system should be required to lock a switch in a given position or fail safe. Work on high redundancy actuation that may be applicable to this application has been undertaken at Loughborough University by Steffen et al [14].

4 Concept analysis, evaluation, and selection

This section provides analysis of the results from concept down selection using a 'Pugh Matrix' methodology. Each concept was assessed on a scale between 0-10 for various categories, where: 0 means a negative contribution; 5 is neutral; and 10 is highly positive. The new track switch concepts were compared against the established track switch generic design. The evaluation process was aimed at ranking the concepts based on the weighted sum of the markings they received according to the given criteria. The evaluation sheets, once gathered from the project participants, were averaged to gain an overall result and statistics were performed to determine the robustness of the approach. Analysis further looked at the sensitivity of the rankings in several ways: (a) by excluding groups of individuals based on their affiliation; (b) by grouping evaluations according to the evaluators' expertise; and (c) by varying weightings of the categories.
For the analysis mentioned above, concepts in section 1.1 were evaluated using the 'Pugh Matrix' as described in S-Code deliverable 1.1.
The analysis shows robustness in the decision process based on: the exclusion of groups based on their affiliation; subjecting the evaluation marks to different weighting; and evaluators' expertise. In addition, the sensitivity of the selection process to varying the weighting of the categories show that the probability of ranking for the concepts 'U' and 'B' remaining unchanged is good (at 94% and 84%, respectively). Other concepts also show a good range of ranking probability (> 50%) and one can see that the top 6 scoring concepts mostly changed their ranking amongst themselves.
The concept selection process is outlined in Figure 13.

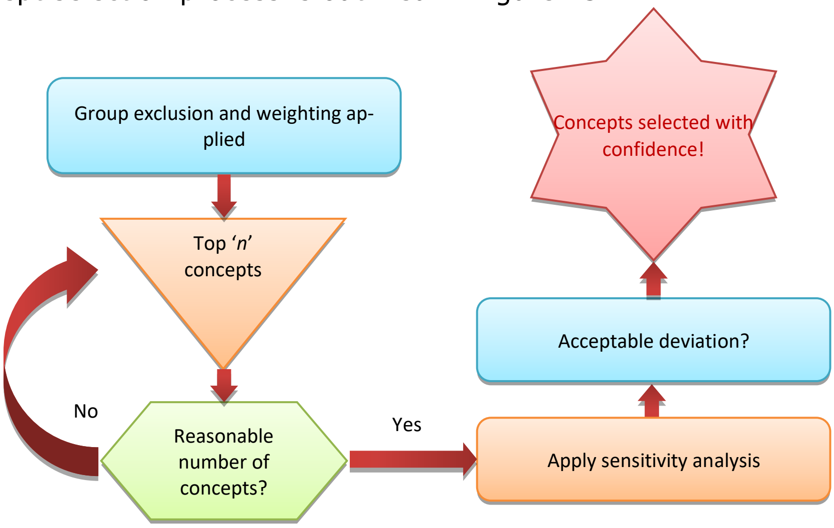


Figure 13. Concept selection process

4.1 Analysis of Concept Evaluation

The analysis of the concept evaluation data was performed in a multi-step process. Firstly, the obtained data was prepared for the analysis by compiling all of the submitted evaluation forms. The mean, variance and standard deviation were calculated for each concept that received marks in each category. Furthermore, the analysis of ranking sensitivity to various inputs was performed, as mentioned in relevant sections below.

4.1.1 The data source

Evaluation data was collected from a wide group of people with a range of backgrounds working on rail focused problems. This included academic researchers and practicing industrial engineers working on railway track related projects.

Table 4. Information on evaluation data

Data Name	Expertise	Industry/Academia
ORG1_02	Track Engineer Track Engineer Track Engineer Civil Engineer Civil Engineer Civil Engineer	Industry and academia
ORG1_01	Track Engineer Track Engineer	Industry
ORG1_03	Track Engineer	Industry and academia
ORG3_01	Track Engineer	Industry
ORG3_02	Track Engineer	Industry
ORG5	Track Engineer S&C Design Engineer S&C Design Engineer Mechanical Engineer S&C Design Engineer Mechanical Engineer Electrical Engineer S&C Design Engineer Track Engineer	Industry
ORG6	Track Engineer	Industry
ORG2_01	Mechanical Engineer	Academia
ORG2_02	Control Engineer	Academia
ORG2_03	Control Engineer	Academia
ORG2_04	Track Engineer	Academia
ORG2_05	Mechanical Engineer	Academia
ORG8	Track Engineer Track Engineer Track Engineer Track Engineer	Industry
ORG7_01	Track Engineer	Industry
ORG4_01	Control Engineer with S&C Experience	Academia
ORG4_02	Mechanical Engineer	Academia
ORG4_03	Track Engineer	Academia
ORG4_04	Track Engineer	Academia
ORG4_05	Systems Engineer	Academia
ORG4_06	Mathematician, Control Engineer	Academia

4.2 Data preparation

Before beginning the analysis, the data was screened to see if there were any blank cells in the spreadsheet. Blank cells were present where the evaluators did not feel they had the appropriate expertise to grade a concept. These blanks were replaced with a neutral response, i.e. an evaluation that the new concept had the same or similar attributes as the existing S&C.

There was an error in setting up the benchmark for the existing S&C. The existing S&C cannot score higher than 0 in the category “Radically different” as it cannot be considered radically different on basis that it has been structurally the same throughout the railway’s history. Conversely, the existing S&C cannot score lower than

10 in the categories "Retrofitting", "Existing machinery/process can be used?" and "Time to market" as no new concept can be considered better than the existing S&C in these categories. Therefore, the benchmarks were adjusted after the data were received and subsequently the markings were also adjusted accordingly by using the following formulae.

For benchmark that was decreased from 5 to 0:

$$y = 2(x - 5) \qquad \text{Equation 1}$$

For benchmark that was increased from 5 to 10:

$$y = 2x \qquad \text{Equation 2}$$

Here, y is the adjusted mark and x is given mark. Table **5** shows information on the data that was subjected to adjustments for the said categories and concepts. Some data were not subjected to adjustments in the said categories because those data had already received the appropriate marking based on a 0-10 scale.

Table 5 Information on data preparation

Data name	Adjusted "Radically different"	Adjusted "Retrofitting"	Adjusted "Existing…used?"	Adjusted "Time to market"	Comment
ORG1_02	Yes	Yes	Yes	Yes	
ORG1_01	Yes	Yes	Yes	Yes	
ORG1_03	Yes	Yes	Yes	Yes	
ORG3_01	Yes	No	Yes	Yes	
ORG3_02	Yes	No	Yes	Yes	
ORG5	Yes	Yes	Yes	Yes	Concept 'O' and 'S' was given neutral response
ORG6	No	No	No	No	Concept 'V' was given neutral response
ORG2_01	Yes	No	Yes	Yes	
ORG2_02	No	No	No	No	
ORG2_03	Yes	No	Yes	Yes	
ORG2_04	No	No	No	No	
ORG2_05	Yes	No	Yes	Yes	
ORG8	No	No	No	No	
ORG7_01	Yes	No	Yes	Yes	
ORG4_01	No	No	Yes	Yes	
ORG4_02	No	Yes	No	No	
ORG4_03	No	Yes	Yes	Yes	
ORG4_04	Yes	No	Yes	Yes	
ORG4_05	Yes	Yes	Yes	Yes	
ORG4_06	Yes	No	Yes	No	

4.3 Statistics

Data processing was performed in the mathematical MATLAB® software environment. An array (3-dimensional) was created of the collated data, with the mean and standard deviation being calculated using the formulae below for each.

$$\boldsymbol{Mean}, \bar{x} = \sum_{i=1}^{n} \frac{x_i}{n} \qquad \text{Equation 3}$$

$$\boldsymbol{Standard\ deviation}, \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \qquad \text{Equation 4}$$

The data obtained was then exported back to the Microsoft Excel® environment and rankings were generated based on the weighted sum.
A number of sensitivity analyses were performed to determine the robustness of the ranking to possible skews in the data. These are outlined in the following sections.

4.3.1 Sensitivity analysis by exclusion of groups

To see if the concepts were favoured by a partnering group, data from the interested group was excluded from the statistics to see if any bias was inherent.

4.3.2 Sensitivity analysis by expertise of evaluators

In providing opinion, one generally bases this on their experience and skills. Therefore, it was necessary to see if there was some bias in the evaluation of concepts due to this. Individuals were grouped by their skill sets and experience into: (a) track engineers; (b) mechanical engineers; and (c) control engineers.

4.3.3 Sensitivity analysis by application of weighting

The weighting categorisation was determined by a focused team before the selection matrix was sent to the participants. To see if the ranking was sensitive to the weighting of categories, different weighting was applied. Suggestions of different weightings were received from Neil Gofton (RSSB) and Otto Plášek (BUT) and were applied to determine any variation. In addition, 'radically different' was removed to see what effect it would have on the ranking of concepts as per Otto's suggestion.

4.3.4 Sensitivity analysis by varying weightings sequentially

To see how sensitive the rankings were to the weighting of a category, each was gradually increased to the limit and subsequently gradually decreased to a minimum with the variation in ranking being recorded at each step. As the sum of all weightings must be 1, the weightings of the other categories were adjusted in proportion and this process was performed for all of the categories.
The following equations demonstrate the relationship between the weightings being adjusted.

$$\boldsymbol{w_{i_a} = w_{i_g} + \Delta w_{i_g}\ ;\ for \left\{0 < w_{i_a} < 1\right\}} \qquad \text{Equation 5}$$

$$\boldsymbol{w_{j_a} = w_{j_g} - \left(\frac{\Delta w_{i_g}}{total\ number\ of\ categories - 1}\right);\ for\ \left\{0 < w_{j_a} < 1\right\}} \qquad \text{Equation 6}$$

Here, subscripts a and g indicate 'altered' and 'given' weightings respectively, w_i is the weighting that is being varied and w_j is for rest of the weightings, Δw_i is the change in the weighting. Figure 14 shows the weightings that were applied for all of the categories against the iterations in ranking calculations.

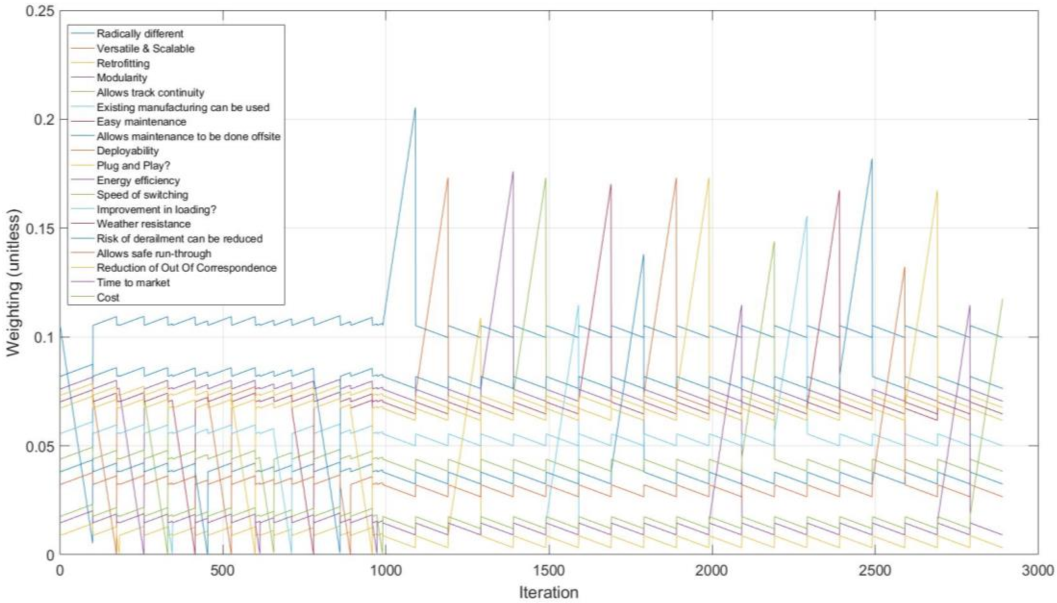


Figure 14. Weighting applied for the sensitivity analysis

The ranks were recorded whilst the categories were subjected to these weighting variations. These were used to extract the number of times a rank appears for a concept. This was then converted to a percentage giving a notional probability of ranking for the given concept. The weightings are varied by using the given weightings as the baseline and therefore, there may be some resulting bias from that. The Monte Carlo uses random inputs to the system and looks at the outputs to deduce the probability. The approach used here is similar to that except for the application of inputs whereby the input is provided in sequential manner – varying the variable 'One At a Time'. This is an acceptable procedure to study the sensitivity of results to the weightings of the subjected categories as shown in [15]. Varying the variable 'One At a Time' allows one to see the sensitivity due to the affecting category clearly as the other variables do not change too significantly, as shown in Figure 14.

4.4 Results and Discussion

4.4.1 Overall ranking of concepts

Table 6 shows the averaged marks received by all of the concepts and their overall rank. A lower number in the rank field indicates a more favoured concept, i.e. a rank of 1 is the highest rated concept.

Table 6. Averaged results from concept evaluation and overall rankings

	Concept Selection Matrix	**Weighting**	**Existing S&C**	**Concept A**	**Concept B**	**Concept C**	**Concept D**	**Concept E**	**Concept F**	**Concept G**	**Concept H**	**Concept I**	**Concept J**	**Concept K**	**Concept L**	**Concept M**	**Concept N**	**Concept O**	**Concept P**	**Concept Q**	**Concept R**	**Concept S**	**Concept T**	**Concept U**	**Concept V**
Design	Radically different	**0.105**	0	4.75	4.90	4.95	5.70	2.25	4.35	1.90	2.80	5.55	4.75	5.05	4.40	5.00	6.85	6.80	5.10	5.45	7.00	6.50	6.05	5.80	5.85
	Versatile and scaleable (can be adapted to various situations)	**0.073**	5	5.30	5.90	4.25	2.85	6.20	4.75	5.65	5.40	4.95	6.30	4.45	5.80	4.55	3.90	6.00	5.75	5.15	5.35	5.80	5.25	6.35	5.70
	Retrofitting	**0.009**	10	5.80	6.25	4.15	3.50	8.15	5.90	7.50	6.80	3.55	6.35	4.80	6.55	5.25	2.80	4.10	5.95	4.55	4.05	4.20	5.95	6.75	6.20
	Modularity	**0.076**	5	5.70	4.90	4.20	3.10	6.05	4.75	5.35	5.20	5.20	6.05	4.80	5.80	4.85	4.20	4.80	5.45	5.35	6.85	5.25	5.60	6.80	6.40
	Allows track continuity	**0.073**	5	5.15	7.20	5.30	4.75	6.20	5.45	6.70	6.55	4.60	6.25	4.85	5.70	6.35	7.15	4.95	4.85	5.30	4.05	5.80	5.80	6.65	6.05
Manufacturing	Existing machinery/process can be used?	**0.015**	10	7.58	6.90	6.05	5.40	8.65	6.75	8.65	8.15	5.65	7.40	6.05	7.30	7.55	4.05	5.30	7.30	7.70	5.00	4.50	6.75	5.75	6.15
Maintenance	Easy maintenance	**0.07**	5	5.15	4.30	3.60	2.65	5.60	4.10	4.70	4.30	4.60	4.40	3.75	4.50	4.25	3.20	4.35	4.50	5.05	2.85	3.15	4.90	4.35	4.10
	Allows maintenance to be done offsite	**0.038**	5	5.75	4.90	3.55	2.70	4.75	4.60	4.70	4.35	5.10	5.55	4.65	5.45	4.45	3.35	6.45	4.95	4.80	5.50	6.60	5.30	5.20	5.30
Logistics	Deployability	**0.073**	5	5.05	5.15	3.05	2.30	5.50	4.75	5.30	4.90	4.10	4.95	4.40	5.00	4.45	2.70	4.55	4.60	4.55	4.60	4.15	4.60	5.40	5.10
	Plug and Play?	**0.073**	5	5.35	5.45	4.25	3.75	5.80	4.60	5.00	4.95	4.10	5.25	4.50	4.80	4.30	3.80	4.55	5.05	5.15	4.60	4.75	5.00	5.25	5.05
Operation	Energy efficiency	**0.015**	5	4.20	5.45	2.60	3.35	5.65	5.75	4.50	3.95	6.45	4.50	4.90	4.30	4.85	3.45	5.35	5.10	5.20	2.75	4.45	4.10	5.15	5.75
	Speed of switching	**0.044**	5	5.10	5.25	3.05	3.00	5.30	5.35	4.65	4.80	5.55	4.80	4.80	4.40	4.65	3.20	5.55	5.15	5.35	3.60	5.05	4.05	5.35	5.45
	Improvement in loading?	**0.056**	5	5.85	5.40	5.40	3.65	6.35	4.70	6.70	6.30	4.70	6.55	4.60	5.85	6.10	4.60	5.35	4.75	5.05	4.20	4.85	5.65	5.60	5.70
	Weather resistance	**0.067**	5	5.05	5.95	4.75	4.20	5.35	4.75	4.75	4.30	5.50	4.60	4.70	4.30	4.45	4.05	6.85	5.25	5.55	4.00	6.05	4.50	4.85	4.00
Safety	Risk of derailment can be reduced	**0.082**	5	5.80	5.65	5.85	5.25	4.75	5.15	5.85	5.70	4.75	5.75	4.90	5.45	5.15	4.15	3.90	4.90	3.20	5.35	3.60	5.55	5.45	5.20
	Allows safe run-through	**0.032**	5	2.95	3.90	2.70	2.60	5.15	4.50	4.95	4.60	5.60	3.50	3.65	3.00	3.65	3.50	6.35	3.95	3.80	3.10	5.85	3.90	4.70	5.70
	Reduction of Out Of Correspondence	**0.067**	5	5.50	5.65	4.65	4.15	5.20	5.20	4.70	4.50	6.25	4.05	4.60	4.30	5.00	4.30	5.05	5.10	4.85	3.90	5.30	4.95	5.25	5.30
Other	Time to market	**0.015**	10	6.40	6.60	6.15	5.65	7.90	5.55	8.40	7.40	3.85	6.75	4.95	5.60	6.00	3.35	3.10	5.35	5.45	3.85	3.35	4.95	4.65	4.50
	Cost	**0.018**	5	4.75	5.00	3.35	3.15	5.85	4.60	4.85	4.30	2.50	4.10	3.45	4.70	4.10	2.70	1.85	4.45	4.00	2.65	2.50	4.50	3.80	3.65
Weighted Sum			5	5.27	5.43	4.40	3.83	5.35	4.84	5.09	4.94	4.97	5.28	4.61	5.01	4.90	4.32	5.23	5.04	4.97	4.74	5.05	5.19	5.53	5.34
Rank				6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4

Accordingly the concept ranking orders can be summarised as shown in Table 7.

Table 7 Ranking of concepts

Rank	Switch Only	Crossing only	S&C	Brief description
1		U		Filling the gaps between the tracks with smart materials
2	B			Vertical movement of track parts/inserts
3		E		Flange bearing frogs
4		V		Spring loaded pins
5		J		Sliding panels for crossings
6	A			Bending of stock rail
7	O			Active steering
8	T			Single switch rail
9		G		Actuated nose for crossings
10			S	Dynamic flanges
11	P			Flange-back steering
12		L		Pivotable rail for crossings
13	Q			Single-flange steering
14	I			Guiding the trains from the tracks
15		H		Moving wing rail
16		M		Overrunning of crossings
17			F	Rotation of tongue

				about the longitudinal axis
18			R	Multiple section switch
19	K			Rotation of stock rail or part of it
20			C	Moving the switch section laterally
21			N	Diverging bridge
22			D	Rotating the switch section/panel along its principle axis

Table 8 shows the standard deviation of each field. The colour indicates the relative scale of standard deviation where 'red' is maximum and 'green' is minimum. Categories 'Radically different', 'Retrofitting', 'Allows track continuity', 'Existing…used?', 'Allows safe run-through' and 'Time to market' have received larger deviation in comparison to other categories. In addition, concepts 'I', 'O' and 'S' have received large deviation in most categories. It should be noted that concepts 'I', and 'S' have ranked very low and therefore, the larger deviation may not be critical in this case but only in the case of concept 'O', should it be considered, since it is a higher-ranking concept. However, upon the consideration of concepts, the categories that received highest deviation could be discussed amongst evaluators to find out the reason behind high deviations. There may be several plausible reasons why large deviations in marking had occurred, some of them are given below:

(a) Understanding for those categories was perhaps not at the same level amongst the evaluators.
(b) The experience of evaluators varied largely for those categories such as manufacturing.
(c) The concept was not well described for the category in question.

Table 8. Standard deviation for each marking field

	Concept Selection Matrix	Weighting	Existing S&C	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Concept I	Concept J	Concept K	Concept L	Concept M	Concept N	Concept O	Concept P	Concept Q	Concept R	Concept S	Concept T	Concept U	Concept V
Design	Radically different	0.105	0	1.80	2.45	2.14	1.78	2.17	2.03	2.05	2.14	2.35	1.80	2.01	1.67	1.84	2.39	2.95	1.41	2.56	1.89	3.07	1.61	2.24	2.28
	Versatile and scaleable (can be adapted to various situations)	0.073	5	2.43	1.33	1.94	1.09	1.79	1.62	1.39	1.14	2.35	1.38	1.61	1.61	1.23	1.83	2.18	1.59	1.81	2.11	2.04	1.86	1.18	1.13
	Retrofitting	0.009	10	2.12	2.27	2.54	2.42	1.69	2.25	2.31	2.35	1.73	2.28	2.12	2.16	2.47	1.82	3.14	2.16	2.65	3.10	3.12	2.48	1.97	3.02
	Modularity	0.076	5	1.75	1.55	2.17	1.80	1.28	1.21	1.50	1.15	1.36	1.10	1.40	1.01	0.93	1.44	2.12	1.15	1.04	1.84	2.00	1.43	1.06	1.31
	Allows track continuity	0.073	5	3.07	1.44	3.29	3.42	1.70	1.54	1.59	1.32	1.67	1.83	1.79	2.15	1.35	2.08	2.16	1.14	1.38	3.02	2.02	2.12	1.35	1.32
Manufacturing	Existing machinery/process can be used?	0.015	10	2.19	2.40	2.61	2.52	1.95	2.34	1.87	2.13	2.85	2.30	2.48	2.52	2.48	2.46	3.42	2.36	2.20	2.55	3.00	2.57	2.79	2.46
Maintenance	Easy maintenance	0.07	5	1.60	1.03	1.23	1.14	1.43	0.79	0.66	1.30	1.79	1.23	1.02	1.43	1.16	1.64	2.68	0.95	1.19	1.84	1.84	1.41	1.53	1.68
	Allows maintenance to be done offsite	0.038	5	1.29	1.37	2.06	1.92	1.37	0.88	0.98	1.04	1.71	1.88	1.31	1.96	1.05	1.81	2.09	1.28	1.01	2.09	1.96	1.34	1.51	1.56
Logistics	Deployability	0.073	5	1.36	1.31	1.79	1.42	0.83	0.91	1.08	1.07	1.65	1.39	0.82	1.12	1.00	1.69	2.24	1.14	1.10	2.46	2.35	1.54	1.27	1.21
	Plug and Play?	0.073	5	1.50	1.15	1.83	1.62	1.24	0.82	0.92	1.05	2.36	1.74	1.00	1.24	0.98	1.99	1.96	1.32	1.57	2.19	2.31	1.26	1.21	1.85
Operation	Energy efficiency	0.015	5	1.36	1.28	1.23	1.69	1.18	0.97	1.28	1.00	1.32	1.24	0.91	1.22	1.18	1.76	2.54	0.85	0.83	1.02	2.54	1.29	1.14	1.25
	Speed of switching	0.044	5	1.68	1.16	1.70	1.78	0.66	0.75	1.18	1.24	2.52	1.20	1.20	1.23	1.04	1.99	3.38	0.81	0.99	1.76	2.76	1.47	1.46	1.76
	Improvement in loading?	0.056	5	1.50	0.99	1.98	1.14	1.50	0.73	1.87	1.59	1.42	1.15	1.10	1.57	1.21	2.06	2.25	1.02	1.15	1.51	1.69	1.50	1.85	1.78
	Weather resistance	0.067	5	1.79	2.01	2.15	1.74	0.88	1.02	1.29	1.03	1.79	0.88	0.86	1.08	0.83	2.06	2.23	1.07	0.94	1.41	2.48	1.57	1.42	1.03
Safety	Risk of derailment can be reduced	0.082	5	1.61	1.31	1.84	1.74	1.33	0.93	1.53	1.13	2.38	1.65	1.02	1.61	2.03	1.57	2.20	0.91	1.70	1.50	1.98	1.39	1.36	1.32
	Allows safe run-through	0.032	5	2.76	2.05	2.64	2.46	0.59	1.36	1.54	1.31	2.70	2.21	1.87	2.22	2.06	2.46	2.52	1.50	1.74	2.75	3.10	2.51	1.78	1.59
	Reduction of Out Of Correspondence	0.067	5	1.15	1.31	2.01	1.84	0.62	0.83	1.42	1.24	2.38	1.28	1.27	1.30	1.17	2.00	3.15	1.25	1.69	2.59	2.79	1.39	0.72	1.17
Other	Time to market	0.015	10	1.60	1.82	2.56	2.41	2.45	2.16	2.16	2.37	1.90	2.24	1.96	2.44	2.75	2.08	2.81	2.08	2.19	1.98	2.50	2.14	2.48	2.31
	Cost	0.018	5	1.37	1.30	1.63	1.57	1.35	0.94	1.35	1.13	1.73	0.97	1.00	1.30	1.07	1.56	1.46	0.94	1.97	1.27	1.76	1.43	1.24	0.93
Rank				6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4

Table 9 shows the weighted standard deviation where the deviations are multiplied by the weighting of the category. It is evident that the category 'Existing…used?' has become uncritical due to its weighting, although it has a higher standard deviation whereas, 'Radically different' looks critical.

This data can be used in conjunction with the ranking obtained to see if there needs to be more discussion and negotiation around selecting those concepts where the deviation in those categories is high.

Table 9. Weighted standard deviation for each field

	Concept Selection Matrix	Weighting	Existing S&C	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Concept I	Concept J	Concept K	Concept L	Concept M	Concept N	Concept O	Concept P	Concept Q	Concept R	Concept S	Concept T	Concept U	Concept V
Design	Radically different	0.105	0	0.19	0.26	0.23	0.19	0.23	0.21	0.22	0.23	0.25	0.19	0.21	0.18	0.19	0.25	0.31	0.15	0.27	0.20	0.32	0.17	0.24	0.24
	Versatile and scaleable (can be adapted to various situations)	0.073	5	0.18	0.10	0.14	0.08	0.13	0.12	0.10	0.08	0.17	0.10	0.12	0.12	0.09	0.13	0.16	0.12	0.13	0.15	0.15	0.14	0.09	0.08
	Retrofitting	0.009	10	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.03	0.03	0.02	0.02	0.03
	Modularity	0.076	5	0.13	0.12	0.16	0.14	0.10	0.09	0.11	0.09	0.10	0.08	0.11	0.08	0.07	0.11	0.16	0.09	0.08	0.14	0.15	0.11	0.08	0.10
	Allows track continuity	0.073	5	0.22	0.10	0.24	0.25	0.12	0.11	0.12	0.10	0.12	0.13	0.13	0.16	0.10	0.15	0.16	0.08	0.10	0.22	0.15	0.15	0.10	0.10
Manufacturing	Existing machinery/process can be used?	0.015	10	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.04	0.04	0.04	0.05	0.03	0.03	0.04	0.04	0.04	0.04	0.04
Maintenance	Easy maintenance	0.07	5	0.11	0.07	0.09	0.08	0.10	0.06	0.05	0.09	0.13	0.09	0.07	0.10	0.08	0.12	0.19	0.07	0.08	0.13	0.13	0.10	0.11	0.12
	Allows maintenance to be done offsite	0.038	5	0.05	0.05	0.08	0.07	0.05	0.03	0.04	0.04	0.07	0.07	0.05	0.07	0.04	0.07	0.08	0.05	0.04	0.08	0.07	0.05	0.06	0.06
Logistics	Deployability	0.073	5	0.10	0.10	0.13	0.10	0.06	0.07	0.08	0.08	0.12	0.10	0.06	0.08	0.07	0.12	0.16	0.08	0.08	0.18	0.17	0.11	0.09	0.09
	Plug and Play?	0.073	5	0.11	0.08	0.13	0.12	0.09	0.06	0.07	0.08	0.17	0.13	0.07	0.09	0.07	0.15	0.14	0.10	0.11	0.16	0.17	0.09	0.09	0.14
Operation	Energy efficiency	0.015	5	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.01	0.02	0.02	0.01	0.02	0.02	0.03	0.04	0.01	0.01	0.01	0.04	0.02	0.02	0.02
	Speed of switching	0.044	5	0.07	0.05	0.07	0.08	0.03	0.03	0.05	0.05	0.11	0.05	0.05	0.05	0.05	0.09	0.15	0.04	0.04	0.08	0.12	0.06	0.06	0.08
	Improvement in loading?	0.056	5	0.08	0.06	0.11	0.06	0.08	0.04	0.10	0.09	0.08	0.06	0.06	0.09	0.07	0.11	0.13	0.06	0.06	0.08	0.09	0.08	0.10	0.10
	Weather resistance	0.067	5	0.12	0.14	0.14	0.12	0.06	0.07	0.09	0.07	0.12	0.06	0.06	0.07	0.06	0.14	0.15	0.07	0.06	0.10	0.17	0.11	0.10	0.07
Safety	Risk of derailment can be reduced	0.082	5	0.13	0.11	0.15	0.14	0.11	0.08	0.13	0.09	0.19	0.14	0.08	0.13	0.17	0.13	0.18	0.07	0.14	0.12	0.16	0.11	0.11	0.11
	Allows safe run-through	0.032	5	0.09	0.07	0.08	0.08	0.02	0.04	0.05	0.04	0.09	0.07	0.06	0.07	0.07	0.08	0.08	0.05	0.06	0.09	0.10	0.08	0.06	0.05
	Reduction of Out Of Correspondence	0.067	5	0.08	0.09	0.13	0.12	0.04	0.06	0.10	0.08	0.16	0.09	0.09	0.09	0.08	0.13	0.21	0.08	0.11	0.17	0.19	0.09	0.05	0.08
Other	Time to market	0.015	10	0.02	0.03	0.04	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.04	0.04	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.04	0.03
	Cost	0.018	5	0.02	0.02	0.03	0.03	0.02	0.02	0.02	0.02	0.03	0.02	0.02	0.02	0.02	0.03	0.03	0.02	0.03	0.02	0.03	0.03	0.02	0.02
Rank				6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4

4.4.2 Sensitivity analysis by exclusion of groups

Table 10 shows the results of ranking when a group is excluded from the analysis. It is quite clear that there was a consensus on concepts 'B', 'E' and 'U' to be the top-ranking concepts, whilst concepts 'C', 'D', 'F', 'K', 'N' and 'R' appear to be the less favoured concepts.

It can also be seen that when evaluations from ORG2 are not included in the analysis, concepts 'A' and 'O' received rank 12 and 13, respectively, which is much higher than the overall rank (6 and 7) they had originally received. This means that ORG2 preferred concept 'A' and 'O' more, in comparison to other evaluators. Again, excluding evaluations from ORG1 shows that concept 'V' was favoured as it ranked 8 without using their evaluations and between 2-4 otherwise.

Table 10. Ranking of concepts when a group is excluded from the analysis

Group excluded	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Concept I	Concept J	Concept K	Concept L	Concept M	Concept N	Concept O	Concept P	Concept Q	Concept R	Concept S	Concept T	Concept U	Concept V	No. of evaluations
None (U)	6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4	20
U – ORG1	3	2	19	22	4	17	11	15	10	7	20	13	16	21	5	12	14	18	9	6	1	8	17
U – ORG3	7	2	20	22	5	18	8	12	13	4	19	15	16	21	6	10	14	17	11	9	1	3	18
U – ORG5	5	2	20	22	3	17	9	15	13	6	19	12	16	21	7	11	14	18	10	8	1	4	19
U – ORG6	5	2	20	22	4	17	9	15	14	6	19	12	16	21	7	11	13	18	10	8	1	3	19
U – ORG2	12	4	20	22	5	17	7	14	15	3	19	8	11	21	13	9	10	18	16	6	1	2	15
U – ORG8	7	2	20	22	3	17	9	15	11	5	19	13	16	21	6	10	14	18	12	8	1	4	19
U – ORG7	6	2	20	22	4	17	9	13	15	5	19	11	16	21	7	12	14	18	10	8	1	3	19
U – ORG4	2	3	21	22	5	15	12	16	17	7	18	10	14	20	6	11	13	19	9	8	1	4	14
U – ORG9	8	2	20	22	5	17	9	15	16	4	19	7	12	21	10	11	14	18	13	6	1	3	17

4.4.3 Sensitivity analysis by expertise of evaluators

Table 11 shows the ranking of concepts when analysis was grouped based on the evaluators' expertise. Whilst there was consensus on the less favoured concepts, there seems to be a polarised view on some of the concepts. Some important observations can be drawn from this analysis

(a) It seems that track engineers did not favour the concept 'O' which is based on vehicle active steering and rather preferred concept 'P' which is based on flange-back steering.
(b) Control engineers and mechanical engineers preferred concept 'O' (active steering) and concept 'S' (dynamic flanges).
(c) Control engineers did not seem to favour concept 'E' (flange bearing frogs).
(d) Control engineers and mechanical engineers were less inclined to favour concept 'V' (Spring loaded pins).

A word of caution is that these rankings are based on averaged markings using all the evaluations for the group in question. It has not been intended to reflect on personal views from any individual.

Table 11. Ranking of concepts according to groups of similar expertise

Group	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Concept I	Concept J	Concept K	Concept L	Concept M	Concept N	Concept O	Concept P	Concept Q	Concept R	Concept S	Concept T	Concept U	Concept V	No. of evaluations
All (U)	6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4	20
Track Engineers	7	2	20	22	4	13	9	14	15	5	17	10	12	21	16	6	11	19	18	8	1	3	12
Control Engineers	6	3	15	22	11	18	12	13	8	9	21	16	20	19	1	17	14	7	2	5	4	10	4
Mechanical Engineers	3	5	19	22	4	18	14	11	12	9	21	13	15	17	2	16	20	10	1	7	6	8	4

4.4.4 Sensitivity analysis by application of weighting

Table 12 shows the ranking results by applying the weightings on the categories that was originally agreed between four individuals in the project (Christopher Ward, Hitesh Boghani, Marcelo Blumenfeld and Louis Saade) when the evaluation matrix was set up and weightings provided by Neil Gofton and Otto Plášek. In addition, the rankings were also generated by excluding the category 'radically different'. The results show that the rankings were not significantly different and did not affect the top-ranking concepts greatly, apart from concept 'G' (actuated nose for crossing), which scored higher by applying the altered weightings.

Table 12. Ranking of concepts according to application of different weighting

Weighting from	Concept A	Concept B	Concept C	Concept D	Concept E	Concept F	Concept G	Concept H	Concept I	Concept J	Concept K	Concept L	Concept M	Concept N	Concept O	Concept P	Concept Q	Concept R	Concept S	Concept T	Concept U	Concept V
Original	6	2	20	22	3	17	9	15	14	5	19	12	16	21	7	11	13	18	10	8	1	4
Neil	7	3	20	22	1	17	4	10	15	5	18	11	16	21	9	12	14	19	13	8	2	6
Otto	7	3	20	22	1	15	2	8	13	5	18	11	14	21	9	12	17	19	16	10	4	6
Exc. Radical	7	4	20	22	1	16	3	8	13	5	18	11	15	21	9	12	17	19	14	10	2	6

To assess the sensitivity of ranking to a particular category the weightings were altered in 'One At a Time' fashion, as mentioned in section 4.3.4.

When the sensitivity analysis was performed by varying the weightings using the originally given weightings as the baseline, the ranking frequencies were received as shown in Figure 15.

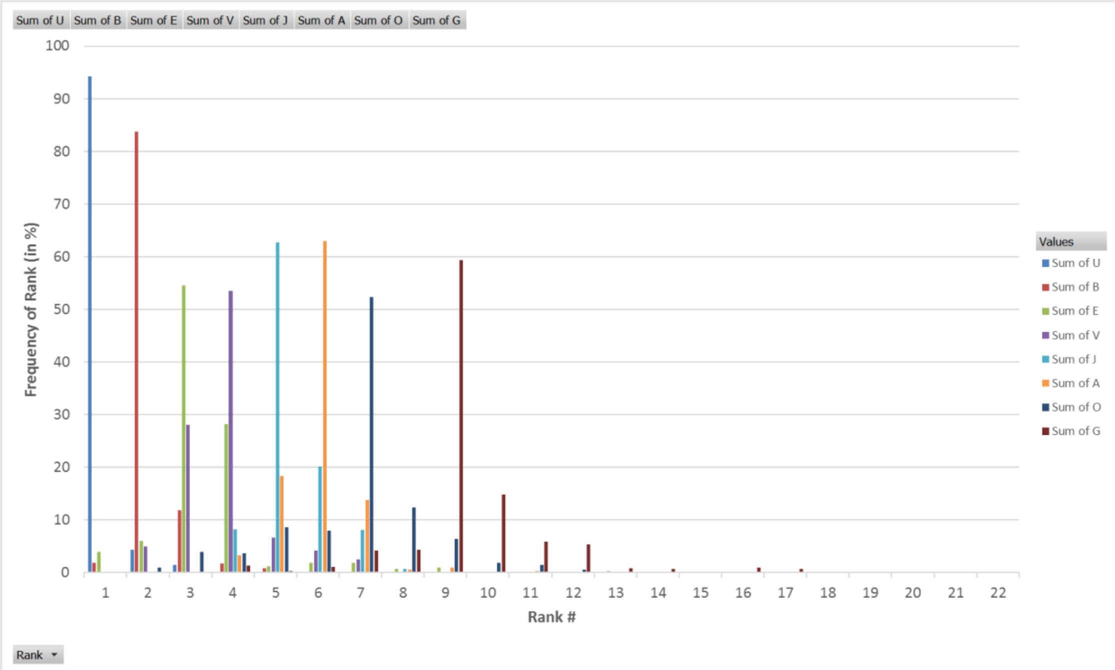


Figure 15. Frequency of ranking of concepts as weightings were varied

It is evident that the concept 'U' has received rank 1 for 94% of the time whereas other concepts had received their original rank for about 50% – 65% of the time. Concepts 'E' and 'V' seem to have tendencies to swap each other's ranking depending on the weighting and so do concepts 'J' and 'U'. Concept 'O' seems to have an equal spread around its base rank. Concept 'G' is included here as it had scored < 5 when different weightings were applied (please see Table 9). Again, it has tendency to score greater than its base rank 9; however, it can score <9 if some of the weightings were favourable.

An example of sensitivity data is given in Figure 16. Here, one can see that the rank of concept 'A' is relatively stable and varies between 4 – 6 most of the time. However, when the categories 'radically different' and 'allows safe run through' are made much more significant than the other categories by increasing their weighting, the scoring is adversely affected. This is plausible as concept 'A' features a stub switch and according to the concept description (provided in Deliverable 1.1), a similar system is being used in rack railways; meaning it was viewed as less radical than other candidate concepts. Also, for category 'allows safe run through', concept 'A' would score badly as it is worse than the conventional switch for this category because it has a cut rail at the switch section which must be joined appropriately for the route selection. This category is viewed with negligible significance by the track engineers in the UK as the occurrences of 'run through' usually only occur during maintenance possessions, which means that maintenance procedures should ideally be reviewed to eliminate 'reverse' operation of trains regardless of the type of switch involved.

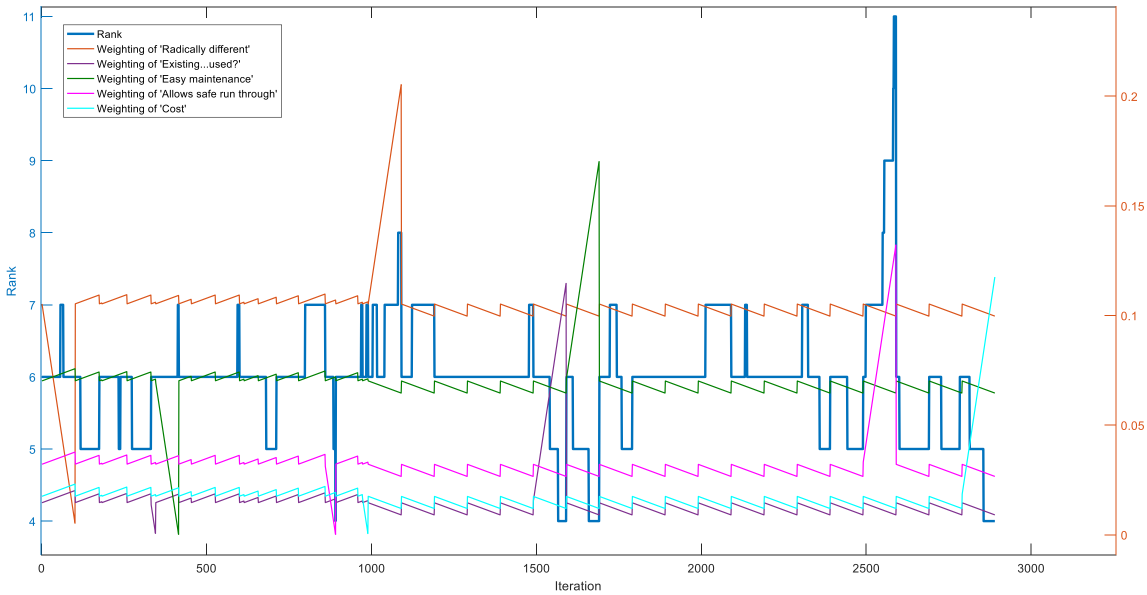


Figure 16. Ranking of Concept 'A' and weighting of categories 'Radically different', 'Existing…used?', 'Easy maintenance', 'Allows safe run through', and 'Cost'.

In addition, concept 'A' would score higher (rank number towards lower value) if categories 'existing machinery/process can be used?', 'easy maintenance' and 'cost' are made more significant. This is once again plausible as concept 'A' is structurally much simpler than the existing S&C.
Furthermore, Table 13 below provides a summary of the top-ranking concepts sensitivity to the weightings. For clarity, categories are mentioned only if the ranking is affected by more than ±1.

Table 13. Sensitivity of top scoring concepts to the weighting of categories (causing change in the rank > ±1)

Concept	Baseline rank	Categories that affected rank positively	Categories that affected rank negatively
A	6	Existing machinery/process can be used? Easy maintenance Cost	Radically different Allows safe run through
B	2	-	Radically different Allows safe run through
E	3	Existing machinery/process can be used? Time to market	Radically different Allows maintenance to be done offsite Risk of derailment
G	9	Retrofitting Existing machinery/process can be used? Time to market	Radically different Versatile and scalable Modularity Allows maintenance to be done offsite Energy efficiency Speed of switching Weather resistance Allows safe run through Reduction of Out of Correspondence
J	5	Modularity Allows track continuity Improvement in loading	Radically different Speed of switching Weather resistance Allows safe run through Reduction of Out of Correspondence
O	7	Radically different Allows maintenance to be done offsite Weather resistance	Retrofitting Existing machinery/process can be used? Risk of derailment

		Allows safe run through	Time to market Cost
U	1	-	Existing machinery/process can be used? Time to market
V	4	Radically different Modularity Allows safe run through	Existing machinery/process can be used? Weather resistance Time to market

It is interesting to note that concepts 'B' and 'U' are the least sensitive whilst concept 'G' is the most sensitive to weighting variation. It is possible to look at the root causes of the sensitivities in these concepts and improve the concepts by combining and borrowing some features from other concepts wherever possible. For example, it may be possible to combine concepts 'G' and 'V' (by using a spring loaded actuated nose to receive the benefits from both) where categories 'Radically different', 'Modularity' 'Allows safe run through', 'Existing…used?' and 'Time to market' affects those concepts inversely. It is granted that some of these categories may not be transferrable across the concepts. In addition, the adversely affecting category may be ignored during the concept selection process if it has less weighting, i.e. is a less significant category.

4.5 Concept selection (using evaluation matrix)

Using the sensitivity analysis as previously shown, the top four ranking concepts are shown in Figure 17 and Figure 18, they are,

Switch only: B, A.
Crossing only: U, E, V, J, G.

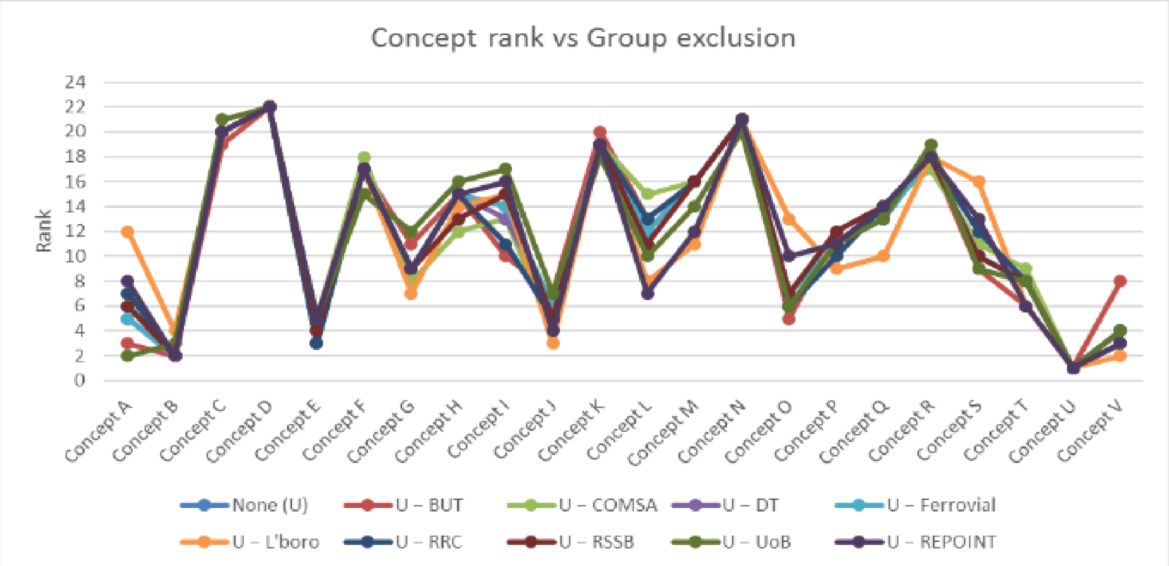


Figure 17. Top scoring concepts when sensitivity analysis applied using exclusion of groups

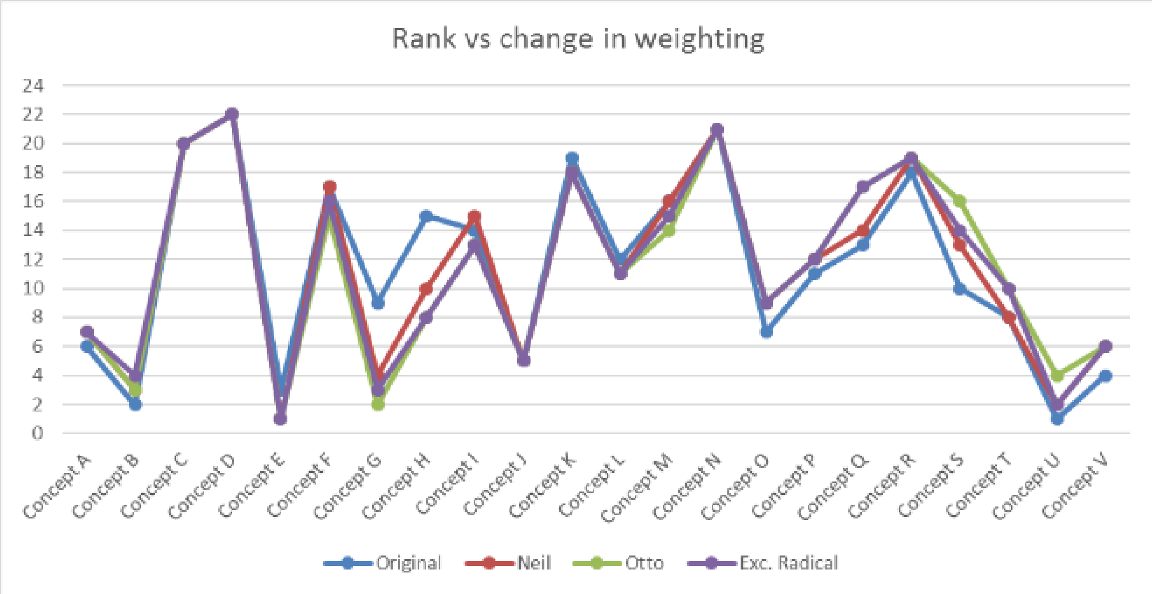


Figure 18. Top scoring concepts when sensitivity analysis applied using different weighting.

It can be seen in Table 14 that there are several fields where the standard deviation is relatively high. If a maximum acceptable standard deviation value of 2.5 is chosen, then one can see that concepts 'B', 'E', 'G' and 'J' are within the boundary. Concept 'V' shows a standard deviation of 3.02 in the category of 'Retrofitting' which is probably because the concept is not described well so that the judgement in this category can be made clearly. Again, concept 'A' shows higher standard deviation in the 'Allows track continuity' category. This is probably because the construction is based on a stub switch and the geometry of matching ends of the rails was probably subject to the evaluators imagination/knowledge. Some evaluators who have seen the REPOINT demonstration or video may have scored it differently than the ones who had not. This is because the REPOINT features the geometry that allows track continuity [16]. However, it is not clear why the category 'Allows safe run-through' had received higher standard deviation for concept 'A'.

Concept 'U' is difficult to assess for the category 'Existing machinery/process can be used?' whether it can or cannot be manufactured using the available technology because it features smart materials. Likewise, as the concept 'V' features spring loaded pins/structures and without developing it up to at least TRL2-3, it may be difficult to assess for its ability to retrofit and this may be the reason why concepts 'U' and 'V' may have received higher standard deviation for the said categories.
Category of Manufacturing seems to have consistently higher standard deviation. However, Table 6 above shows that this category has lesser standard deviation than other categories due to its weighting.

Table 14. Standard deviation in markings for selected concepts

	Concept Selection Matrix	Weighting	Existing S&C	Concept A	Concept B	Concept E	Concept G	Concept J	Concept U	Concept V
Design	Radically different	0.105	0	1.80	2.45	2.17	2.05	1.80	2.24	2.28
	Versatile and scaleable (can be adapted to various situations)	0.073	5	2.43	1.33	1.79	1.39	1.38	1.18	1.13
	Retrofitting	0.009	10	2.12	2.27	1.69	2.31	2.28	1.97	3.02
	Modularity	0.076	5	1.75	1.55	1.28	1.50	1.10	1.06	1.31
	Allows track continuity	0.073	5	3.07	1.44	1.70	1.59	1.83	1.35	1.32
Manufacturing	Existing machinery/process can be used?	0.015	10	2.19	2.40	1.95	1.87	2.30	2.79	2.46
Maintenance	Easy maintenance	0.07	5	1.60	1.03	1.43	0.66	1.23	1.53	1.68
	Allows maintenance to be done offsite	0.038	5	1.29	1.37	1.37	0.98	1.88	1.51	1.56
Logistics	Deployability	0.073	5	1.36	1.31	0.83	1.08	1.39	1.27	1.21
	Plug and Play?	0.073	5	1.50	1.15	1.24	0.92	1.74	1.21	1.85
Operation	Energy efficiency	0.015	5	1.36	1.28	1.18	1.28	1.24	1.14	1.25
	Speed of switching	0.044	5	1.68	1.16	0.66	1.18	1.20	1.46	1.76
	Improvement in loading?	0.056	5	1.50	0.99	1.50	1.87	1.15	1.85	1.78
	Weather resistance	0.067	5	1.79	2.01	0.88	1.29	0.88	1.42	1.03
Safety	Risk of derailment can be reduced	0.082	5	1.61	1.31	1.33	1.53	1.65	1.36	1.32
	Allows safe run-through	0.032	5	2.76	2.05	0.59	1.54	2.21	1.78	1.59
	Reduction of Out Of Correspondence	0.067	5	1.15	1.31	0.62	1.42	1.28	0.72	1.17
Other	Time to market	0.015	10	1.60	1.82	2.45	2.16	2.24	2.48	2.31
	Cost	0.018	5	1.37	1.30	1.35	1.35	0.97	1.24	0.93
Rank				6	2	3	9	5	1	4

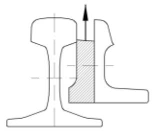
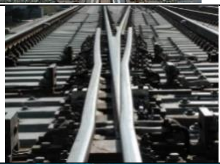
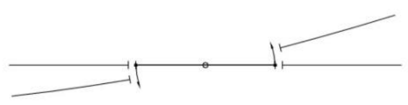
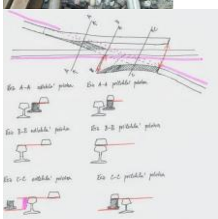
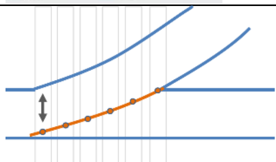
4.6 Summary

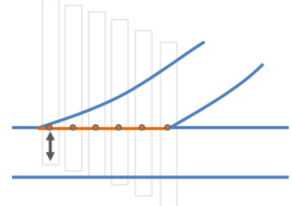
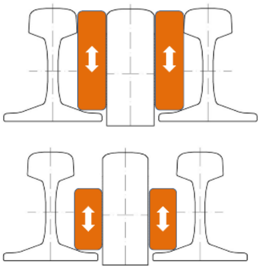
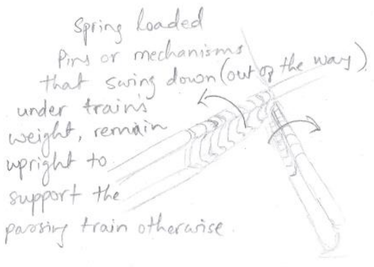
It has been shown that the concept down selection can be aided greatly by employing 'Pugh Matrix'. The analysis of sensitivity shows that the selection process was robust. Although the evaluations of these concepts were based on the opinion of the evaluators, it seems that there was a great degree of consensus. It is also worthwhile noting that the evaluators have appropriate expertise in the field of application (S&C) and so the evaluation results can be taken forward with confidence. Furthermore, the switch concepts that can be selected using the evaluations are concepts 'A' and 'B' and; crossing concepts are 'U', 'E', 'V', 'J' and 'G'. Here, further down selection is required in crossing concepts.

4.7 Resulting concept selection

The following concepts were selected from the 22 concepts that were generated in the project.

Concept	Title	Illustration	Comment
A1	Bending of stock rail + Crossing required		Switch

A2	Bending of stock rail + Crossing NOT required		Switch
B	Vertical movement of track parts/inserts	 	Switch
E	Flange bearing frogs	 	Crossing
G	Actuated nose for crossings		Crossing
J	Sliding panels for crossings		Crossing
L	Pivotable rail for crossings		Crossing
M	Overrunning of crossings	 	Crossing
T	Single switch rail		Switch

			
U	Filling the gaps between tracks		Crossing
V	Spring loaded pins		Crossing

4.8 Kinematic solutions extracted from the concepts

The types of motions that can be extracted from the top scoring concepts are as shown below.

a. Bending of stock rail (along its both principle axes) – Concept A1 + A2 + T
b. Vertical movement of removable parts (no bending) – Concept B + U
c. Pivoting rail section about its 'z' axis (vertical axis) – Concept L + M
d. Sliding panels – Concept J
e. Rotational parts – Concept V
f. No moving parts on the track

The following five potential solutions can be generated as combinations of the above-mentioned concepts.

4.8.1 Concept T combined with A1 (at switch section) + E (at nose section)

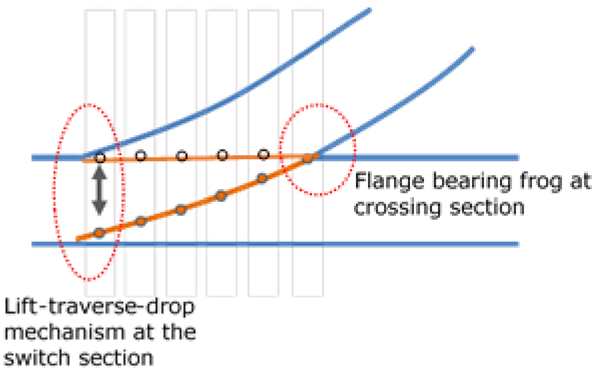


Figure 19. Concept T combined with A1 + E

Figure 19 shows a conceptual design of a track switch where the switch rails are vertically lifted, moved laterally and then dropped, sequentially; in a similar manner to the track switch design in REPOINT (Concept A1). At the crossing section, flange bearing is to be used. The switch rails can be fixed to one-another using a stretcher bar or moved independently. Structurally, this solution looks similar to the traditional S&C. However, the switching mechanism/motion is different.

4.8.2 Concept T combined with A2

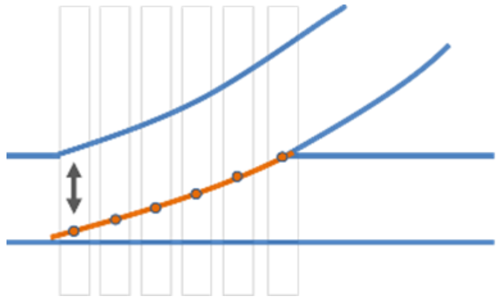


Figure 20. Concept T + A2

Figure 20 shows a conceptual design of a track switch where only a single switch blade is utilised. Here, multiple actuation elements will be needed (such as shown in concept A2) as the track geometry requirement is different for the straight and the curved track.

4.8.3 Concept T combined with L

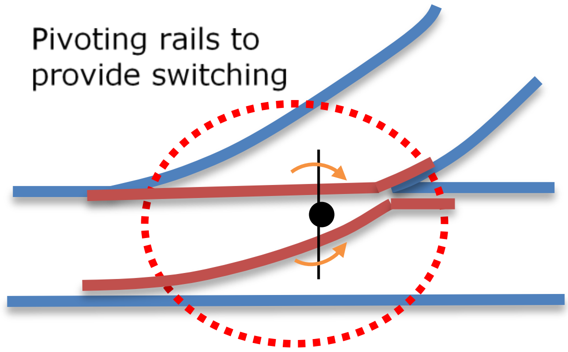


Figure 21. Concept T + L

Figure 21 shows a track switch where the switch panel is attached to a pivoting element. Here the entire section is to be pivoted around the pivot point as shown, in order to perform the switching action.

4.8.4 Concept T combined with B and V

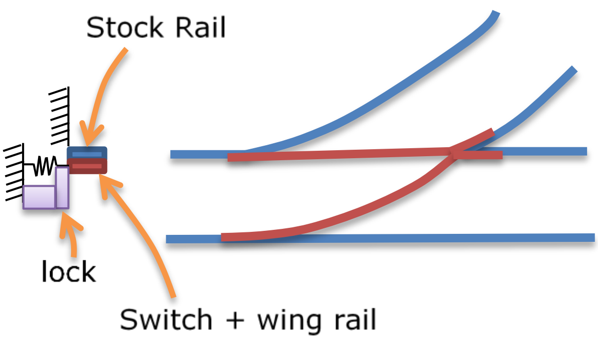


Figure 22. Concept T + B + V

Figure 22 shows a track switch where the switching rails are allowed to sink into the ground under the weight of the train and are lifted back up using the energy stored in the springs underneath once the train has passed. Switching in this concept is performed by restricting the sinking action by setting an appropriate lock to the relevant switch rail. The unrestricted switch rail should give way to the train under its weight. This solution will need to consider the problems of waterlogging and accumulation of debris or stone in the vertical gap (or groove) underneath the switch section.
It should be stated that for the radical new S&C to be successful (maximum availability and reliability, low LCC and guaranteed safety) it is vital that the complexity of the system, as well as the number of moving parts, are kept to a bare minimum. This should not only simplify installation and maintenance, it will also reduce the wear on the system as a whole and therefore extend its life cycle. This concept (T + B +V) comes very close to this idea.

4.8.5 Concept T combined with E

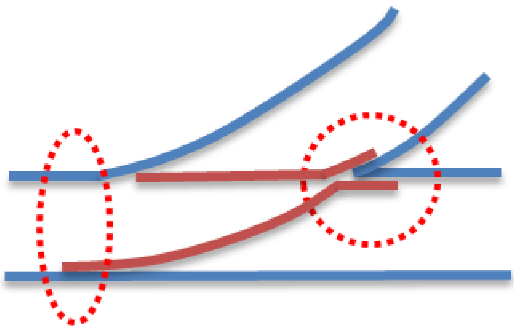


Figure 23. Concept T + E

Figure 23 shows a track switch where the track is fixed at the switch and crossing sections. The support may be provided at the gaps allowing the vehicle to run on the wheel flanges. The switching in this case could be achieved by actively steering the vehicle to the appropriate direction. As there are no moving parts on the track, the failure modes are transferred to the vehicle. Backward compatibility may be designed so that conventional vehicles are able to switch between tracks in the conventional way.

5 Selection of candidate technologies

5.1 Identification of likely capabilities

As part of the methodology, the selection of operational concepts involves identifying the technical and technological gaps between current capabilities and the desired future systems. To do so, the leading partners of work packages 3, 4, and 5 were asked to list recent, upcoming, and future technologies as seen fit to enable the development of the concepts. Subsequently, they were asked to evaluate the capability and technological needs of each concept so that they can be quantified in terms of feasibility and complexity.
The rationale behind this process is that a concept that needs various technologies which are still not available must be acknowledge as more uncertain than one which relies on proven capabilities. Therefore, partners were asked to populate the table of capabilities and technologies and concepts using values of either 0,1, or 2. A value of zero means that the concept does not require the technology in question. In contrary, if the concept can only function if the technology is in place, then a value of 2 is assigned. Finally, if the technology is not essential but could significantly improve the operational concept, then a value of 1 is given.

Table 15. Capability and technological gaps of selected concepts

Technologies	Concept A1	Concept A2	Concept B	Concept E	Concept G	Concept J	Concept L	Concept M	Concept T	Concept U	Concept V
Embedded multiple sensors	1	1	1	1	1	1	1	1	1	1	1
Self-powering sensors	1	1	1	1	1	1	1	1	1	1	1
Sensing vehicles	1	1	1	1	1	1	1	1	1	1	1
Online monitoring	1	1	1	1	1	1	1	1	1	1	1
Ad hoc COMs network	1	1	1	1	1	1	1	1	1	1	1
Standard interface 'Plug & Play'	1	1	1	1	1	1	1	1	1	1	1
Data integration from online sources	1	1	1	1	1	1	1	1	1	1	1
Adaptive and learning algorithms	1	1	1	1	1	1	1	1	1	1	1
Fault-tolerant control	1	1	1	0	1	1	1	1	1	1	0
Immune system (self-diagnostic)	1	1	1	0	1	1	1	1	1	1	0
Noise & vibration reduction	0	0	0	1	2	2	2	2	2	2	2
Less components	2	2	0	1	0	0	0	0	2	1	1
Self-healing concrete	1	1	1	1	1	1	1	1	1	1	1
Geosynthetic support	1	1	1	1	1	1	1	1	1	1	1
Prospective new materials	1	1	1	1	1	1	1	1	1	2	2
Steel with improved contact resistance	1	1	2	2	2	2	2	2	1	0	0
Manufacturing - grinding	2	2	0	2	0	2	0	0	2	1	1
Reduction of dynamic impacts	0	0	1	2	2	2	2	2	2	2	2
Equivalent conicity & transition geometry	2	2	0	0	2	2	2	2	2	0	0
New fastening system	1	1	1	1	1	1	1	1	1	1	1
Non-destructive testing	1	1	1	1	1	1	1	1	1	1	1
Novel actuators	1	1	1	0	1	1	1	1	1	2	0
Distributed actuation	1	2	1	0	1	0	0	1	2	2	0
New materials (actuators, etc.)	1	1	1	0	1	0	1	1	1	2	0
Redundancies	1	1	1	0	1	1	1	1	1	1	0
Minimise friction	1	2	2	0	1	1	1	1	1	1	0
Novel locking mechanisms	2	2	2	0	2	2	2	2	2	1	0
Interlocking	2	2	2	0	2	2	2	2	2	2	0
Weather resistance	1	1	1	1	1	1	1	1	1	1	1

5.2 Risk and uncertainty analysis

These values act as the weighting in the Pugh Matrix, indicating initially the need for certain technologies and technical capabilities. To that, technological readiness levels (TRL)[1] are taken into account for each technology of the list. The most common definition for TRLs are listed in Table 16.
Using the TRLs, work package leaders can assess the technical and technological uncertainty surrounding each concept. If a given concept requires various technologies

[1] http://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

which are at TRL 1, the solution may be highly innovative, but at a cost of high uncertainty as well. Conversely, a solution which is grounded on high TRLs might be feasible yet not radically innovative.
The key outcome of using this assessment is to define the highest innovation to uncertainty values so that a solution can be radically innovative yet feasible in the foreseeable future.

Table 16. Technology Readiness Levels

TRL	Definition
1	basic principles observed
2	technology concept formulated
3	experimental proof of concept
4	technology validated in lab
5	technology validated in railway environment
6	technology demonstrated in railway environment
7	system prototype demonstration in operational railway environment
8	system complete and qualified
9	actual system proven in operational environment (competitive manufacturing exists)

6 High level design of next generation concepts, materials and components

6.1 Introduction and definition of categories

We establish the following definitions of railway track categories because some concepts may only be suitable for one specific category and seem unsuitable for another. These categories will be referred to in the following text. The definitions are based on the category definitions in EN 13 146-1.

6.1.1 Light rail

These are rail tracks which are usually operated in towns – tram transport, light rail (Stadtbahn) and metro. In the case of a tramway track, the track is typically run in the area of a street and in the case of metro and light railway the track is usually run in separated sections, often through tunnels in town centres. Tracks are quite often run also on flyovers. They are characterized by a lower load on the axle (from approx. 8 up to approx. 16 tons) and smaller radii of directional bends (from approx. 25 m for trams and from approx. 100 m for metro). Lower running speeds (usually up to 80 km/h) and frequent stopping are also typical. Only passenger transport is usually considered in this category. Smaller rail profiles (49 E1 and 54 E1) or grooved rails, where the track is situated on a road, are typical. The sleeper spacing is also sparser due to a lower load. Some systems (especially trams) use running on the wheel flange when running through switches and crossings and the running contour of the wheel is very different from that of a conventional railway, for example, for this reason.

Figure 24. Example of Light Rail – underground in Prague and tram in Milan

6.1.2 Conventional rail

These are the main tracks of conventional railways where both passenger transport and goods services can be operated. The load on the axle is usually up to 25 tons. The radii of the directional bends on these tracks are usually not less than 600 m, the inclinations do not exceed 30 ‰ and the rail support spacing is usually 600 mm. The speeds on these tracks are up to 200 km/h, or up to 250 km/h in some places. This category usually uses a 60 E1 (60 E2) shape rail.

Figure 25. Example of conventional rail – main line in Slovakia

6.1.3 High speed rail

These are high speed tracks characterized by the operation of high speed units, usually with a lower axle load (approx. 18 tons). With regard to the geometry of the track, greater radii of directional curves and smaller gradients are designed in high speed rail. The sleeper spacing and the rail profile used are usually the same as that for the conventional rail category. The speeds are different all over the world; although they are within the range of 250 to 350 km/h in most cases. High speed tracks require elements with maintenance demands as low as possible and therefore a dedicated track is also very often used.

6.1.4 Heavy haul rail

These are railway tracks either intended exclusively for goods service or where mixed transport is operated. The axle load may be up to 30 tons and the bend radii may be smaller, down to 150 m. The maximum speeds are lower, usually up to 160 km/h. The support spacing is usually 600 mm, but can also be thicker. The rails used are typically of the 60 E1 shape; however, rails with a greater cross-section may also be used.

Figure 26. Example of heavy haul rail in Australia

6.1.5 Special rail

These are various tracks that do not fall into any category mentioned above. These can be factory sidings, storage sidings, depot sidings, rack railways, funicular railways, marshalling yards, and other similar tracks, for example. Very low speeds (up to 50 km/h) and small directional bend radii are characteristic.

6.2 Concept A

6.2.1 Discontinuity of long-welded rails

Steps back:

- **Solution to the transmission of longitudinal forces in continuous welded rail**

This concept creates the discontinuity of continuous welded rail. If a rail is interrupted, two "breathing" ends are created in the long-welded rails – one in the direction from the point blades and the other in the direction of the frog part. From the viewpoint of longitudinal forces, the frog can be regarded as a more rigid area; it is usually called a fixed point. For this reason, rails will expand differently in the continuation of the point blades towards the frogs. Without solving the transmission of longitudinal forces, this concept is only suitable for TC Special Rail. It will be necessary to construct a frame for the transmission of longitudinal forces (6.2.1.2) under the running rails for this purpose.
The discontinuity of continuous welded rail could also be solved by installing an expanding device before and after the switches and crossings. However, in this case this seems to be an unsuitable solution because the continuous welded rail will be interrupted at all ends of the switches and crossings, and thus "breathing" ends will be created. This would therefore mean installing three expanding devices for single turnouts. An expanding device is also an area of the rail that has high maintenance demands and can be an area of increased dynamic action.

- **Frame for the transmission of longitudinal forces originated in continuous welded rail**

A frame must consist of longitudinal forces transmitting longitudinal beams. The cross-section of the steel longitudinal beams must be at least such as the appropriate number of rails according to the number of branches. The frame must transmit tensile and pressure forces, i.e. it must ensure the stability of the continuous welded rail against buckling. The frame must be placed so that it is stable both transversally and longitudinally (6.2.1.3). It will be necessary to find a way to attach the frame to the related rails (6.2.1.4).

- **Placing a frame for the transmission of longitudinal forces from continuous welded rail**

Placing a frame into the railway bed or into the concrete bearing plate will require an increased thickness of the railway bed or the bearing plate. It will be necessary to ensure the longitudinal frame sliding resistance; more rails will be attached on the frog side than on the point blades side. With regard to additional flexural stress, the frame will require that stability in the vertical direction and sufficient flexural stiffness must be ensured. The frame must be able to resist additional dynamic effects induced by a wheel running on irregularities of the running surface of the rails.
The frame will create a place with a different vertical stiffness of the rail track and will require the creation of transitional stiffness areas for the related adjacent sleepers or bearing plate.

- **Transmission of longitudinal forces from rails to the frame**

The rails and the frame will be at different height levels and the transmission of a force will induce additional bending moments on the rails. It will be necessary to solve how to attach the rails to the frame so that no slipping of the rails in relation to the frame occurs (probably by welding). Any additional flexural stress may induce vertical deformations of the rails, or of the frame (see 6.2.1.3).

6.2.2 Rail joints

Steps back:

- **Reduction of additional dynamic forces when a wheel passes from one rail to another one**

Any interruption of rails always means irregularities of the height and directional shape of the running surface. Due to the impossibility of ensuring the perfect geometrical shape and dimensions of point blades, it will also be necessary to find a solution that is tolerant of these effects. Such a solution should include the arrangement of rails permitting tolerance of the longitudinal setting of the rail ends (the oblique or otherwise shaped ends of rails) (6.2.2.2). It will also be necessary to find a solution to the vertical and transversal stiffness of the joint of related rails (6.2.2.3). If such a solution is not found, this is suitable for TC Light Rail and TC Special Rail.

- **Oblique or otherwise shaped joint of rails**

Any oblique or otherwise shaped joint of rails will also require that the rails are lifted up a little (placing one rail over another) in addition to the transversal movement of the rails. This solution will require a comprehensive method of switching the points (REPOINT); it requires that the placing and fastening of rails along the point blade length on the sleepers or the bearing plate when placing the rails one over another is solved. It will be necessary to find a placing of the rails such that the vertical and transversal stiffness corresponds to that of a common rail. A problem also arises when various branches are run on asymmetrically, when the geometrical conditions on the joint will get worse due to the wear on the rails. It will also be necessary to solve the creation of plastic flow at the rail ends.

- **Solution to ensure vertical and transversal stiffness at the joint**

A rail joint is always a place with reduced transversal and vertical flexural stiffness. In the case of operationally created joints during the switching process the situation will be even worse. A solution may be a device that will adjust the rails to the correct height and directional position after switching and create the prestressed clamping of the joint. Longitudinally prestressed perpendicular rail joints are not possible due to the short length of the rails that it would be necessary to prestress to each other.

6.2.3 Switching points

Steps back:

- **Special switching system with a wide range**

The concept requires a switching system with a long switching track for rails; in the case of placing rails one over another, and also including lifting up the rails (REPOINT). For a solution without the frog, it will be necessary to create a flexible rail grillage system that creates the required geometry of the points, keeps the required gauge, or creates the required extension of the rail gauge for the bends with small radii after switching. Small radii occur just in the TC Light Rail and TC Special Rail categories.

6.3 Concept B

Vertical movement of track parts/inserts (example: winterproof)
This concept describes rail turnouts where changing the direction is solved by vertically movable parts that enable a railway vehicle to pass smoothly by creating or filling in the related grooves. Vertically movable blocks can be used both in point blades and in a frog. The central part of the turnout of the same design or of a design similar to that of standard turnouts can be used in this concept. An example of this solution may be turnouts of a winterproof type; but only the point blades part is solved there. However, the design of a frog can basically be solved in a similar way, where grooves will be filled in appropriately with vertically movable blocks.

6.3.1 A Vertically movable insert switching system

Steps back:
- **A.1 Movement of filling insertions**

The vertically movable block switching system requires the vertical movement of groove fillings throughout the branching length. (6.3.1.2). It will be necessary to create the geometric shape of a filling insertion so that there are no fundamental geometric irregularities for wheel running, causing dynamic effects (6.3.1.3). With regards to inevitable higher dynamic effects, it will be appropriate to manufacture inserts using materials of a higher quality (6.3.1.4).
- **Switching and supporting filling inserts**

A movement must be synchronous throughout the insert length; it must be supported throughout the length after switching to the end position. It is also necessary to ensure the same vertical rigidity of the stock rail running surface and the placing of the groove and the synchronous deflection of the stock rail and the groove. A trouble-free movement will require solving the lubrication of individual parts to avoid seizing. The solution will also be very demanding as regards the accuracy of manufacture and it will also be necessary to take account of possible one side wear caused by running and adapt the sliding parts to this operational wear during the design process.
- **Geometric solution to the relation between the filling insert and the stock rail**

The vertical movement of an insert requires that the shape of the adjacent stock rail is adapted, or it is possible to modify the angle of slipping out the insert with respect to the required shape into which the stock rail is machined and the resulting contour of the stock rail. It will be necessary to solve transition to the usual cross section of the rail in the area where the stock rail machined part ends. It will also be necessary to solve the safety passage of a vehicle in the area where the block is not inserted (an edge will be created in the running surface on the stock rail).
- **Materials of higher quality for parts with running surfaces**

Movable inserts and possibly also the related rail will have to be made of materials that will better resist the dynamic load arising in these areas. This should be such material that can be produced using existing technologies, can be machined without problems and on which it is possible to weld if need be. Plastic flow may occur to a very limited extent only on the insert. This plastic flow would prevent the insert from moving freely.

Homogenization of the vertical stiffness of a rail track in the place of switching

Blocks, including the switching system, stock rails and adjacent rails create areas with significantly increased flexural stiffness. It will be necessary to create the elastic placing of the stock rail and the inserts and this cannot be ensured by placing an elastic layer under the fastening node. Due the flexural stiffness of the point blades area, it would be appropriate to consider making it elastic (making rigidity uniform) by making it elastic in the fastening area or by means of sleeper pads. Dynamic stiffness will be significantly influenced by the sufficient weight of the switching mechanism.

Defrosting point blades

The concept will require a new method of defrosting point blades. The usual heating of points, where melted snow flows away to the railway bed, cannot be used because water would get into and then freeze in the switching mechanism. A different method of removing snow and ice will have to be found – mechanically, blowing out by pressured air, the comprehensive heating of the entire switching mechanism, for example.

6.4 Concept E

The principle of this concept is that a vehicle runs on its wheel flange through the frog. This engineering solution for a frog is commonly used for tram points and its use is meaningful for a great angle of turning, where no other solution to support a wheel continuously can be found. This concept is suitable for TC Special Rail and, under specific conditions, for TC Light Rail.

6.4.1 Kinematics of running

This solution radically changes the relation between the wheel and the rail and thus the kinematics of running. When passing from the running surface of a wheel to the wheel flange, a sudden, step change in the diameter of the rolling radius occurs. If this change is not symmetric on both wheels, the axle would quickly turn. The only way is to ensure the same way of movement of the other wheel in the wheel set, which is the case of perpendicular crossings or crossings approximating to perpendicular ones. For other frogs, this will require a special modification to the opposite rail (6.4.1.1). This requires a relatively low running speed because this solution reduces safety against the derailment of a wheel set (6.4.1.2).

- **Solution to ordinary frogs with usual angles**

For common crossings with the usual angles of crossing, a solution may be filling the groove between the continuous rail at the check rail and the check rail opposite the frog so that both wheels run on their flanges. In the case of current tram points the leading wedge reduces the depth of the groove into which a wheel flange runs, and the wheel is lifted up a little, which causes a considerable impact at higher speeds. For a rail that is not on a road, it is possible to lower the frog point so that a wheel runs on its flange and its height position is almost unchanged. This way of passing will require that the optimum height shape of the surface on which wheel flanges run is found out. With regard to possible wear on wheel running contours, it is however impossible to find the optimum solution; it is only possible to approximate it within the permissible tolerances (wear) on the wheel running contours.

- **Reduced safety against derailment**

Running on a wheel flange means that the effect of the taper as a basic method for centring the wheel set in relation to the rail axis is cancelled. Guiding is provided by the wheel flanges only, but their effective area is lower (as if the wheel flange is lower). To increase safety against derailment, it is possible to increase the height of the check rail and the wing rail (or flanges in the case of grooved rails).

6.4.2 Resistant materials for grooves

The size of the contact surface between the wheel and the rail depends, among other things, on the radius of the contact surface on the wheel running contour. This radius is considerably smaller on the wheel flange than on the wheel running surface. The contact surface will be considerably smaller, i.e. contact stresses as well as the related wear and created groove will be greater. The groove filling material must be of steel more resistant to wear caused by contact stress. Increased demands will also be placed on the material of the wheels. It is possible to consider, for example, various heat treatment of the material in the area of a wheel flange versus the contact surface of the wheel or generally the material of a wheel with increased resistance to contact fatigue and dynamic strength (beyond the established standards).

6.5 Concept G

A movable-point frog is a well-known solution, which has been used often for many years. This type of frog is used in places where the presence of an interrupted running edge is suitable. An uninterrupted running edge enables the speed to increase in both the straight direction and the branching-off direction and radically reduces the dynamics of a railway vehicle.

6.5.1 Solution to a frog frame

There are many well-known structural designs of a movable-point frog that differ mainly in the design of the frog frame (wing rails). The most frequent design of a frame is solved using rails or a casting.

6.5.2 Solution to a frog movable point

Compared to the fixed frog solution (cast frog, forged frog, etc.), a movable-point frog is much more complicated.
For a movable-point frog, the following must be solved:

- **Transmission of a force from a continuous welded rail**

Frog points are usually welded into a continuous welded rail. The force acting on frog points from the continuous welded rail must be transmitted to the frog frame. If this force is not transmitted, the locking system would be in danger of being damaged due to the expansion of the points. Therefore, the design of the movable-point frog root must be optimized so that it sufficiently absorbs the forces from the continuous welded rail.

- **Locking system**

Compared to fixed frogs, the switching of the points must be solved in the case of a movable-point frog. To switch the points, a modified locking system is used to switch tongues in points. As regards the locking systems in movable-point frogs, attaching the lock to the main point must be solved. It is also necessary to solve how to make the points elastic to reduce the switching resistances.

- **Point switching geometry**

In the case of movable-point frog points, it is also necessary to ensure that the profile (material) of a point is as rigid as possible in the vertical direction, but that it is also pliable to switching in the horizontal direction at the same time.

- **Frog running geometry**

From the viewpoint of the interaction of a railway vehicle and a rail, the passage of a wheel from the wing rail to the frog point must be solved; the passage of a wheel without its descending trajectory is regarded as ideal. The passage of a wheel without its descending trajectory is solved as standard in the case of a cast frog frame, but new wing rail production technologies (reforging, bending out, etc.) must be solved in the case of a rail frame.

6.5.3 Rail track stiffness

A frog is generally a place with increased vertical stiffness of the rail track, which is caused by increased flexural stiffness for more rails and also by longer sleepers. The vertical stiffness of a track can be modified through making the fastening of the rails to a sleeper elastic and by means of sleeper pads.

6.6 Concept J

The sliding block frog concept consists in a cast carrier (frog casting) in which a movable insert will be switched.

6.6.1 Insert carrier

An insert carrier can be pictured as a standard frog casting, having a free space for inserting an insert in the area where a wheel passes. It is necessary to solve the surface on which the insert will move – to reduce friction (or rollers) and to enable the surface to be maintained. In addition to supporting the insert, it is necessary to ensure that the insert moves transversally in such a way that it does not jam. Four rails will be attached to the insert carrier and the insert carrier will transmit longitudinal forces from the continuous welded rail.

6.6.2 Solution to the geometry of an insert

Two grooves (straight/branch-off direction of running) will be milled out in an insert. The fastening of an insert in the carrier will be sliding so that the grooves milled out in the insert can be switched to the required position for a railway vehicle running in the straight or branch-off direction. The top surface can be shaped so that the equivalent taper is kept. The geometry of an insert should take account of possible thermal expansion. Any irregularities in the running surface will cause increased dynamic effects, which can be reduced by an appropriate solution in terms of the stiffness of the mounting of the rails.

- **Modification of rail mounting stiffness**

A frog is generally a place with increased vertical stiffness of the railway track, which is caused by increased flexural stiffness for more rails and also by longer sleepers. The vertical stiffness of a track can be modified through making the fastening of the rails to a sleeper elastic and by means of sleeper pads.

6.6.3 Material of an insert

An appropriate material for its production will have to be selected for the design of this type of frog. The carrier must be tough and ductile, but its great part will be in direct contact with a railway vehicle wheel at the same time; this means that it must also be hard enough. The material of a movable insert should also have all the properties described above. The essential requirement for the carrier and insert materials will be their resistance to bonding in the area of transition between the carrier and the insert. Bonded edges would mean that the insert cannot be switched.

6.6.4 Insert switching and locking system

It will also be necessary to solve the system for switching and locking in the switched position. The system should be resistant to climatic effects due to its principle. Switching must ensure that the insert is kept in the vertical direction. The switching system must be supplemented with heating protecting it against the effects of frost.

6.7 Concept L

Pivoting rail for crossings – substitution of the crossing with a pivoting rail.
This concept considers the substitution of a frog with a pivoting part that would provide a continuous running edge at extreme positions when a wheel runs through the frog. Here there seems to be a problem with the passage of a wheel from the rail to the pivoting part and from the pivoting part to the rail. In the case of an oblique joint, where the end parts of the pivoting part will be chamfered, the running edge is interrupted at one joint due to the chamfer of the part for the other end position. This could be solved by a perpendicular joint, but the consequences of this are greater dynamics and problems with absorbing forces from the continuous welded rail. It will be necessary to develop a special switching mechanism and a joint to which the pivoting part is fastened.

6.7.1 Pivoting insert carrier

The insert carrier can be pictured as a standard frog casting, with a free space for inserting a pivoting insert in the area where a wheel runs. Four rails will be attached to the insert carrier and the insert carrier will transmit longitudinal forces from the continuous welded rail.

6.7.2 Solution to the geometry of a pivoting insert

There seems to be a problem with the passage of a wheel from the rail to the pivoting part and from the pivoting part to the rail. In the case of an oblique joint, where the end parts of the pivoting part will be chamfered, the running edge is interrupted at one joint due to the chamfer of the part for the other end position. This could be solved by a perpendicular joint, but the consequences of this are greater dynamics. In the case of chamfering, the pivoting insert will have to be lifted up during the switching process (similar to REPOINT). Any irregularities in the running surface (both the perpendicular contact and the oblique contact) will cause increased dynamic effects, which can be reduced by an appropriate solution in terms of the stiffness of the mounting of the rails (B.1).

- **Modification of rail mounting stiffness**

A frog is generally a place with increased vertical stiffness of the railway track, which is caused by increased flexural stiffness for more rails and also by longer sleepers. The vertical stiffness of a track can be modified through making the fastening of the rails to a sleeper flexible and by means of sleeper pads.

6.7.3 Material of a pivoting insert

In terms of materials, this concept puts increased demands on the resistance of the material in the area where the pivoting part passes to the rail. Therefore, it is appropriate to use, for example, a steel pivoting part in combination with increased strength and a welded-on layer on the end part of the rails or a welded-on layer on the running surface of both parts (pivoting part and rail) in the area of passage at the same time.

6.7.4 Pivoting insert switching and locking system

It will also be necessary to solve also the system for switching and locking in the switched position. The system should be resistant to climatic effects due to its principle. Switching must ensure that the insert is kept in the vertical direction. The switching system must be supplemented with heating protecting it against the effects of frost.

6.8 Concept M

Overrunning of crossings

In a standard frog the rails cross at one level. This solution always requires that a groove for a wheel flange is created in some way. These grooves may either be permanently in the frog (fixed frog), so that a wheel must overcome them, or variable, which is enabled by a movable-point frog. The best solution would be that a rail is not interrupted at all at the crossing and has the same cross section constantly if possible. This solution is offered by a grade-separated frog for the main traffic direction. In the straight direction a rail without any interruption and without a change in the transversal shape will be used and in the branch-off direction the crossing will be solved by using a "bridge" over the straight direction rail. There are two fundamentally different solutions. A frog can be solved as fixed without movable parts. In this case a railway vehicle wheel will have to run on its flange in a certain section (high contact stress will have to be taken into consideration here, see Concept E, regular running will create a groove in the rail head) and a check rail will have to be installed near the opposite stretch of rails, which will substantially limit also the speed in the branch-off direction. The other solution is with movable parts. This solution does not create any interrupted edge even in the branch-off direction and running will be smooth. There are 2 movable parts, where one has the character of a stock rail and the other has the character of a tongue. When the two parts are pushed to each other, they create an uninterrupted running surface. Solving a frog by grade separation enables a train to run at almost unlimited speed in the straight direction. In the branch-off branch, lifting up the stretch of rails must be solved; there are 2 possible basic solutions:

Only the stretch of rails running over the frog will be lifted, which creates a height difference in the branch-off branch that enables a train to pass at higher speeds. A problem will be how to solve the superelevation ramps at the ends of the bend; this can be especially problematic in the area of point blades. (This height difference will be very small and the superelevation ramps will also be short).

Both stretches of rails will be lifted up, which increases the formation line of the points branch-off branch and the track will constantly be without a height difference. This solution would be more suitable in crossovers because a change in the height difference does not have to be solved.

This solution, especially using movable parts, seems to be suitable for TC Conventional rail corridor tracks and also for TC High speed rail due to the expected possibility of high speeds in the straight direction. The solution with the fixed frog is the most suitable one exceptionally for crossovers and for derailing points because running into the branch is used minimally in these cases.

6.8.1 Gradient of rails towards a frog

Lifting up stretches of rails will have to be solved by design in the fastening nodes. Finding the relation between the maximum moving dimensions, permissible vertical wear on the rails and wear on wheels, i.e. especially the maximum possible height of a wheel flange, will be essential.

6.8.2 Crossing of rails

A solution to the frog part with this type of frog will not require the use of above-standard materials. Generally, materials with increased resistance to contact fatigue can be used to eliminate the initiation of contact fatigue defects and to extend the maintenance intervention interval.

6.8.3 Interaction between vehicle and rail

Due to the more complex geometry of a point branch-off branch, the interaction between vehicle and rail will have to be solved, both when a fixed frog is used and when a movable frog is used. For a fixed frog, where a vehicle will run on its wheel flange, the contact geometry characteristics will have to be examined and the safety against derailment will have to be assessed. In the case of the use of movable parts it will also be necessary to design the optimization of the passage of a wheel from the stock rail element to the tongue element.

6.8.4 Elimination of dynamic stress

As the full use of unlimited speeds in the straight direction is expected for these points, the elimination of any possibilities that dynamic stress occurs in the points must be solved. Therefore, the optimization of stiffness along the length of points should be solved by adjusting the correct stiffness of the fastening systems or by using sleeper pads, and the kinematic optimization of passage through the point blades should be solved.

6.9 Concept T

Single switch rail - using single section of switch rail to guide the bogie to appropriate path.
This concept substitutes tongues and a frog with the use of one movable part that guides a train from the beginning of the points to the crossing in the frog area. The shape of the front of this part will be similar to the movable point of the frog, i.e. a point for running on both sides. Unlike the frog point, the angle is smaller here and thus this part will be much slimmer. A joint in the area of the crossing will have to be developed and this part will turn at this joint. The length of this movable part will be considerable (approx. 85 % of the length of the points); it will have to be made by welding more parts together for slimmer geometries. A problem seems to be switching such points; at the beginning switching is in the size of gauge (1435), slide chairs of the relevant length will have to be implemented throughout the area and stop supports will have to be in the area of extreme positions. A greater number of switching mechanisms will be required along the length of the part to be switched, with the appropriate size of switching. These mechanisms will have to be newly developed.

6.9.1 Geometrical arrangement of tongues

It will be difficult to find the geometry of a point movable on both sides and this is impossible without bringing imperfections into the geometrical arrangement. The so-called offset arrangement of tongues together with the flush mounted point will probably be applied.
The area of the movable part point will be slim along a greater length and material resistant to abrasion and of higher quality will probably have to be used. Special material will also probably be used in the area of the joint.

- **More resistant material of a point**

In terms of materials, the concept requires the use of materials with higher dynamic strength and toughness compared to standard rail steel. Material must also have corresponding contact fatigue resistance and be suitable for the renovation of contact surfaces by welding on. It must be stated that these requirements are rather contradictory (especially increased impact resistance in combination with contact fatigue resistance at the same time), i.e. in terms of materials, the concept is rather demanding even if we do not consider fundamentally new materials and a solution is looked for within special steels. When designing a point, it will probably be impossible to use the existing assortment of rails manufactured that are currently used as input material for production.

6.9.2 Design of the end of a long tongue

Passing from the stock rail to the movable part is similar to that for the existing movable-point frogs; there is probably an oblique joint between the end of the movable part and the related rail in the area of the joint. The geometrical arrangement is similar to a tong and a stock rail; with one movable rail ("stock rail") and two related rails ("tongues") in this case. This arrangement allows the longitudinal thermal expansion of the movable part and this part will have its fixed point at the point.

6.9.3 Long tongue switching and locking

New slide chairs of considerable lengths throughout the length of the movable part; supports for extreme positions. Measures for adverse climatic conditions, especially snow. It will be necessary to maintain practically the whole free area between the stock rails.

6.10 Concept U

The structural design of this concept is based on two filling blocks separating the tongue rails and the point rails in the frog area. In terms of its original design, this concept can only be used for a railway vehicle wheel with flange. The flange of such a wheel, rolling in one direction, shapes one of the filling blocks.

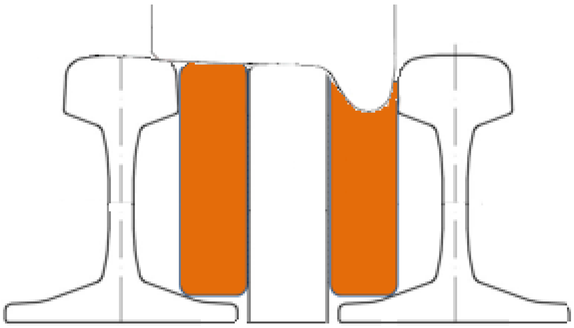


Figure 27. Filling blocks at a crossing

Filling blocks are made of so-called expanding materials (such as D3O) and are characterized by great formability under usual conditions. When a load is of an impact nature, however, this material loses its formability by reason of its changed internal structure; this material becomes almost non-deformable for not a short period.
The implementation of this concept is prevented by the elementary knowledge of expanding material properties. We currently do not know the values of rates of loading, weights of load applying bodies, loading effect times, etc, at which a block made of this material will be formable and at what values it will not be formable. We do not know what the mutual interaction between a wheel flange and the block being formed will look like. Furthermore, we do not know the extent to which the block forming process will influence the running properties of the entire wheel (wheel-rail interface) and we do not know how both blocks will be attached, etc. This concept seems to be almost completely unfeasible in the near future.
A problem is that the rate of loading is the same for both grooves. As a result of this, either both filling blocks will be in a pliable condition and then a wheel is not supported on the running surface, or they will be non-deformable as a result of an impact load, and the wheel does not create a groove. The only one possibility that is feasible is that they will be made of different materials and this principle will not be functional in the branch-off direction.

6.11 Concept V

The structural design of this concept is based on two mechanically flexible blocks (pins) separating the tongue rails and the point rails in the frog area.

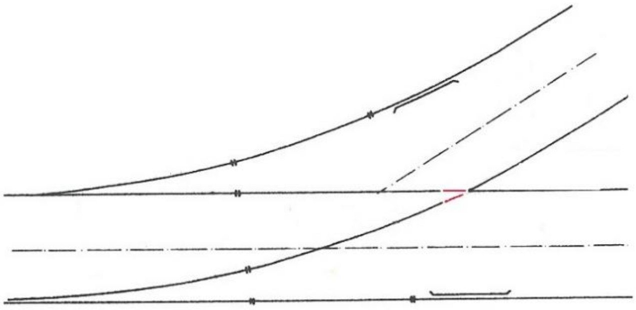


Figure 28. Location of pins in a turnout

In terms of its original design, this concept can only be used for a railway vehicle wheel with flange. The flange of such a wheel, rolling in one direction on a flexible block, hits against the block placed in the other direction. It is required that the other block, on which the wheel is not running, tilts outwards due to the effect of the impact so that the required groove is created between the tongue rail and the point rail.

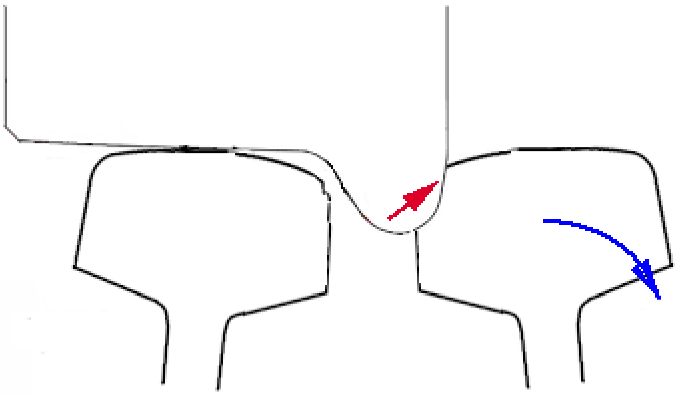


Figure 29. Function of pins

Designing such blocks is very problematic, especially if we consider running on the point. When running on the point, it is impossible to tilt the block on which the wheel is not running outwards due to the existence of an obtuse angle between the point rail and the tongue rail. The block on which the wheel is not running will always tend to tilt inwards.

A certain method is to design these blocks in such a way that the block on which the wheel is not running will make only a translational movement in the vertical direction due to the effect of an impact. The block thus goes down when hit by a wheel flange and a groove is created between the tongue rail and the point rail. This solution seems to be even more problematic. Designing the mechanism in the block that would enable the transmission of an impact load acting in the longitudinal and side directions into the third (vertical) direction, where the impact load component is almost zero, is very difficult. Designing this mechanism is also complicated by the fact that the block must not retract if a wheel is running on it. A block with the appropriate mechanism designed correctly then holds its position firmly when a vertical load is acting on it and moves down vertically when a load that acts downwards outside the vertical direction is acting.

To ensure that this concept is at least a little feasible, any movement of the block on which the wheel is not running must not be controlled by the flange but by the switching system. However, this concept will become very similar to Concept J (Sliding panels for crossings) due to this. Its implementation will require demands similar to those of Concept J.

6.12 High-Level planning

6.12.1 Decisive applicable technologies and their limitations

Table 17. Technologies solved within package WP4

	Steel with improved rolling contact resistance	Noise and vibration reduction	Selfhealing concrete	Manufacturing, grinding	Reduction of dynamic impacts	Equivalent conicity and transition geometry	Support and USP	Nondestructive testing	BIM (Building information modelling)	Prospective new materials	New fastening system	Less components
Concept												
A	0	NO	0	YES	NO	YES	0	0	0	0	0	YES
B	YES	NO	0	NO	0	NO	0	0	0	0	0	NO
E	YES	0	0	YES	YES	NO	0	0	0	0	0	0
G	YES	YES	0	NO	YES	YES	0	0	0	0	0	NO
J	YES	YES	0	YES	YES	YES	0	0	0	0	0	NO
L	YES	YES	0	NO	YES	YES	0	0	0	0	0	NO
M	YES	YES	0	NO	YES	YES	0	0	0	0	0	NO
T	0	YES	0	YES	YES	YES	0	0	0	0	0	YES
U	NO	YES	0	0	YES	NO	0	0	0	YES	0	0
V	NO	YES	0	0	YES	NO	0	0	0	YES	0	0

Table 18. Possible risks

Concept	Trailability	Snow, ice	Continuous welded rail	Next design troubles
A	YES	YES	YES	YES
B	YES	NO	NO	YES
E	NO	NO	NO	NO
G	NO	YES	NO	NO
J	YES	YES	NO	NO
L	YES	YES	NO	YES
M	NO	YES	NO	YES
T	NO	YES	YES	YES
U	YES	NO	NO	NO
V	YES	YES	NO	NO

On the basis of a discussion at the meeting in Vienna a table of technologies and risks of individual concepts was created. The table was filled in with "YES" for the concepts that give an opportunity to solve the technology concerned or "NO" for the concepts that do not give this opportunity. Also "0" was entered where the concept is not dependent on the technology concerned and the technology is generally applicable.
A table of risks was also added because some concepts seemingly show more problems than possible benefits. Where a risk occurs, the option "YES" was selected, and where the risk concerned does not occur, "NO" was selected. The concepts where the option "YES" was selected for 3 or more risks should be excluded from being solved further because they show many elementary problems. The "Next design troubles" item means, for example, problems in fastening movable rails in the vertical direction, unequal wear on the rail head for individual directions, limited wear on rails and wheels, building systems that are not currently feasible, and the like.

6.12.2 Description of technologies

- Steel with improved rolling contact resistance

The use of "advanced" material in particular selected S&C parts
The intention is to interconnect the new material concepts and the optimized structural design of selected S&C parts.
The solution will consist in designing special material for particular parts of selected concepts with an increased dynamic load. In connection with the current state of the designs of individual concepts, vertically movable block concepts ("Winterproof") can be considered.
The substance of the design is the creation of a modular system with a vertically sliding high-strength steel insert (see Fig. 30), with the possibility of mechanical (alternatively electro hydraulic) motion depending on the wear on the contact surface.
The movable segment manufacturing process will be selected considering the minimization of inside defects (in contrast with the existing solution, by using broken compact manganese steel castings, for example).

In combination with the use of sensors (item (1) in Fig. 30) the designed system will enable a new approach to maintenance with the following benefits in compliance with the project requirements:

1. a "self-inspection" and a "self-healing functionality" on the basis of automatic wear indication (an increased dynamic effect indicated by sensors);
2. renewable contact geometry, enabled by repeated grinding;
3. a marked reduction in time and financial costs during reinstallation (without the need for completely replacing a frog, for example); and
4. enhanced operational safety in connection with eliminating the need for renewing by surfacing (welding on), which presents an increased risk of sudden operational damage.

The material will be special steel with increased contact-fatigue strength, where reference samples for material analyses will be manufactured on the basis of a particular structural design. With regard to the increased dynamic strength and safety requirements, impact tests and tests of resistance against the development of inside defects will be carried out.

It will be possible to apply these materials to all concepts; they will however be most suitable for Concept B, where vertically movable blocks can be made of these materials.

This suggestion will be solved in terms of material within Task 4.1 and, in terms of supporting by the pad and inserting a sensor, which will be included in T4.3. Concerning a sensor, cooperation with Work Package 3 can be considered.

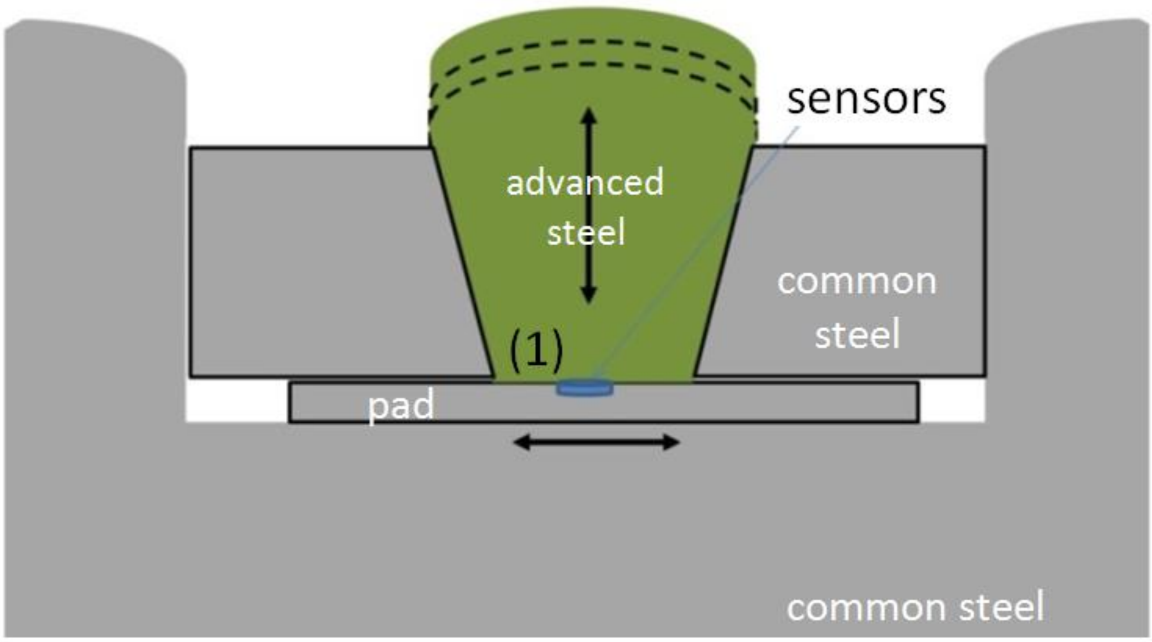


Figure 30. A cross-section through an advanced steel crossing and with the possible location of a sensor

- **Dynamic impact and noise and vibration reduction**

A dynamic effect in frogs arises for several main reasons. The most essential problem is the interrupted inside edge and running surface in frogs. Generally, every interrupted running surface is the most dynamically stressed area in the truck structure and thus a source of noise and vibrations. These are especially rail joints and fixed frogs. There should generally be an effort to minimise these areas in new concepts. That is why exclusively long-welded rails are currently used that eliminate rail joints in a plain track and movable point frogs that eliminate an interrupted running surface in an area where stretches of rails cross each other. A certain improvement may be an oblique joint; due to weakening of the material in the place of the joint, however, it worsens its properties in operation and is run differently, which results in dynamic stress and noise and vibrations again. First of all it is therefore important to eliminate the primary sources of dynamic effects, noise and vibrations. If it is not possible to eliminate these areas with respect to the design, Concepts A or L, for example, it is necessary to solve the joint so that it is as resistant as possible to dynamic effects, noise and vibrations in operation and its design is solved so that the most suitable perpendicular interruption of the running surface does not occur here. Secondly, it will be necessary to suppress noise and vibration propagation from these areas further out to the track structure. Nowadays, many flexible elements are used in the track structure which reduce noise and vibration propagation. For example, these include anti vibration pads or anti-noise walls.

- **Manufacturing, grinding**

Manufacturing, grinding and maintenance will be solved depending on a more detailed design of individual concepts. Some comments on individual concepts are set out below in terms of the manufacturing technologies that are currently used for the standard manufacture of turnouts.

Concept A

The manufacture of a track area is easier; it is not necessary to machine the tongues and cast/machine/install the frog. The manufacture of special sleepers, a grate and a switching system will be realizable using common technologies (welding, machining and surface finishing).

Concept B

Neither the manufacture of a track area nor the manufacture of a switching mechanism is easier than the manufacture of a standard turnout blade part; on the contrary it is more difficult. Machining can be done using standard technologies that are commonly used these days. However, ensuring blocks of the required quality and proper dimensions, for switches and crossings with a lower width-to-thickness ratio and with a longer point blade part, may be more problematic. Due to a greater number of parts fitting in each other, it may be problematic to keep the required tolerances for matching and easy installation.

Concept E

Machining a shallow groove in a frog on a machining centre is not a problem. Just as for Concept B, it is however necessary to ensure a block with the required dimensions. Possible hardfacing could be made using existing technologies.

Concept G

Machining longer parts for switches and crossings with a low width-to-thickness ratio and the handling of them is problematic. Similar to Concept B, there are a greater numbers of parts fitting in each other that must be manufactured with the proper accuracy. In the case of a track frame new wing rail manufacturing technologies (reforging, bending out, etc.) must be solved.

Concept J

A “sliding insert carrier” block with the proper dimensions must be ensured here. Neither machining nor possible heat treatment nor surface finishing of sliding surfaces should be problematic.

Concept L

The manufacture of a mechanism enabling the rotary movement of a rail should be realisable using common technologies, abrasion resistant material, or hard surfacing.

Concept M

Manufacture could be achieved using existing technologies and material with enhanced resistance; there will be a problem with ensuring the required dimensions of semi-finished products.

Concept T

The machining of long tongue rails for switches and crossings with a low width-to-thickness ratio and also ensuring a semi-finished product with the required length and quality will be problematic. Handling and securing a long rail against deformations (both during production and on site) seems to be a problem. Long sliding surfaces, or a switching mechanism, will be manufactured using existing technologies.

Concept U

The "intelligent" material manufacturing technology is not known yet.

Concept V

Manufacture could be achieved using standard materials and standard technologies.

- **Additive manufacturing**

Additive manufacturing (3D printing) is a process during which a product is created by adding thin layer upon thin layer of material. Additive manufacturing is, in fact, the same as 3D printing or rapid prototyping; but unlike these terms, it is used especially for designating processes during which an end product is created and not just a prototype [17]. Therefore, additive manufacturing is a process that creates three-dimensional objects by adding layer-upon-layer of material to create various final shapes according to a CAD model. Unlike conventional manufacturing, no waste is produced in this way. This process is similar to printing using ink or laser printers; the difference is that it prints three-dimensional objects. An object created using layers of a final thickness is only an approximation to the original. The thinner the layer thickness that is used, the more the shape of the object produced approximates to the original.

All commercial devices which use additive technologies use the material layering principle. They differ in the method of creating layers and in how the layers are mutually joined. Different technologies then generate a product produced with different accuracy, mechanical properties, price and time required for manufacturing.

Additive manufacturing (AM) is used in a wide range of applications that is continuously expanding. It has been used the most for so-called "rapid prototyping", which is the manufacture of prototypes using 3D print. These prototypes are mostly unsuitable for higher loads and are mostly used to give an idea of the appearance and for building into a machine or for lower loads. However, the scope of application of AM is wider than the realization of these models. This technology is currently used in various fields of human activity, such as motor vehicles, consumer products, business machines, medical, academic, academic, aerospace, etc., and the scope of application continues to expand into other fields [18]. The manufacture of castings using 3D print is already commonly presented at specialized conferences concerning foundry production. Large car manufacturers in Germany even use printed castings in vehicles during series production.

The following Figure 31 shows a manufacturing process using additive manufacturing technology [18]. First, the required products are modelled using a suitable 3D CAD system at point (1). These systems are currently used quite commonly during design activities because 3D models are often necessary as a CNC machine input during production. In terms of the production of switches and crossings, this is especially the preparation of models for machining centres. A required 3D model can also be made by 3D scanning. This technology is also used in DT, especially for production quality evaluation by comparing the part produced with the model. 3D scanning is also used for evaluating the wear of the running surfaces of switch and crossing parts in operation during the approval process of newly developed structures. However, 3D scanning will not be suitable as a model for 3D print in most cases because a more precise model is achieved directly using CAD system 3D modelling. In the next step (2) the model must be converted into an input format, which is usually an STL. Then, in step (3), the files are imported into an AM device and at the same time simple modifications such as orientation for print can be made. The next step (4) is setting the printing process on the AM device; i.e. the temperature, material quantity, speed, etc, to be specific. The main step (5) is the product printing process itself. This is usually an automatic unmanned process. When printing is completed, in the next step (6) the object is removed from the AM device. As the final printed model is not perfect, it must be then cleaned in step (7); excess material must be removed, etc. In the last step the product is prepared for use.

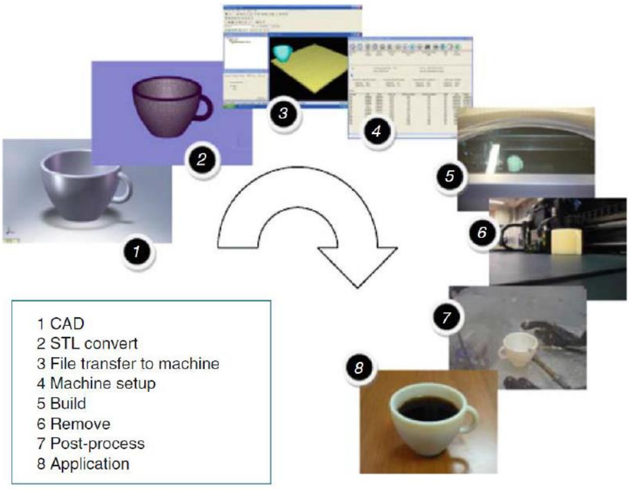


Figure 31: Manufacturing process using AM technology [18]

There are currently many different additive technologies. They differ from each other in the method of creating individual layers of a model and in the materials used. There is also a wide range of additive print method classifications. The most commonly used method is probably the classification by input material [19].

Table 19: Classification of additive technologies by input material

Input material	Technology
Liquid polymer	Stereolitography – SLA
Discrete particles	Selective Laser Sintering – SLS
Molten material	Fused Deposition Modelling – FDM
Solid layers	Laminated Object Manufacturing - LOM

Table 19 gives the basic most frequently used sorting. Some methods, especially new additive methods, do not correspond precisely with the sorting in Table 19; the development of new AM moves forward very quickly.
AM can be used in various different ways in concepts of revolutionary switches and crossings. This technology can find most applications in smaller switch components. These can be, for example, elements of fastening systems (baseplates, spacing inserts, etc.) or in components of switching and locking systems. All of the selected concepts will need rail fastening systems and also a switching device; the use of AM can therefore be considered from this viewpoint in all of the possible concepts for revolutionary switches. The use of AM for the manufacture of rail components does not currently seem to be fully appropriate both in terms of unsatisfactory mechanical properties of printed products and also due to the fact that switch parts such as rails, frogs, stock rails or tongues are very long and robust and would require large 3D printers capa-

ble of printing such large parts. This will is likely to be made possible in future by the ongoing development of AM technology.
In the case of the production of switches, additive technologies can also be considered to be welding on switch parts to increase mechanical resistance, such as hard overlays on the running surfaces of rails that are extremely loaded laterally, see Figure 32.

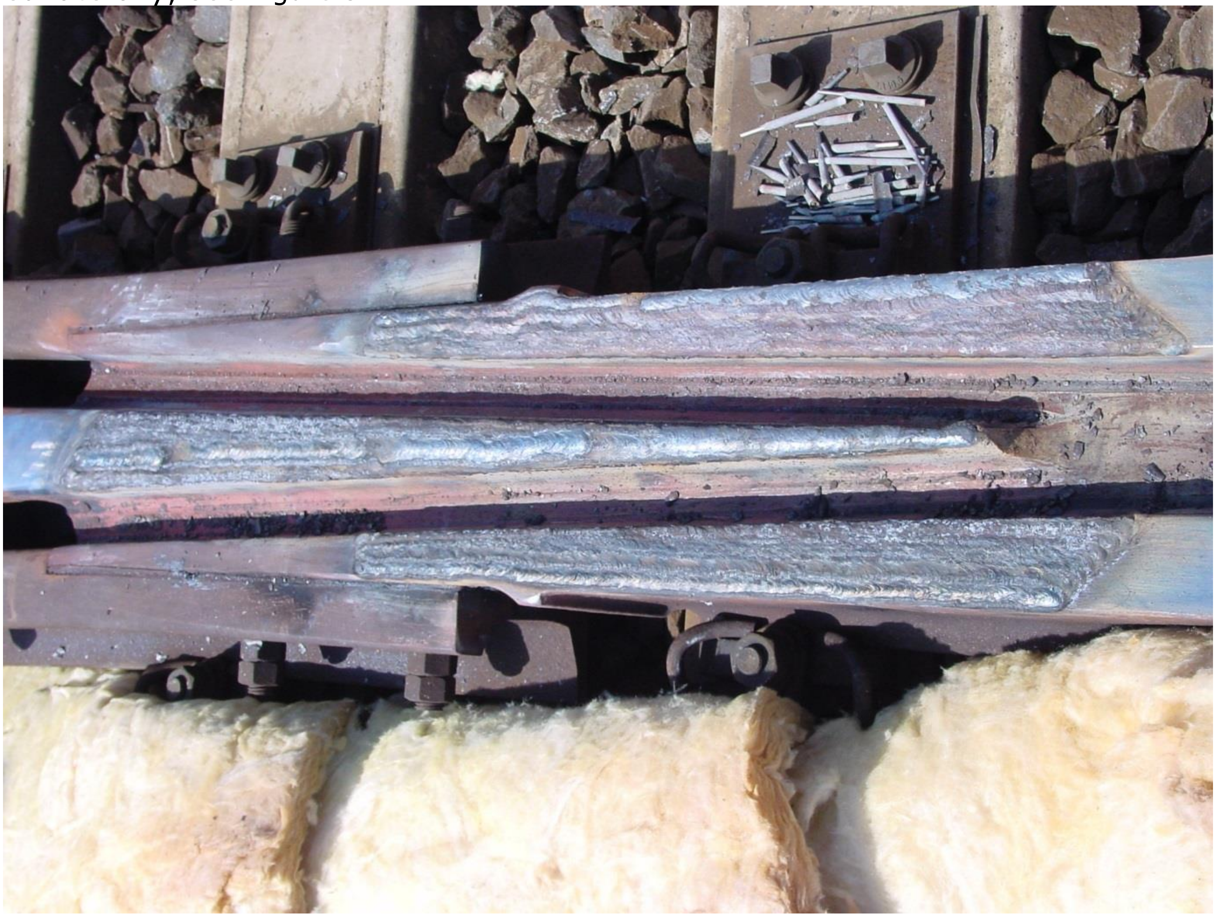


Figure 32: Welded-on overlay on the running surfaces of the frog [17]

Individual concepts place increased demands on applied materials for parts of the structure. In addition, in some cases these requirements are contradictory, such as hardness vs. toughness, and it is also difficult to achieve an increase in contact-fatigue resistance and an increase in the resistance to unstable defect development at the same time.
"Additive manufacturing" type technologies are a possible solution to the problem. These technologies, in principle, enable layers of material to be combined with various chemical compositions to get layered profiles with the different mechanical parameters of individual layers. They also enable the manufacture of parts which have a complex shape. In the application concerned, a combination of material with higher fatigue strength and adhesive-abrasive resistance to the contact surface of rails/frogs and material with higher fracture toughness and impact toughness to the rest of the load-bearing section can be taken into consideration.
This idea corresponds with the proposed technology for making a combined rail profile using the resistance "welding" of special alloyed steel on the standard pearlitic rail steel. The creation of the layered material in the contact area is based on the idea of intentionally influencing the welded-on alloyed steel in terms of heat and pressure during welding so that it positively modifies the resistance of the material in the wheel-rail contact area to the initiation and transverse development of fatigue cracks.

- **Equivalent conicity and transition geometry**

The selected "new designs of switches and crossings" concepts will require an analysis of the action of forces caused by a rail vehicle running so that the wheel is in contact with the rail. For this purpose, a multi-body rail vehicle running simulation system (an SJKV multi-body program) will be developed so that its calculation takes account of the progressive change in the characteristics of the wheel set – rail contact geometry when passing through the structural parts of switches and crossings. Calculation results will give us important information about the location of contact points between the wheel and the rail, including the action of its forces. The results of simulation calculations will be interpreted by the location of the contact points on the rail and the amount of the forces in contact, depending on the transverse cross-sections of the structure of switches and crossings and depending on the defined type of the running profile of the wheel set wheel (the theoretical running profile, operationally worn running profile, and possibly the running profile permissible in terms of limits specified by the European legislation).
Figure 33 shows an example of a particular examination of the contact points in individual cross-sections of the frog area of a turnout when a wheel set with the theoretical running profile passes in the ideal straight direction.
Simulation calculations made by the modified SJKV multi-body program will enable the following:

- optimize individual parts of switches and crossings in order to eliminate sudden changes in the stiffness in the rail on which a vehicle is running (make it more flexible);
- design and optimize new parts of switches and crossings (the operating mechanisms), knowing the action of forces when a vehicle passes through the turnouts; and
- modify quickly the structure of switches and crossings for various operating conditions and customer requirements.

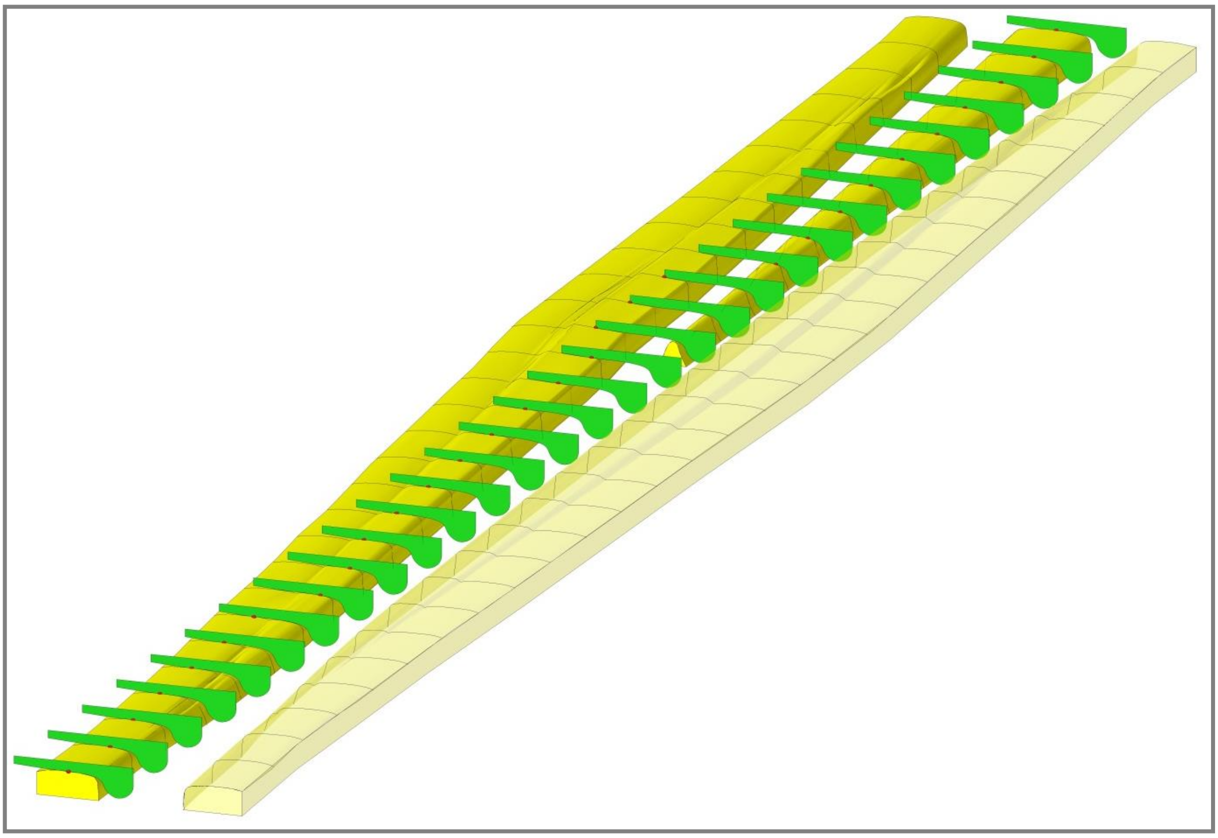


Figure 33. A contact of the running profile of a wheel set wheel with the wing rail and progressive running on the frog point.

Figure 34 shows an example comparing the results of an SJKV multi-body system simulation calculation with measurements on Czech Railways' Pendolino vehicles. The values of the vertical accelerations on the wheel set bearing box when a wheel is passing through the crossing are compared.

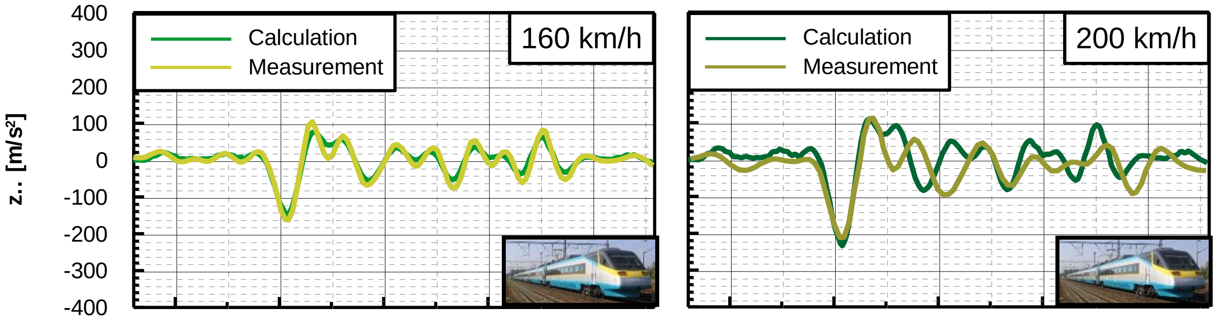


Figure 34. Comparison of an SJKV multi-body simulation with measurement

- Support and USP

All selected concepts will need to be placed on some rail supports. Two basic rail support systems are used these days; a classic design of a track with cross sleepers supported on ballast and a slab track. Wooden and steel sleepers were used in the past; these days we mostly use concrete sleepers.

In terms of sleepers, special attention will be required by Concept A "Bending of stock rail", an example of which is also the REPOINT system. For this system, the development of a new system of supports will be required which enables both switching and a sufficient support for vehicles running through, and also the mechanical properties such as those of the surrounding sleepers. Commonly used hollow steel bearers and a switching mechanism used in them will have to be designed so that they show such behaviour as that of common sleepers in terms of the running of a vehicle. To achieve this target, new materials, especially composite materials, will be used.

Rails and components of switches and crossings are fastened to the rail supports using a fastening system. These fastening systems require high quality both in terms of design and in terms of function in the context of the entire switch and crossing. Fastening systems must have the specified stiffness to ensure the same stiffness of the rail track along the entire points. An example of a new fastening node is a fastening system of the KSN 20 – slide base plate that has been developed in DT so that its stiffness corresponds to the stiffness of the rail track and it also meets the requirement that both the stock rail and the tongue rail are placed on a flexible element. Especially for a slab track, it is also important that fastening systems have a suitable system of changing the track gauge or the transversal switching of the fastening systems on the support and also height adjustability. An example of such a fastening system may be the Vossloh 336 system, for example.

The stiffness of a rail track can also be modified on the loading area of a sleeper using under sleeper pads. Under sleeper pads improve the contact of a sleeper with railway ballast to improve the distribution of loads. A widely discussed question is now a combination of under sleeper pads and a system of fastening made more flexible, because this creates a very complex dynamic system in terms of mechanics which will have to be solved by modelling at first and then by laboratory testing. Fastening which is made more flexible will enable the modification of especially the vertical stiffness and possibly the transverse stiffness of a rail track, and an under sleeper pad can be used to protect the railway ballast against extreme stress.

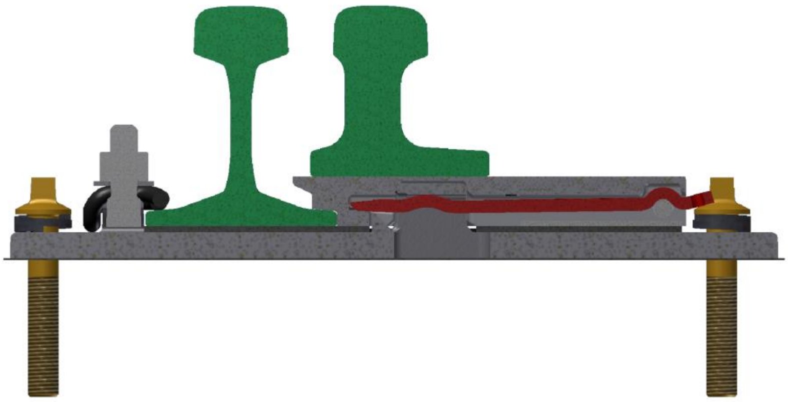


Figure 35. An example of a slide base plate fastening system made more flexible. A flexible pad is also under the slide plate, which makes the tongue rail more flexible as well

- **Prospective new materials**

New advanced materials that have not been used in switches and crossings so far are composite materials, for example. These materials can be used in the structural parts of switches and crossings, such as elements of fastening systems, and elements of support. However, they can also be used as components of switching devices. We also class concrete as composites and it is commonly used for sleepers and supports. In terms of concrete, we can also consider advanced concretes such as self-healing concrete. These materials can be used in all concepts that will be investigated. New types of materials, including composites and self-healing concrete, will be investigated in Task 4.1 (Materials).

- **Composite materials**

Composite materials are nowadays widespread and can be found in practically every engineering application. A composite material is composed of two (mostly) or more components combined in a superior and unique material. The key phase is the matrix, which is continuous and surrounds the other phase. The matrix is mostly fulfilled by fibres or fragments of the other material, generally called the reinforcement. The properties of final composites are a function of the properties of the constituent phases, their relative amounts, and the geometry of the dispersed phase. The main advantage of composites is that mechanical properties can be tailored for a specific application or use.

One simple scheme for the classification of composite materials is shown in Figure 34 - composites can be divided to three main divisions; Particle-reinforced, Fiber-reinforced and Structural composites. The individual group can be also divided, i.e. Structural composites can be Laminates or Sandwich panels etc.

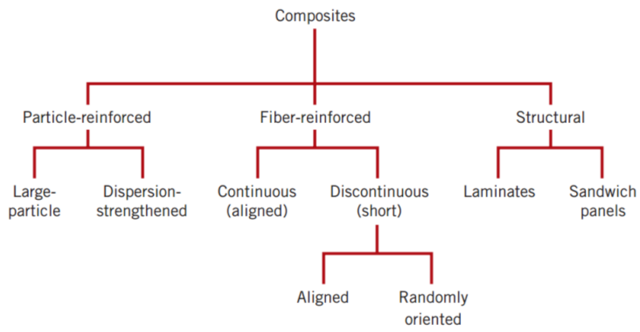


Figure 36. Classification of composite materials

The properties of laminar composites are virtually isotropic in a two-dimensional plane. This is made possible with several sheets of a highly anisotropic composite, which are cemented onto one another such that the high-strength direction is varied with each successive layer. Sandwich panels consist of two strong and stiff sheet faces that are separated by a core material or structure. These structures combine relatively high strengths and stiffness with low densities.

Of the several composite types, the potential for reinforcement efficiency is greatest for those that are fiber reinforced. With these composites an applied load is transmitted to and distributed among the fibers via the matrix phase, which in most cases is at least moderately ductile. Significant reinforcement is possible only if the matrix–fiber bond is strong. On the basis of diameter, fiber reinforcements are classified as whiskers, fibers, or wires. The mechanical properties of continuous and aligned fiber composites are highly anisotropic. On the other hand, for short and discontinuous fibrous composites, the fibers may be either aligned or randomly oriented and despite some limitations on reinforcement efficiency, the properties of randomly oriented short-fiber composites are isotropic.

In large-particle composites, the particles can have quite a variety of geometries, but they should be of approximately the same dimension in all directions (equiaxed). For effective reinforcement, the particles should be small and homogenously distributed throughout the matrix. Furthermore, the volume filler fraction of the two phases influences the behavior; mechanical properties are enhanced with increasing particulate content.

Generally, composites can be found in aircraft, boats and marine, sporting equipment (golf shafts, tennis rackets, surfboards, hockey sticks, etc.), automotive components, tool handles etc.

Composite as Railway Sleepers

In recent years reinforced polymer sleepers have emerged as a potential alternative but because of their high price their uptake has been very slow. Different from steel and concrete, reinforced polymers can be designed to mimic timber behaviour (an essential requirement for timber track maintenance), are almost maintenance free, and are more sustainable from an environmental perspective.

Two different types of polymer sleepers have been available for some time. The first type is polymer sleepers with short fibre reinforcement. These sleepers consist of recycled plastic or bitumen with fillers. The fillers often include sand, gravel, recycled glass or short glass fibres (shorter than 20mm) and they are generally included to increase the stiffness and/or crack resistance. The second type is polymer sleepers with long longitudinal glass fibres. This type of sleeper has long continuous glass fibre reinforcement in the longitudinal direction and no or very short random fibre reinforcement in the transverse directions. The structural behaviour in the transverse directions (shear) is largely polymer based.

The next option could be using hybrid FRP-concrete beam as a rail sleeper. The new design would overcome some of the sustainability issues associated with traditional sleepers. The hybrid system consists of a Rectangular Hollow Section (RHS) pultruded profile filled with geo- polymer concrete. It was found that the proposed composite beam satisfied the minimum flexural requirements for composite railway sleepers as stated in the American Railway Engineering and Maintenance-of-way Association (AREMA) and the Chicago Transit Authority (CTA) standards. In many aspects, the novel system exhibited equal or better performance when compared with existing railway sleepers.

- **Piezoelectric Material**

With the advent of wireless sensors, there has been an increasing amount of research in the area of energy harvesting, particularly from vibration, to power these devices. An interesting application is the harvesting of energy from the track-side vibration due to a passing train, as this energy can be used to power remote sensors mounted on the track for structural health monitoring, for example.

One of the many application scenarios that can benefit from such emerging technology is structural health monitoring (SHM). SHM allows detecting deteriorations and potential damages of a structural system by observing the changes of its material and geometric properties over long periods of time. SHM is a vital tool to help engineers improve the safety of critical structures, avoiding the risks of catastrophic failures. In fact, SHM systems should ideally monitor engineered structures for decades or even perpetually, but traditional wireless sensor nodes are powered by short-lived batteries that, lasting a few years at most, fail to meet the lifetime requirements of long-term deployments. Applying emerging energy harvesting techniques to wireless sensor nodes allows the energy bottleneck suffered by traditional WSNs to be overcome, thus removing the limits that make current WSN-based monitoring systems unfit for SHM applications.

- **Continuous welded rail (CWR)**

To suppress the dynamic effects of rail joints and thus to increase the maintenance interval and enhance the comfort of running, continuous welded rails have been used for many years. These are a track in which stretches of rail are welded to create long stretches of rails, including switches and crossings. Since the rail material is prevented from expanding thermally in continuous welded rails, they are characterized by great tensile and compressive forces that are created in them. Considering the present quality of the construction, maintenance and elements of a superstructure, the track structure is able to transmit these forces without problems.

Switches and crossings are commonly welded into continuous welded rails and thus become part of them. Since switches and crossings are welded into the central part of continuous welded rails, which do not move due to temperature changes, the elements of the turnouts do not move either. Only the freely placed tongues move and, to prevent unsuitable movements, tongue creep preventing supports are installed in points, which also ensure the possible transmission of forces of the continuous welded rails.

It is apparent that some concepts may be problematic in terms of installation in continuous welded rails. These are especially Concepts A and T. For these concepts, it will be necessary to consider a way of transmitting the forces of CWR through switches and crossings, because both concepts have an interruption of both rails and this would also result in an interruption of the CWR. A solution could be a frame which could be placed under the switches and crossings or on the sides of the turnout, for example. When designing a frame, it will be necessary to remember that this could make the whole track in the switches and crossings more flexurally rigid and it will be necessary to develop a way of making it adequately flexible, such as in rail fastening systems. For rail joints that will be solved as oblique, such as REPOINT, the development of a prestressed joint that would also function within CWR can be considered.

These problems should be solved within Task 4.1 (Materials, manufacturing) and Task 4.3 (Support) in cooperation with WP3 and WP5.

- **Installation and logistics**

The transport and laying of switches and crossings will be solved within Task 4.4. Installation and laying considerations will follow on from the work in Task 2.5. The main problem is currently the transport and laying of long switches and crossings intended for high-speed rails. Parts of these switches and crossings are often very long and their conveyance within the manufacturing plant, loading and transport from the manufacturing plant and installation in a track during construction must be solved. During any handling process the parts of switches and crossings must not be subjected to more than a predefined maximum deflection to avoid the creation of permanent plastic deformations. It is also desirable that the parts of switches and crossings are transported to the site in a state which is as fully assembled as possible. Maximum preassembly in the manufacturing plant increases the speed of installation on site and also ensures that the installation of parts of switches and crossings is of higher quality.

7 High level design and integration of next generation control, monitoring and sensor systems

Next generation control, monitoring and sensor systems apply equally to all concepts, except for passive mechanisms (such as concept 'E' and concept 'V') that do not require control systems, although they can still be monitored.
For this reason, the ideas in this section can be applied to any future concept to enhance its reliability, improve maintenance planning and reduce downtime on the railway network.

7.1 Embedded multiple sensors

Sensors can be used to measure most of the parameters in S&C, traditional implementations usually only monitor current and voltage of the point machine, pressure in hydraulic or pneumatic systems and displacement in some newer machines.
Other parameters are usually unnecessary due to the complexity of installation. Embedding such sensors in the design of the S&C would allow for additional types of sensors to be used.

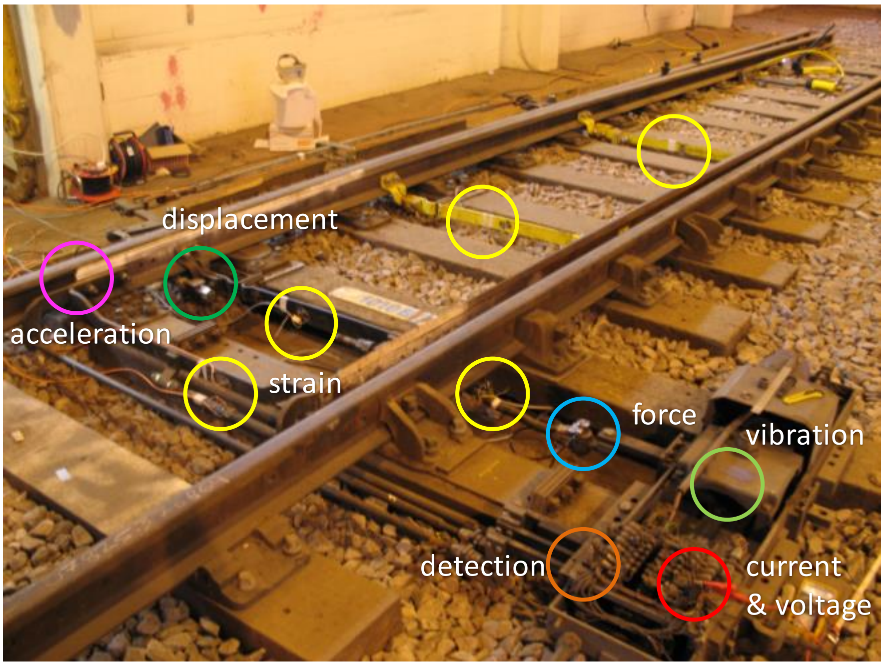


Figure 37. Distributed sensing

Sensors that can be embedded in the machine include:

- Pressure transducers (in hydraulic or pneumatic systems)
- Displacement transducers
- Load pins or strain gauges to measure the drive
- Current and voltage sensors to measure power
- Vibration sensors on the motor

Sensors that can be embedded in the rails include:

- Accelerometers along the S&C to measure impact forces, particularly at the toe and the crossing
- Strain gauges in stretcher bars
- Temperature sensors
- Smart washers that can measure the clamping force between S&C components

Sensors that can monitor the S&C externally:

- Microphones to listen for defects that generate noise in the machine or the mechanism
- Cameras to look for obstructions, measure displacement and remote inspection

7.2 Self-powered sensors

Sensors can be self-powered through energy harvesting, energy storage, or a combination of both. The following technologies are some that have been investigated for use in railways as part of the Capacity4Rail project [4].

- Solar
- Thermal
- Wind
- Electromagnetic
- Kinetic/Vibration
- Energy storage (batteries)

For sensors that are located trackside or in the machine, this is not necessary. For sensors located on the rails, the sleepers or embedded in the S&C, they will need to be self-powered and use wireless communications because the addition of a physical connection can cause problems for maintenance vehicles such as tampers and can make installation require additional time due to the need for track access to run cables and dig trenches.

7.3 Online monitoring and data integration from online sources

Online monitoring is key to reduce the need for maintenance teams to show up on track and increase availability of the network. The ability for experts to be able to review the data remotely and for maintainers to view the data on their computers or phones prior to leaving for the site to ensure that they have the correct equipment
Data integration from online sources can allow the monitoring system to be aware of the railway vehicles that are passing over the S&C or to include datasets from nearby weather stations to take temperature and rainfall into account for the monitoring and control algorithms.
Additionally, if the data collected from the monitoring system is made available online (even behind a secured framework), then other projects can make use of the data.

7.4 Ad hoc COMs network and standard interface 'Plug & Play'

A standard interface for both wired and wireless communications must be defined so that sensors can be added in a 'plug and play' fashion. Such an interface is being developed as part of In2Track and should be used in S-Code as well to allow for interoperability.
The communications will allow for multi-drop wired communications and ad-hoc wireless communications and will consider data rate and range requirements for the railway.

7.5 Adaptive and learning algorithms

Algorithms can make use of the data collected to learn how different faults manifest. There are a variety of different algorithms that can be used to diagnose faults ranging from expert systems to neural networks.
For the data collected from the sensors to be useful, the algorithms must be able to add fault detection through trending, fault diagnosis and fault prognosis along the lines of the ISO 13374 model for condition monitoring shown in Figure 36. This will allow for eventual advisory generation that can feed into the point machine's 'immune system' in an attempt to self-heal [20]. [21]

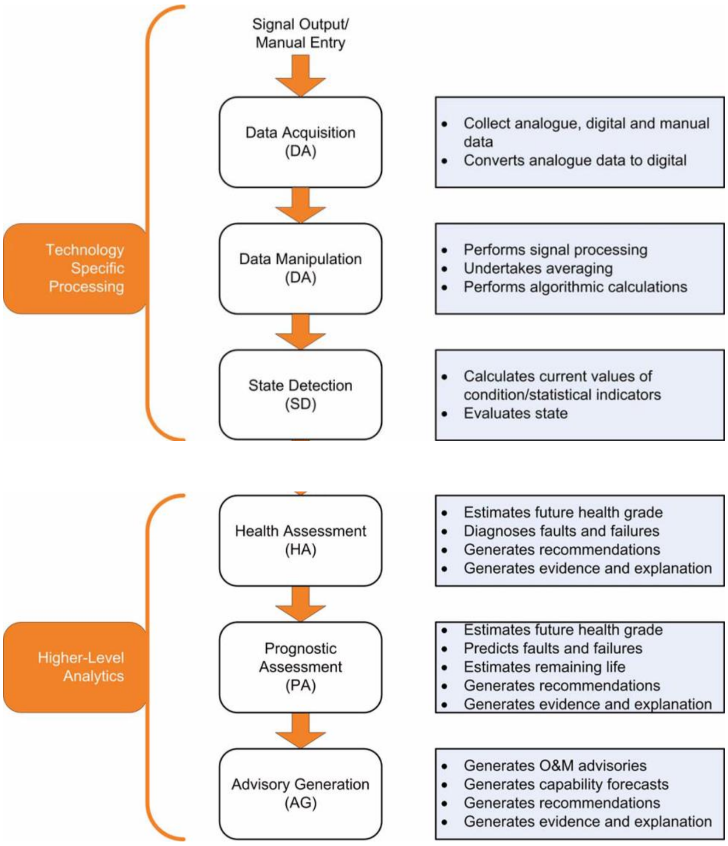


Figure 38. ISO 13374 model

7.6 Immune system (self-diagnostic) and fault-tolerant control

A control system will be developed that makes use of the sensors that are available to compensate for degraded functionality. This will allow the main actuator to compensate for faults that would cause existing actuators to stall or fail.
Additional actuators can be added that can respond to faults that the main actuator cannot deal with, this would allow the system to potentially respond to problems such as obstructions without the need for maintenance teams to visit the S&C [7].

8 High-Level mechatronic design for kinematic solutions

8.1 Actuators

Actuators are key elements of a kinematics system. The solutions presented in section 2 may require different types of actuations, i.e. linear, rotational, etc. Also, the suitability of the type of actuator will depend on particular requirements of the target solution and therefore, an optimal design and the suitability of a particular type of actuator will be explored further. Whilst evaluating their suitability, their key performances such as speed, force, power density (W/m-3) and efficiency will be considered along with their maintainability, durability and modularity [22]. Any design and operational complexity will as much as possible, limit the number of failure modes and simplify the implementation. The actuators may also be designed and developed to meet the bespoke requirements. Electro-mechanic, electro-hydraulic and electro-magnetic means of actuation will be explored in WP5.

8.2 Locking mechanisms

Due to the safety requirements in railways, movable switch components will need to be locked before the vehicle runs over them.

Currently, many S&C installations employ clamp locks such as shown in [23], [24] which secure the switch rail to the adjacent stock rail. A similar locking mechanism will be developed to achieve superior performance to the existing lock. Also, further analysis will be carried out for the suitability of the existing lock mechanisms.
The track switch design from project REPOINT features a mating profile section of rails which interleaves the rails and secures them from transverse motion. A similar approach may be used wherever possible, which could simplify the S&C and at the same time, achieve the functional requirement.

Electro-mechanic, electro-hydraulic and electro-magnetic means of actuation will be explored in WP5.

8.3 Redundancy

Frequently failing components may be improved upon by a better design and the introduction of six sigma in manufacturing. However, this does not guarantee 100% reliability. Where the safety and reliability requirement is high and/or operation failure costs are huge, redundancy is generally required.
Functional redundancy can be achieved mainly in two ways, multiple redundancy and high redundancy [14]. Multiple redundancy is where a component is placed n times to achieve n-1 redundancy, i.e., allowing the n-1 number of components to fail before the machinery/process becomes non-functional. The high redundancy concept uses the concept of connecting relatively large numbers of smaller components in series as well as parallel to build an overall component. In this case, the failure of fewer functional elements within the component does not impact on the overall performance and the reduction in performance will be gradual rather than sudden [14].
Functional redundancy can be statically implemented where all of the components take part simultaneously in performing the tasks and sharing the burden when a fault occurs in their peer component [25] [26]. A dynamic redundancy has only the required number of components taking part in performing a task and the standby components usually take over in the event of the failure of their peer component. Takahashi and Takagi [27] have developed a hybrid redundancy where the monitoring of input and output signals could be utilised to decide on the activation of standby components in dynamic redundancy.
The above-mentioned redundancy approaches will be exploited in the next phase of the project where the redundancies will be considered in multiple functional components such as sensors, actuators and controllers.

8.4 Mechatronics

The above-mentioned functional elements such as actuators and locking mechanisms will be provided with sensors and equipped with appropriate control strategy to allow them to make self-inspection and adjustments as and when the need arises. The inclusion of control strategy will make the track components smarter and will aim at reducing human intervention for trivial problems.

9 Key principles for next generation installation and logistics

9.1 Basic conditions and assumptions for high level design

Generally speaking the life cycle costs (LCC) for S&C as shown in Figure 39 are split into

- Planning;
- Realization;
- Operation and maintenance;
- Removal.

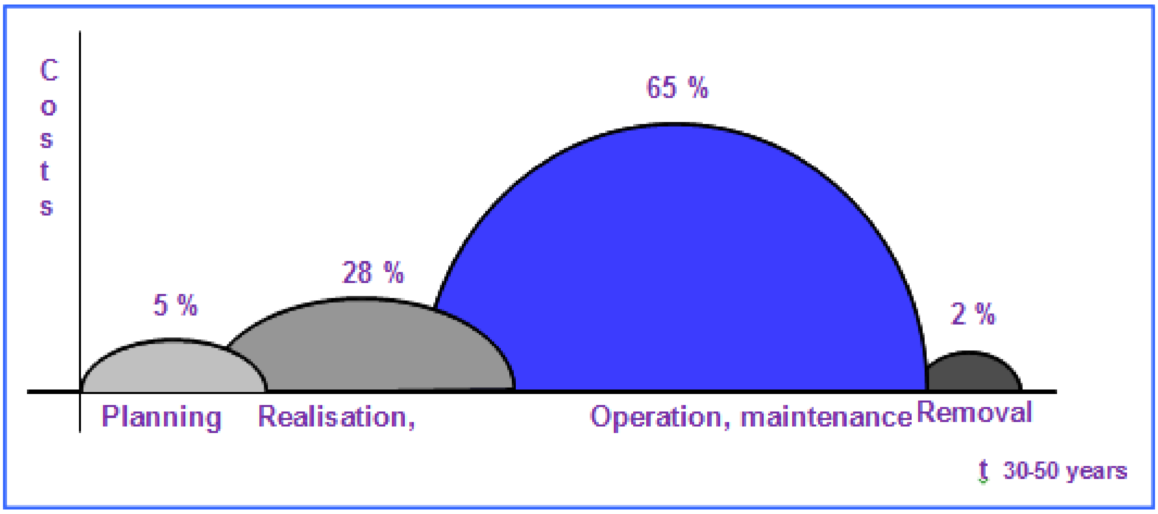


Figure 39. Typical distribution of costs of railway facilities according to their life cycle

These are the numbers experienced for present S&C units. One important target of the S-CODE project is to reduce the total costs by gaining additional availability. Of course, the planning has a significant input in the realization and each solution will have its own distribution of costs.

Task 2.5 considers the removal of existing facilities and installation of the new solution. At a later stage the removal of the newly implemented solution will also be elaborated to get the whole life-cycle of the "radical switch"

The question arises as to when to replace the "old" system with the new one.

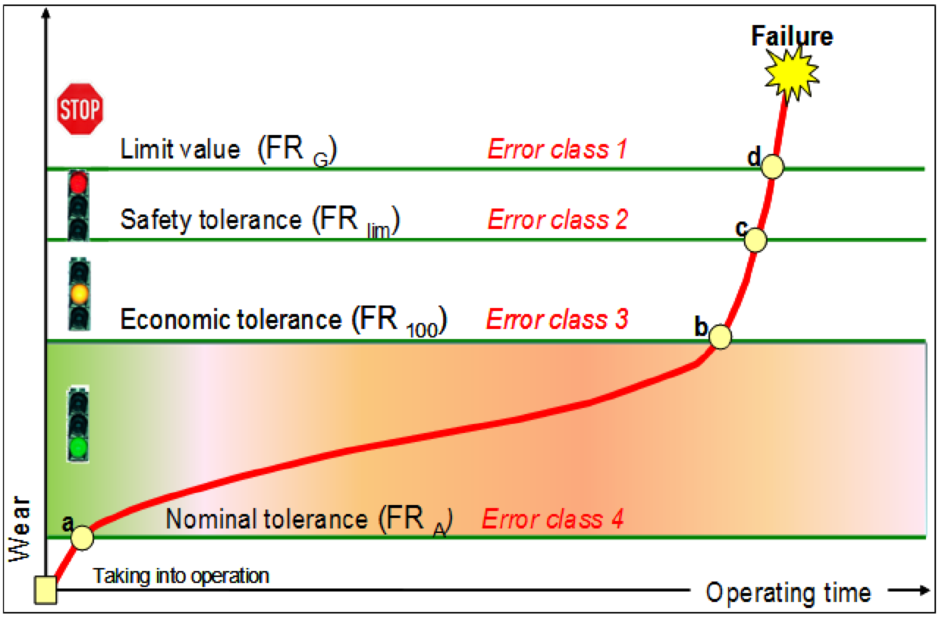


Figure 40. Schematic development of wear with evaluation limits: Tolerances (for the classification of measurement results) and fault classes (for classification of results out of visual inspections) FR = Fault-Reaction

The approach for elaborating Task 2.5 is based on a renewal before the safety tolerance is reached, so normal and planned operation can be carried out without restrictions before the renewal is executed.

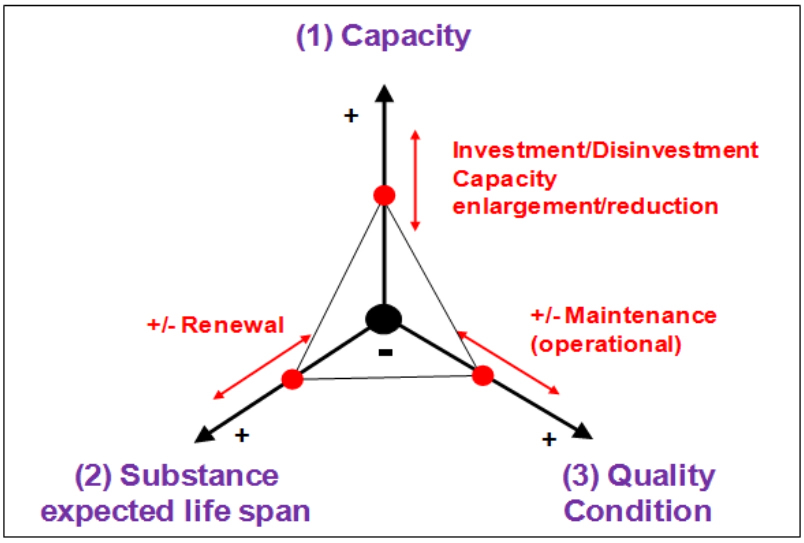


Figure 41. Key parameters of the infrastructure strategy and their most important relationships

9.2 S&C renewal on an actual basis

9.2.1 Basic assumptions and condition

Renewal projects for turnouts and crossovers are very demanding: the possession windows are short, the working space around turnouts and crossover can be very constrained due to their location within the rail network and access to the site can be limited and narrow. The usage of large track construction or renewal trains is not very productive; the complete closure of adjacent tracks is not always possible or needs to be avoided most of the time. In many cases track closures of 24hrs or more are common practice, but this can be an unsatisfactory long interruption of train traffic. In addition, a lot of people with complementing skills are working within a limited space, which increases safety risks. Rhomberg Sersa Rail Group (RSRG) has developed a methodology to reduce the required possession time and to bring the number of people on site to an optimum. In-house developed machines are combined with well-known and proven technologies as well as implementing training programs for a multi-skilled workforce.

Before starting, any S&C renewal project starts with a proper planning procedure. Once it has been established which switch or crossover needs to be replaced, the tracks to be closed to traffic are defined. Usually, this would be two tracks per S&C, i.e. one that is used for the removal of the old ballast, as well as to allow a crane to remove the old S&C elements and place the new ones. The other, adjacent track is used for the transportation of the S&C elements.

In order to be able to start the renewal operation soon after the tracks are closed to traffic, all the required machines and wagons are parked as close to the worksite as possible. Preferably, the same location should also be used after the S&C renewal intervention, so that a maximum utilization can be made of the given track possession.

Furthermore, it needs to be ensured that all necessary worksite protection measures are in place at the time of the intervention.

9.2.2 Key Personnel

Sufficient operating staff must be allocated to the worksite. However, this is not just a matter of counting heads. To efficiently achieve the high performance and quality of work required, the quality, expertise and experience of the personnel play a key role. Therefore, the training of personnel is of paramount importance and an issue that is not to be neglected. This training serves two goals: efficiency and safety.

As the machines in use today are highly complex, very well-trained personnel are needed to operate them to their full performance. A deep knowledge and understanding of the equipment is also mandatory to reduce the risk of accidents.
The introduction of multi skilled workforces, with machine operators, track workers and rail welders improves the work performance. Track workers and rail welders are still required to undertake the original tasks of track work, however they can support machine operators to prepare and operate specialist turnout renewal machines (W+, Reiner+, MFS+), which are discussed below, and tamping machines. The result is a reduction of non-productive work hours on site and a reduction of staff. A reduced work site area with one hotspot only is established rather than multiple hotspots along a larger work site. The workplace safety will benefit from this procedure.

9.2.3 Logistics

The next step in worksite organization for the construction itself concerns time scheduling for machine operation. Basically, there are three phases:
Phase 1: travel to the worksite and machine preparation;
Phase 2: the actual S&C renewal intervention;
Phase 3: machine closedown and travel from the worksite.

Figure 42. Working close to a live railway line

Phases 1 and 3 should be as short as possible. Besides the aforementioned requirement that, prior to the closure the machines should be stabled as close to the worksite as possible, the machines (once at the worksite), should quickly be put into operating mode. This process can be optimized by letting the machines with the first tasks start their work whilst the other machines required at a later stage are still being prepared for operation. Thus, a maximum utilization of the track possession is achieved. After works have been completed, the machines should quickly be closed down, ready for return travel to the stabling yard.
Phase 2 (the actual S&C renewal intervention) requires an optimal flow of material delivery and removal (just in time). For conventional switches, the WTM turnout transport wagons provide a quick and easy way for the logistics of S&C elements to be delivered to the highest quality, already tested in the workshop. In order to optimize the ballast logistics and minimize costs, it is essential that only poor ballast is removed. Good, re-usable ballast should be retrieved on site.

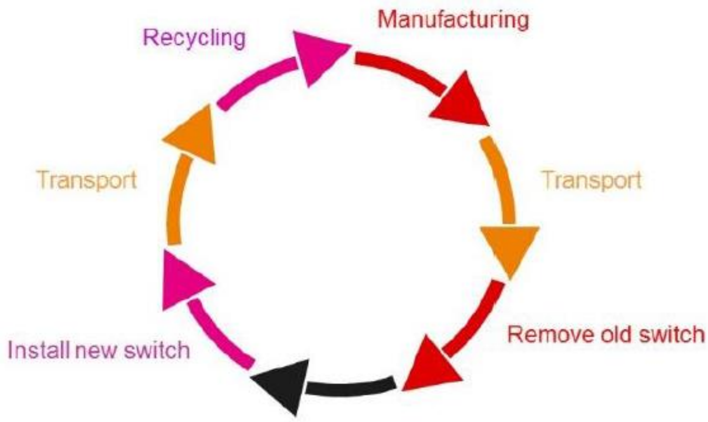


Figure 43. Closed cycle of T&C replacement (just in time)

By the combined use of the new high-performance W+ ballast excavation machine and the REINER+ ballast cleaning & transport wagon, a new dimension of performance in S&C renewal is achieved. Both machines have been developed by Rhomberg Sersa on the basis of a concept study by Sersa.

9.2.4 Description of the individual machines

The discussed method of S&C renewal is most efficient when combining the machines described below.

- **W+ and REINER+**

The continuously-working bucket-wheel excavator W+, which features an excavation capacity of up to 250m3/h, an excavation width of over 8 metres and an excavation depth of 1m removes the existing bottom ballast down to the top of the capping layer (or even lower if required). The excavated material is then conveyed to the large high-capacity screen on the REINER+, a multifunctional ballast screening unit. Cleaned and reusable ballast is returned directly to the W+, which then places the ballast as part of the new bottom ballast layer back into track. If required, additional ballast can be supplied from ballast trains (MFS wagons) moving on adjacent tracks and feeding the REINER+ by means of the Universal Material Handling wagon UMH (described below). Poor, non-recyclable ballast is transported from the REINER+, via its conveyor system, directly into an MFS+ ballast transport wagon (ballast shuttle).

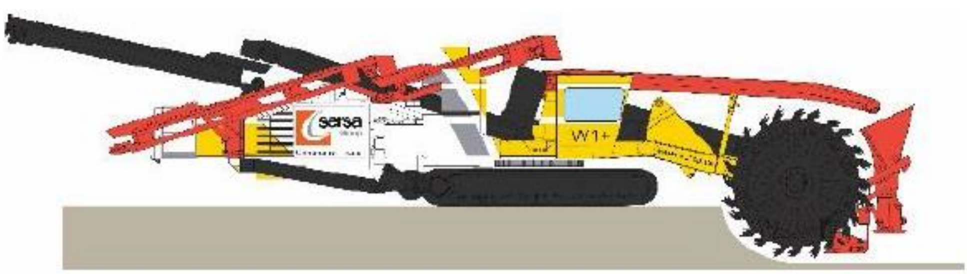


Figure 44. W+

The built-in survey system guides the W+ during the excavation process and guarantees that the design requirements regarding excavation depth and grade are met. This complex survey system includes a gyroscope to define the actual position of the W+ and a surface laser. The survey system will be set up by the machine operators, there is no need for additional survey field parties.

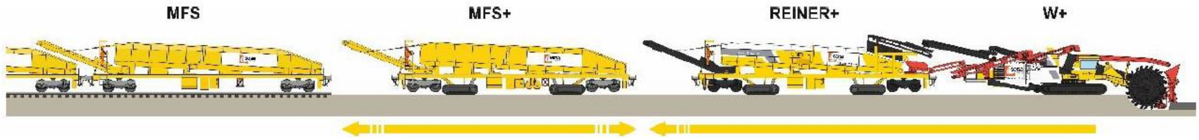


Figure 45. Set-up including Reiner+

The W+ and REINER+ are two independent machines, each equipped with both rail-bound travelling mechanism and caterpillar tracks. The latter allows them to travel on the trackless section where the turnout has been removed and to return to the track after work has been completed, with no ramps required and therefore saving time and costs. Once in operating mode, a complex communication system ensures a smooth and safe interaction between the two machines and as a result a very efficient operation.

- **MFS+ and MFS**

The ballast transport wagons MFS+ (transport and storage spoil hopper) and MFS (various spoil hoppers) represent an optimal compromise between size/weight and transport volume. The MFS+ works as a material shuttle between the Reiner+ and the MFS wagons to allow for continuous work of W+ and Reiner+. The number of ballast transport wagons used is determined on the basis of the amount of ballast to be excavated and the expected ballast quality, which also allows the stabling area required at the station nearby to be kept to a minimum. If more ballast has to be disposed of than initially anticipated, then this poses no problem as the MFS/MFS+ together with a transfer unit called UMH are capable of unloading ballast to the side of the track or into standard (and cheaper) ballast wagons on the adjacent track. Alternatively trucks parked on nearby access roads can be loaded.
As the MFS+ needs to travel between track and trackless sections, it also features caterpillar tracks, unlike the MFS which operates rail-bound only. A centering system for the front bogie and rollers in front of the rear caterpillar tracks of the MFS+ allows for a rapid re-railing back on track.

- **UMH**

The Universal Material Handling wagon (UMH) is usable for a variety of options to manage materials like formation and capping material or ballast:

- Buffer / spacer wagon for MFS wagons.
- Transfer of excavated materials from MFS into empty wagons parked on adjacent track.
- Placing of new materials from MFS into worksite from adjacent track.
- Placing of top ballast using ballast sleeves to control distribution.
- Feeding of REINER+ with new ballast from adjacent track.

Figure 46. UMH placing excavated material

- **Rail crane**

A rail crane (e.g. from supplier Kirow) works with a telescopic jib to use its full working radius. Rail cranes offer the ultimate on-rail lift and carry capability in a highly flexible configuration which can work on virtually any worksite. The rail mounted crane has numerous design features including: an integral safety management system (PAT) to monitor and control all lifting duties both free on rail and propped. A self-leveling device which allows the full duties to be utilized on track cant up to 160mm.

- Ability to operate at full duties with boom horizontal, allowing long and heavy loads to be carried free on rail.
- A range of lifting beams delivered with the crane and the associated runner wagons, a range of lifting beams will be carried by the crane unit to meet specific client and company requirements on individual worksites.

At best only one large crane (e.g. KRC1200) should be used to remove the existing T&C panels and place the new T&C components in a very efficient way.

Figure 47. Kirow crane placing new panels

- **WTM**

The turnout transport wagon WTM (also known as WTW) enables efficient transport of all types of turnout at least up to size of 800:18.5 and sleepers of up to 4.8 meters in length. As an option, the loading platform can be moved sideways into a horizontal position by 500mm so as to avoid obstacles such as posts, platforms or so as not to interact with the clearance requirements of the adjacent track. Both ends of the WTM are equipped with floodlights, removing the need to install lighting at the worksite when working in the dark.

Figure 48. WTM

- **Turnout tamping machine**

A versatile turnout and plain track tamping machine can achieve optimum performance levels and complete the tamping tasks of the renewed and re-installed turnout and track components.

- **Ballast regulator**

A high capacity ballast regulator with an in-built ballast hopper for ballast recovery and redistribution completes the T&C renewal process in the most efficient way.

9.3 Parameters for working on selected S-CODE solutions

After discussing the actual technology for the renewal of existing S&C, the question now is how to approach the implementation of the new solution. However, it is not yet determined if the part to be replaced will affect the whole turnout or just a single part, and it is not fixed where these interfaces will be or which type of equipment will be used. Every solution which is more or less "radical" has a certain impact and complexity. Therefore, the following parameters will serve for the high-level design considerations and will form the basis for further more detailed work at a later stage:

9.3.1 Size

The actual size of the pieces to be transported and located at the right place has a significant impact on the whole logistic chain and handling.

9.3.2 Weight

Similar to the size, the weight of items to be handled makes a big difference in installation considerations.

9.3.3 Complexity for installation

The question of whether just one item or many small items have to be connected and installed demands different approaches and logistic solutions.

9.3.4 Level of prefabrication

In context with the complexity of the system, the possibility of prefabrication (under considerations of size and weight) will have an impact on the methodology. Further on in the design, quality assurance and procurement have to be adapted accordingly.

9.3.5 Sensitivity to handling

The robustness of the new solution to be implemented affects the equipment for transport and installation as well as the workforce. A lot of starting quality is actually lost by not giving enough consideration to the right early treatment during manufacturing, transport and installation.

9.3.6 Level of renewal

The level of renewal will consider the necessity of movement of masses and volumes. Remaining material or the entire replacement of a S&C unit plus changes of the subgrade and/or sub-ballast have to be considered and treated accordingly.

9.3.7 Efforts for new equipment

The closer the new "radical" switch will be to the existing technology, the more already existing equipment can be used in the future – or maybe existing equipment will be enlarged by adding modules or similar. These differences will have a significant impact on the time and cost of renovation.

9.3.8 Time of closure

More complex works with heavy equipment and a lot of people on site or a high possible level of prefabrication, assembling and preparation prior to the actual works of replacement determine the required time for closure. Here we shall have an idea of the possible consequences of the different solutions.

9.3.9 Safety and level of required measures

Here we will resolve the question of what items, parts and pieces have to be changed, how eventual hardening or curing processes affect the time until re-opening, what type of cuts and weldings leave the track open, and how steering and monitoring systems will be integrated into the system. These and other factors are also crucial to determine the safety level for works and operation.

9.3.10 Magnitude of personnel involved

Part of the evaluation of the renewal and installation is also understanding the number of people required and their level of education. The method and its feasibility also has to include a description of the different steps required and the people needed for execution of the replacement.

9.3.11 Costs for renewal and installation

Here the pure costs for the works and efforts to install the new items and replace the old ones will be considered. These costs do not include those which relate to the system itself as this is discussed in a different work package.

10 REFERENCES

[1] L. Le Pen, G. Watson, W. Powrie, G. Yeo, P. Weston e C. & Roberts, "The behaviour of railway level crossings: Insights through field monitoring.," *Transportation Geotechnics,* vol. 1(4), pp. 201-213, 2014.

[2] B. Palsson, "Design optimisation of switch rails in railway turnouts. Vehicle System Dynamics, 51(10), 1619–1639. https://doi.org/10.1080/00423114.2013.807933".

[3] B. Palsson, "Optimisation of Railway Switches and Crossings.," 2014.

[4] Capacity 4 Rail (7th Framework Programme), "D4.2.2 Next generation monitoring and inspection technologies," 2013-2017.

[5] S. Whitmore, Understanding Track Engineering, 2014.

[6] J. Blitz e G. & Simpson, "Ultrasonic Methods of Non-Destructive Testing.," *New York: Springer - Verlag,* 1991.

[7] S. D. Bemment, E. Ebinger, R. M. Goodall, C. P. Ward e R. Dixon, "Rethinking rail track switches for fault tolerance and enhanced performance," *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit,* 2016.

[8] M. F. Rusu, "Automation of railway switch and crossing inspection. School of Electronic, Electrical and Systems Engineering, University of Birmingham," 2017.

[9] In2Rail (H2020 Research and Innovation Programme), "Deliverable D2.3 Embedded & Integrated Sensors: Systems Design Hierarchy Report," 2014-2017.

[10] R. Bogue, "Sensors for condition monitoring: a review of technologies and applications.," *Sensor Review,* vol. 33(4), pp. 295-299, 2013.

[11] In2Rail (H2020 Research and Innovation Programme), "Deliverable D2.7 Self Inspecting / Adjusting S&C: Systems Concept Design Report.," 2014-2017.

[12] T. Asada, "Novel condition monitoring techniques applied to improve the dependability of railway point machines.," University of Birmingham, 2013.

[13] K. S. Grewal, R. Dixon e J. T. Pearson, "Model-based fault detection and control design applied to a pneumatic Stewart-Gough platform. Actuator 10, 12th Conference on New Actuators, Bremen, Germany, 14-16 June 2010".

[14] T. Steffen, F. Schiller, M. Blum e R. Dixon, "Analysing the reliability of actuation elements in series and parallel configurations for high-redundancy actuation," *International Journal of Systems Science,* vol. 44, nº 8, pp. 1504-1521, 2013.

[15] Y. Chen, J. Yu e S. Khan, "Spatial sensitivity analysis of multi-criteria weights in GIS-based land suitability evaluation," *Environmental Modelling & Software,* vol. 25, nº 12, pp. 1582-1591, 2010.

[16] S. D. Bemment, R. Dixon e R. M. Goodall, "Railway Points," 2015.

[17] T. T. Ivo Špička, "Aditivní výroba a automatizace ve slévárenství," *Slévárenství 3-4,* 2017.

[18] J. Hodek, "Aditivní technologie. Zpráva o stavu 3D tisku pro Českou technologickou platformu STROJÍRENSTVÍ," 2013.

[19] I. Gibson, "Additive Manufacturing Technologies," *New York: Springer,* 2010.

[20] H. Bai, "A generic fault detection and diagnosis approach for pneumatic and electric driven railway assets.," University of Birmingham, 2010.

[21] J. A. Simon, "Operational industrial fault detection and diagnosis: railway actuator case studies. Department of Electronic, Electrical and Computer Engineering, University of Birmingham.," 2009.

[22] J. E. Huber, N. A. Fleck e M. F. Ashby, "The Selection of Mechanical Actuators Based on Performance Indices," *Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences,* vol. 453, nº 1965, pp. 2185-2205, 1997.

[23] AZD Praha, "VZ 200 – JAW (CLAMP) POINT LOCK," 2017. [Online]. Available: https://www.azd.cz/admin/files/Dokumenty/pdf/Produkty/Kolejove/40-VZ-200-ENG.pdf. [Acesso em 22 09 2017].

[24] Schwihag AG, "Switch locking device," 2009. [Online]. Available: https://www.schwihag.com/en/products/switch-lockingsystem.html. [Acesso em 22 09 2017].

[25] L. F. Corio, R. L. Brundrett, M. Ralea e R. W. Brown, "Electromechanical braking system with power distribution and redundancy". United States Patente US 6402259 B2, 11 06 2002.

[26] S. D. Bemment, R. M. Goodall, R. Dixon e C. P. Ward, "Improving the reliability and availability of railway track switching by analysing historical failure data and introducing functionally redundant subsystems," *Proceedings of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit,* pp. 1-18, 2017.

[27] M. Takahashi e T. Takagi, "Adaptive fault-tolerant control based on hybrid redundancy," *Asia-Pacific Journal of Chemical Engineering,* vol. 7, nº 5, pp. 642-650, 2012.

[28] R. de Roos, Functional description Winterproof Railway Turnout Version 2.0 (WRT 2.0).

[29] Innotrack (6th Framework Programme), "D3.3.4 Algorithms for detection and diagnosis of faults on S&C.," 2006-2009.