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Development and Evaluation of New Concepts and Systems for Railway Switches and Crossings

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Abstract

The Shift2Rail/Horizon2020 project "Switch and Crossing Optimal Design and Evaluation" (S-CODE) is a partnership of nine organizations who have come together to consider radical solutions for the future of railway switching. The project used horizon scanning and backcasting techniques to identify potential game-changing technologies and concepts that may feature in future switch designs. Technical development and evaluation work streams have elaborated and prototyped these elements, allowing evaluation of their suitability both in isolation and as integrated sub-system solutions. The project is currently developing subsystem demonstrators and recommendations for technological elements to be included in future switching solutions. This paper presents a subset of the concepts and some of the technological developments being considered across the different technical work streams. The paper considers: condition monitoring and fault-tolerant control, wheel/rail interface optimization, locking and actuation mechanisms, Neoballast, and self-healing concrete and composite bearers, in the context of three novel S&C concepts.

Keywords: Switches and Crossings (S&C); Railway tracks; S-CODE project.

1. Introduction

Railway track switches and crossings which are among the most valuable assets of the railway network, guide the vehicles to different routes securely. The safe performance of switch systems is important because any failure or faults in these systems can potentially lead to accidents, and their performance impacts the overall capacity and reliability of the rail network. The aim of the S-Code project is to achieve a cost-effective and reliable infrastructure within the Shift2Rail Joint Undertaking under the European Union's Horizon 2020 research and innovation program. The present research aims to identify radically new technological solutions at technology readiness level 3 or 4, which can be developed in other Shift2Rail JU projects, such as In2Track2, in the future (Network Rail Infrastructure Ltd, 2019)

Most conventional switch systems use switch rails which slide laterally over slide chairs. This movement is guided by mechanical linkages and the source of actuation has now evolved from a mechanical lever to electro-mechanical, hydraulic and pneumatic means. But the basic operating principle and the actuation method has not changed much since the inception of railways, and switches are still one of the assets which need a high degree of maintenance for the smooth running of the system. Thus, there is a need to improve these systems to improve the reliability of the rail network.

Recently, several researchers have focused on individual elements of switch systems to improve their functionality. The concept of multiple redundancy in actuation, which was motivated by aerospace research, is used in Repoint type of actuation mechanism (Bemment et al., 2017) . The new approaches to condition monitoring are employed in the switch system which can improve its reliability (García Márquez et al., 2008, García Márquez et al., 2010). The introduction of a closed loop controller into the switch system can also improve the switch actuation and ensure safe operation of the system (Dutta et al., 2018, Kaijuka et al., 2018). The impact of the vehicles over switches and the effect of run-throughs was studied by (Shih et al., 2017). New ballast designs such as Neoballast (Fontserè et al., 2016, Sol-Sánchez et al., 2018) show higher abrasion resistance which can be used in new switch systems to improve the ballast track dynamics, which is also researched widely. New design concepts and materials for the sleepers have also been developed which can improve the performance of the network (Griffin et al., 2015). But an integrated approach to bring all these concepts and new innovations into different sub-systems within a switch system has not been explored much.

The present S-CODE project aims to investigate and develop radical new ideas for switches and crossings (S&Cs) which aim to increase the capacity, reliability and, most importantly, the safety of the rail network (University of Birmingham, 2019). In this study, the switch and crossing of today is being considered as the benchmark to be improved with a concept of the future, so no limitations of the current concept are listed. The initial phase of the project has focused on the requirements of the switch systems and on horizon scanning to identify and generate potential solutions to be used in a radically new switch system. In this phase, different possible concepts were generated for different subsections of railway track switches, such as actuation, the locking mechanism, detection, ballast, new permanent way design, sensors etc.

The second phase of the project focused on evaluation of the concepts in a modular way and integrated different concepts which can be developed further. The main objective of this phase was to group those selected concepts to form a technology tool kit. As an example, the new concept of a back-to-back bistable switch actuation mechanism was integrated with the use of a feedback controller to follow the trajectory and control the motion of the switch rails. The last phase of the project focuses on validation of the concepts and future advancements. The individual concepts were developed as physical or software demonstrators and then evaluated against the readiness levels. Then, the technology tool box modules, which consist of more than one individual concept were evaluated.

In this paper, the different concepts which were generated in the horizon scanning process are discussed in section 2, which further explains the three downselected novel S&C concepts. Section 3 describes different mechatronic solutions for the switch systems which include condition monitoring and fault-tolerant control techniques. Section 4 focuses on new technologies in infrastructure components, such as actuation and the locking mechanism. Developments in substructure like ballast and bearers are discussed in section 5. The next section describes the logistics and feasibility study of the different concepts and subsystems.

2. Horizon scanning

2.1. Evaluation of ideas for a novel S&C

Amongst a consortium of engineers from different organizations, ideas were generated in several rounds of brainstorming on how future S&Cs should overcome the disadvantages of the conventional S&C. The consortium comprised engineers from industry and academic research fields with varied fields of expertise such as track, infrastructure, mechanical and electrical engineering as well as regulatory roles. They belong to nine organizations distributed in four countries of the EU.

These discussions, along with a review of different S&C designs existing in various parts of the world, led to a comprehensive list of 22 novel concepts. These concepts were then systematically evaluated using detailed criteria and weightings. Thorough evaluation with a Pugh matrix (Chen et al., 2010) gave a ranked list of these concepts. Sensitivity analysis was performed on this ranked list to verify the robustness of the results. Consistency of the ranks were verified against the weightings given to criteria, evaluators from individual organizations and the expertise of engineers. The top three concepts as described in the section below were further analyzed for their feasibility.

2.2. Novel S&C concepts

The following three subsections elaborate the downselected concepts which resulted from evaluation. These concepts were studied further with multi-body simulation (MBS) and finite element (FE) modeling methods for quantitative analysis. In parallel, a SWOT analysis was also performed to assess them qualitatively.

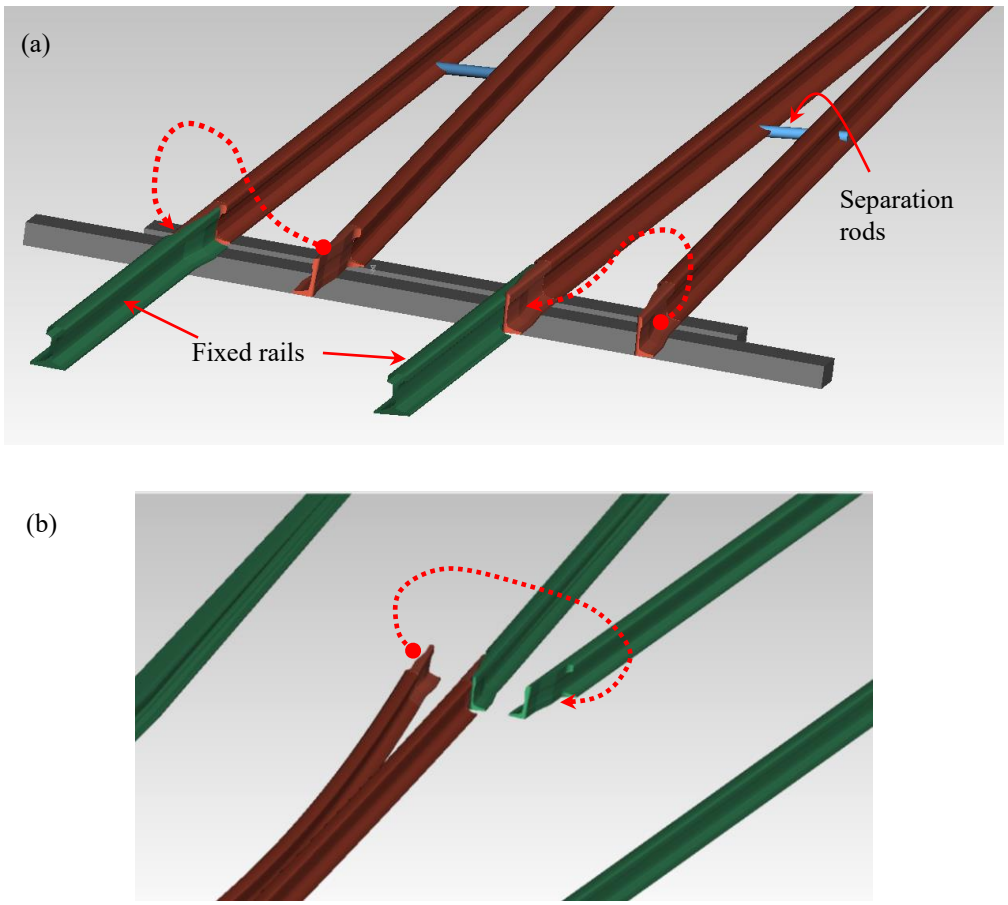

Fig. 1: Back to back bistable concept showing actuation trajectories at (a) switch (b) crossing regions

2.2.1. Back-to-back bistable S&C

Overcoming some disadvantages of the linear actuation in a conventional S&C, this concept suggests curve-type actuation with the help of a linkage mechanism. An expansion joint is designed between the switch and stock rail for a better wheel load transfer. In the crossing section, the crossing nose has also been replaced with an expansion joint. These details along with shapes of the actuation trajectories are shown in Fig. 1.

Simulations from multi-body dynamic analysis have shown that it leads to an improvement the lateral wheel-rail peak forces by 31% in the switch region. Due to the absence of a crossing nose, thereby eliminating impact forces, the lateral wheel-rail peak forces are reduced by a factor of three at the crossing region.

2.2.2. Single slender S&C

The pivotal element of this novel concept is the single switch blade over the entire length of the turnout. This switch blade functions in both directions and the main expected advantage is the fact that most stress is on a single movable part located in the turnout, which can be quickly replaced with a completely new one during maintenance work, if necessary, thereby significantly shortening the track closure time needed.

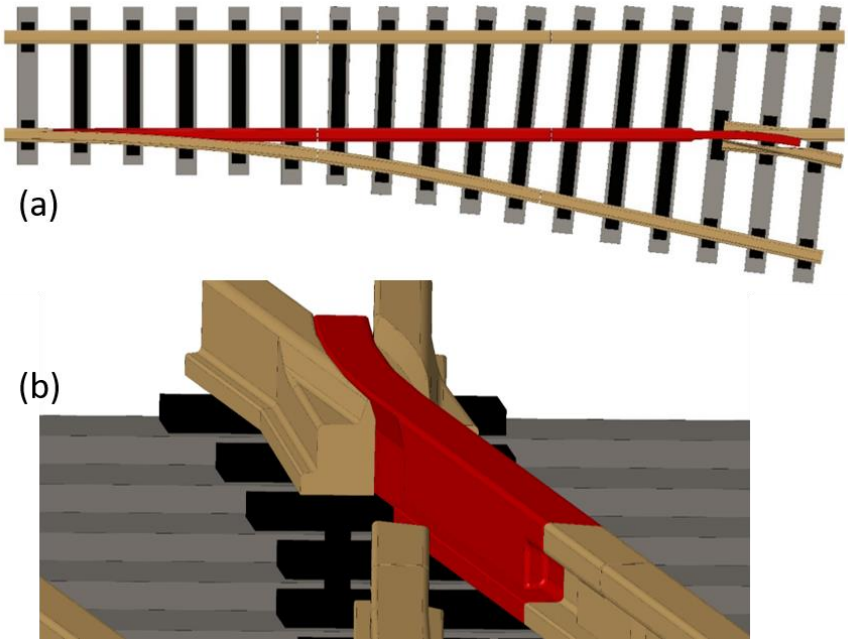

Fig. 2: Single slender S&C concept (a) Its layout in a turnout (b) Crossing region

Firstly, the Single Slender Switch alternative was elaborated according to the original idea, i.e. with a single long switch blade across the entire length of the switch as shown in Fig. 2(a). The solution of the concept was divided into three partial issues. The first is a solution for the 'switch panel', i.e. the point of the switch blade's contact with the stock rails and the wheel transition. The second partial solution is the 'crossing panel', i.e. the point where the switch blade is in contact with the fixed rails at the end of the switch. The last area considered was the issue of switching and locking the switch blade. Some problems were identified in that concept, particularly in the "switch part" in terms of switch rail geometry. An intermediate solution has been found, in which the switch section can remain as a conventional switch, while only the crossing section is modified as shown in Fig. 2(b). The solution for the "crossing" has been found to be useful for the next step of development as a new type of crossing with movable parts.

2.2.3. Vehicle based switching

The third concept pushes the steering action to the vehicle ideally by a mechatronic system and restrict the track switch to being passive and non-moving. This entire new operation method paves the way for automatic or autonomous decentralized driving over a longer time horizon. This paradigm shift needs to be implemented with an appropriate migration plan which gradually reverses the role of the switching action to the vehicle.

3. Mechatronics

Improving the reliability of S&Cs, which is one of the goals of this project is achieved using mechatronics. With the help of sensors and algorithms, deteriorating conditions can be identified earlier, and faults can be overcome without affecting the downtime.

3.1. Condition monitoring

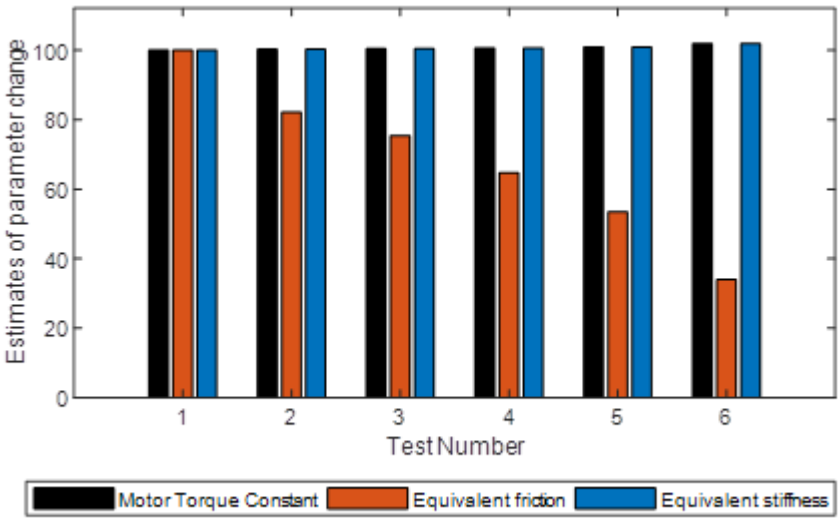

Fig. 3: Estimation of parameters (as a percentage of nominal values)

Switch systems are prone to failure which can lead to accidents. Thus, scheduled maintenance procedures are needed to ensure the safety of the network. The maintenance of the switch can be improved by monitoring the health of the switch system.
A model-based condition monitoring approach was developed and integrated with a MBS model in Simpack®. Several tests were performed with degraded parameters in the switch panel and actuation mechanism (motor torque constant, friction/damping elements of the system, stiffness of the components and inertia of the system). The simulation study showed that the estimation technique developed is able to determine any changes in the system parameter. The two types of sensor data used in this method are motor current and displacement of the switch rails, which are available from the selected switch (Dutta et al., 2018). Fig. 3 shows the estimation of the parameters over six tests in a case where the frictional resistance between the sleeper and the switch rails.

3.2. Fault tolerant systems

Advanced controllers rely on feedback signals from sensors in the railway network which are often exposed to harsh environment and can fail. Any fault in the sensor data can affect negatively the system performance, and in turn reduce the overall reliability of the system. With advances in the controller of the switch actuator, it is important to develop a control algorithm, which is tolerant to any sensor fault.

The actuator of the switch systems is developed to control the movement of the switch rails with feedback data from three sensors, which are motor current, motor velocity sensor and displacement sensor. The fault tolerant control scheme developed (shown in Fig. 4) accommodates faults occurring in these sensors. In the event of sensor failure, they are detected and substituted by signals generated by observers, thereby not affecting the overall functioning of the S&C. The future aim of the work is to integrate the fault tolerant control approach with the condition monitoring algorithm for better maintenance of the switch system.

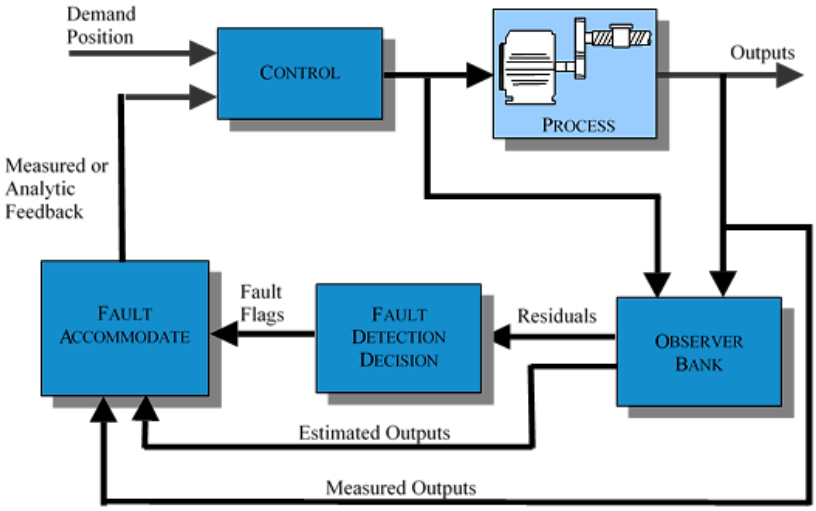

Fig. 4: Fault Tolerant Control approach for the railway switch actuator

4. Developments in infrastructure components

Different areas of the infrastructure were analyzed by teams of engineers and are summarized below. They include wheel-rail interaction as well as incorporating mechatronics for rail locking and switch actuation.

4.1. Improved wheel-rail interface modeling

The results of the research activities for wheel-rail interface modelling are based on a new approach to computation of railway vehicle dynamic behavior passing over the turnout. The new approach takes into account the transition of the wheel-rail contact point from the wing rail to the crossing nose. The new approach to the computation of a wheel-rail contact enables the acquisition of more exact courses of the appropriate turnout component loading.

Using the radically improved interaction between wheel and rail which was implemented into the software "SJKV UPa" leads to these new opportunities:

- Analysis of the dynamic effects of the vehicle running on the exactly determined trajectory of the turnout rails (theoretically defined as well as measured).
- Consideration of the rail support parameters' variability along the full length of the turnout.
- Analysis of the wheel and turnout rail profile wear to increasing their service life and operational safety in high-speed conditions.

4.2. Locking mechanisms

The current locking mechanism locks the switch rail against the stock rail by mechanical components which are of different types such as clamplock and Facing point lock (FPL). However, this design does not accommodate the wear in different components over time, after which the locking becomes less effective.
Two types of locking have been proposed to overcome this disadvantage. The first method uses smart materials such as a dilatant or magneto-rheological fluid. Due to their fluidic nature at some of their operating ranges, they can tolerate very well the dimensional changes due to wear of a conventional lock. The second type of locking uses the theory of magnetism by either permanent- or electro-magnets. Detailed force calculations aided with CAD models show that it is very feasible to lock the rails using magnets. Electromagnetic compatibility was also analyzed to prove that there is no significant effect of this concept on the electromagnetic environment of the rail body.

4.3. Novel actuation

Hardware redundancy is necessary for critical or frequently failing components to ensure a fault tolerant operation. In this regard, a high redundancy actuator (HRA) was built with a number of smaller actuating elements (Dixon et al., 2009). They are assembled in series and parallel to achieve the equivalent displacement and forces respectively. This concept as shown in Fig. 5 is being analyzed to evaluate its ability to withstand lateral forces coming from

the rail environment.

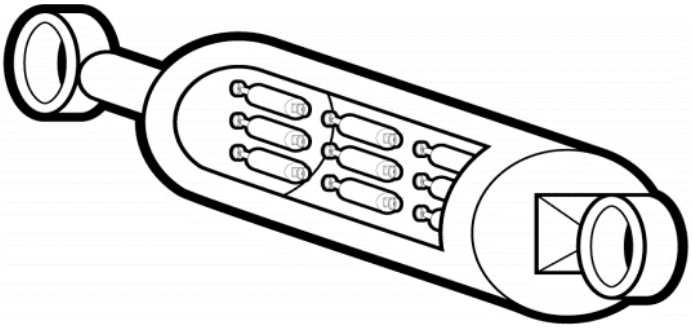

Fig. 5: Conceptual design for a high-redundancy actuator (Dixon et al., 2009)

5. Developments in substructure

There are many items of the substructure such as ballast, sleepers and bearers which were also developed to create a novel track substructure. They are described below in respective sections.

5.1. Neoballast

Neoballast (COMSA, 2019) is a new solution consisting of a conventional ballast aggregate covered by an innovative coating made of rubber powder coming from end-of-life vehicle tires and an advanced binder that adheres it to the stone. The main benefits of Neoballast are a longer lifespan, a reduction of stiffness, better performance in terms of noise and vibrations (N&V) and increased energy dissipation and load distribution, which in turn can lead to a reduction of the ballast layer thickness. Neoballast is, therefore, very convenient in areas with large ballast degradation, in urban areas, which typically have N&V problems, in tunnels and bridges with reduced gauge and in high stiffness zones of the track, such as S&Cs. In addition, Neoballast provides a larger contact area with sleepers, which implies less track deterioration and maintenance needs for the track in general and S&Cs in particular. It can be used with recycled aggregates and low quality aggregates (e.g. limestone) which are not fit to be used as ballast. Finally, it can also be combined with other solutions for track support (e.g. plastic bearers, FFU sleepers).

(a) (b)

Fig. 6: Neoballast (a) whole and (b) dissected

5.2. Self-healing concrete bearers

Concrete is a common material used in rail infrastructures. In the S-CODE project, a novel innovation in crumb rubber concrete has been developed to co-create key dual benefits: (1) improved damping of material against poor performance under occasional impact load conditions and (University of Birmingham, 2019) enhanced self-healing capability to automatically heal small cracks in concrete bearers in order to considerably increase component durability by accelerated crack filling. Through the use of modal testing, ultrasonic pulse velocity tests, and micro-scope crack measurements, the study revealed that the novel crumb rubber concrete demonstrates self-

healing capability in which the self-healing rate of the sample with 2% fibre is the highest, and increases from 3.6% to 3.8% at around 30 days after cracking (Huang and Kaewunruen, 2019).

5.3. Composite Sleepers and Bearers

Fibre-reinforced foamed urethane (FFU) composite has recently gained momentum in application for support infrastructure of S&Cs, due to its superior performance under service load conditions and relatively much lower life cycle cost and carbon footprint (Kaewunruen et al., 2017). In this project, design optimization of FFU composites has been established. Despite the recent popularity of FFU composites, there is no design guideline or maintenance standard (Silva et al., 2017). Using non-destructive testing approaches such as modal analysis and acoustic emission (AE) insights into the structural behaviour, service performance and failure mode of the FFU composites, and the relationship between cumulative damage and responses were obtained.

Fig. 7: Laboratory test showing failure mode (brittleness) of FFU composite bearers

A proof of concept for 3D printing of composite bearers was carried out following the success in applications of FFU composite to S&Cs. Numerical simulations and small-scale experimental tests were carried out. An FE model was adopted to create the novel functionally graded composite material by implementing various layers of 3D-printed full-scale composite bearers. The structural response of 3D printed composite bearers was then benchmarked with the performance of FFU composite bearers subjected to a three point bending test. The experiment results, which were obtained earlier, are used to validate the models. The parametric studies on the thickness of various layers and material properties were carried out, to optimize the design of the 3D-printed composite bearers.

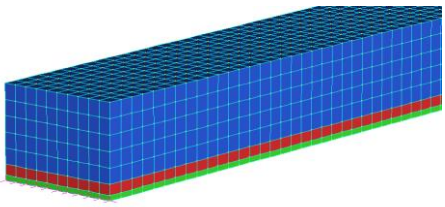

Fig. 8: 3D-printed, functionally-graded composite bearers

6. Feasibility and lifecycle analysis

6.1. Feasibility study of technologies

The S-CODE project also focuses on feasibility, validation of new concepts and technologies and their demonstration. The selected technologies, which were developed in more detail, were validated or verified in laboratories, with the help of demonstrators, or in simulation up to Technology Readiness Level (TRL) 4 in all major areas of the solution, i.e. monitoring and sensor system concepts, materials and components concepts and kinematic system concepts. Most of the demonstrators are in the physical sample design stage, and appropriate testing of required properties are expected in upcoming stages of the project. They are either models of new switch

concepts, real product parts of the future element (e.g. Neoballast) or related hardware equipment. Some demonstrators such as mechatronic monitoring systems exist as validated algorithms.

Emphasis is also placed on the combination of individual technologies and system integration and hence one complex demonstrator (section of the switch part) is being prepared. This contains two segments of plastic FFU sleepers, an innovative rail fastening system with replaceable cartridge and magnetic locking. The demonstrator will also include the stock and switch rail segments. The results will then be evaluated in the final phase of the project.

6.2. Integration, Installation and logistics

The selected technologies within S-CODE do have a very different impact on the efforts to implement them. The more radical the approach, the more severe the consequences for implementation of the system within the existing network. As possession windows are short and the work space around turnouts and crossovers can be very constrained due to their location, the use of large track construction or renewal trains are not always very productive.

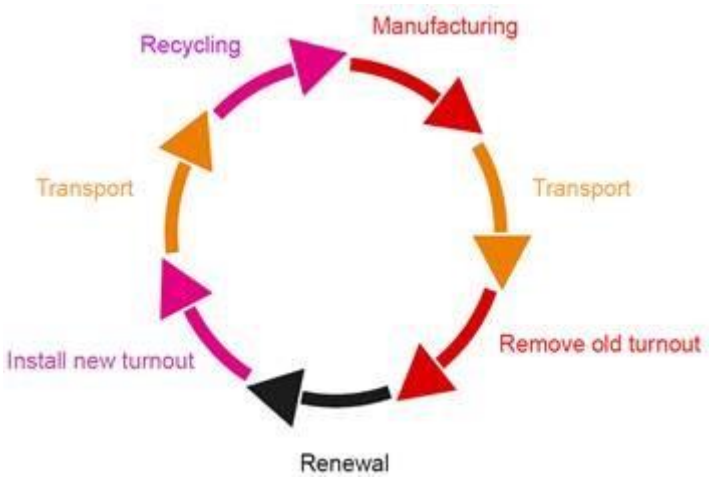

Fig. 9: Best practices diagram for a switch and crossing

Thus, one of the topics within the project was to estimate the effects on installation and logistics by applying different methods. Best practice of existing methods or other measures to improve the final quality of the structure by looking at the entire life cycle were considered and they are listed below. These measures are pictorially represented in Fig. 9 and listed as guidelines below.

- Always consider principles to lower risks associated with handling of sensitive rail products,
- Clear labelling of turnout parts,
- Details such as dimensions and weight should be readily available and at hand,
- Lifting and hoisting equipment suitable for the task/shape of product,
- Clearly marked and sufficient attachment points,
- Order in which the delivery should take place,
- Detailed assembly of single units.

In order to calculate and evaluate the impact of the selected alternatives, an evaluation matrix has been developed to quantify the impact, and includes criteria such as size, weight and costs. The results of the evaluation made within S-CODE will help to evaluate and calculate the costs and effects of implementing different solutions.

7. Conclusions

This article has discussed several novel concepts for the switch and crossing of the railway track and also developed most of the subsystems within it. Starting from mechatronic solutions and extending to installation and logistics, a holistic improvement of existing concepts has been investigated. Three novel approaches to the S&C layout, and other innovative actuation and locking concepts were conceptualized and analyzed at a simulation level. Better materials for the substructure and their samples were generated for further laboratory testing. All the technologies, concepts and materials developed were further constructed as demonstrators to prove their

feasibility. Upon further engineering developments of these concepts they have the potential to increase the capacity, reliability and safety of the S&C as a whole, while reducing operating costs. It is intended that the concept demonstrators, described in this paper, will be developed further to achieve higher Technology Readiness Levels (TRL) through future research.

Acknowledgements
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