Knowledge transfer from Shift2Rail

Report for Mistra InfraMaint Project 3.3.

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Summary

The European research program Shift2Rail (S2R) invests almost one billion Euro in R&D in the railway sector, including digitalisation and automation as two important areas. At the same time, extensive research and competence building is now underway on digitization in other socially important infrastructure at the municipal level, such as water, sewage and streets. The purpose of this study is to investigate the potential for benefiting from and transferring relevant knowledge and experience regarding digitalisation, asset management and maintenance developed within the European railway cooperation to Swedish needs owners in water and sewerage and streets. The study shows that there are good opportunities for knowledge transfer in areas such as inspection and condition assessment of facilities, risk management, and prediction. However, there are major differences between the railway sector and municipal infrastructure in terms of organization, actors and structure that must be taken into account. Municipalities and sector-wide organisations should consolidate their efforts to create a stronger innovation ecosystem, strive for standardization and a closer collaboration with industry, as well as reviewing competence and organisational development needs.

Sammanfattning

Det europeiska forskningsprogrammet Shift2Rail (S2R) investerar ca. SEK 9 miljarder i FOU inom järnvägssektorn, med bl.a. digitalisering och automatisering som två viktiga områden. Samtidigt pågår nu omfattande forskning och kompetensuppbyggnad kring digitalisering inom annan samhällsviktig infrastruktur på kommunal nivå, såsom vatten, avlopp och gator. Syftet med denna studie är att undersöka potentialen för att dra nytta av och överföra relevant kunskap och erfarenhet kring digitalisering, tillgångsförvaltning och underhåll utvecklad inom det europeiska järnvägssamarbetet till svenska behovsägare inom VA och gata. Studien visar att det finns goda möjligheter till kunskapsöverföring inom områden som inspektion och tillståndsbedömning av anläggningar, riskhantering, och prediktion. Det finns dock stora skillnader mellan järnvägssektorn och kommunal infrastruktur i fråga om organisation, aktörer och struktur som måste beaktas. Kommunala aktörer och branschorganisationer bör kraftsamla för ett starkare innovations-ekosystem, sträva mot ökad standardisering, söka närmare samarbete med aktörer i privat sektor, samt se över sina behov av kompetensmässig och organisatorisk utveckling.

1 Introduction

Large technical systems are backbones of our modern societies. Electrical power networks, roads, railroads and piped water infrastructure cut across countries and cityscapes, connecting consumers, producers and services. Infrastructures are "the connective tissues and the circulatory systems of modernity" to cite historian Paul Edwards[1]. However, just like parts of the human body, we notice them particularly when they fail; when they do not deliver the services we expect from them. Maintenance and asset management are keys to sustained services, yet maintenance of large scale infrastructure is notoriously a forgotten and disregarded area. Estimates by Svenskt Vatten (Swedish Water Providers Association) show that the maintenance backlog in municipal water infrastructure means that sector re-investments now must increase by 40%, or an additional 700 million Euro on annual basis, until the year 2040[2]. Combined with similar needs in e.g. the road sector, it is clear that municipally owned infrastructures in Sweden face major challenges in the years to come, exacerbated by pressure from demographic and climate changes. This is the backdrop and raison-d'etre of the MISTRA InfraMaint research programme (MIM)[3]. In this programme, a wide group of actors from the academic, public and private sectors work together for finding new and better ways of working with sustainable asset management and maintenance. An important assumption in this work is that digitalisation, including various applications of Information and Communication Technologies (ICT), Internet-of-Things (IOT) and Artificial Intelligence (AI), can unlock dramatic improvements in efficiency as well as decision-making.

For the railway area, Information Technology and Operational Technologies have been present for a long time, not least in vehicle design and maintenance. With digitalisation, organisations experience technology not just as a means for production, but as an enabler of building new organisational relationships which is creating value in new ways. These relations involve People-to-people interaction (P2P), people-to-machine (P2M), as well as fully automated data exchange between machines (M2M). The accelerating connectivity allows creation of business value through data analysis and automation. A major transformation of maintenance may happen when a large number of components, like vehicles, rails and switches, but also users and infrastructure sensors are inter-connected in an integrated ecosystem. This may also pave the way for increased automation in train services and traffic control, including driver-free trains, improving efficiency and reliability. Several large European train operators like DB, UIC and PKP have embarked on a journey of digital business transformation.[4]

This study is conducted within the MISTRA InfraMaint (MIM) programme (project 3.3). Our purpose is to explore the potential of transferring knowledge and applications from the European railways arena - and specifically from the Shift 2 Rail R&D programme - to water, sewerage and city streets in Swedish municipalities. These infrastructure services are entirely the responsibility of Sweden's 290 municipalities. The starting point of this study is that substantial and valuable lessons can be learned from the railway sector, in terms of innovations, science and processes, but also that there can be important differences with water and roads sector that should be taken note of.

[1] Edwards 2003
[2] Svenskt Vatten 2020
[3] www.mistrainframaint.se
[4] Pieriegud 2018

2 Study approach

2.1 Methods and material

This study was primarily carried out as a desk review, based on published reports and literature as well as web articles, most of them emanating from within the Shift2Rail and its sub-projects. Being a EU-funded R&D programme, many of the results in the Shift2Rail are published on open websites. However, there are also results that are restricted due to commercial interests and property rights. It is reasonable to assume that the R&D activities in such a large programme have produced much more than what is reported on the official websites. Hence, what we reported on here can be regarded as the tip of an iceberg in terms of details and depth. In addition, we also conducted a few interviews with people with key insights into the S2R programme.

This study was carried out between April 2021 and February 2023. A presentation of preliminary findings was presented and discussed at the MIM Annual Meeting on October 7 and to the programme's Board of Directors on 18 Nov, 2021 and a draft report was circulated within the programme team in March 2022. During 2022, three specific areas were identified where knowledge transfer was deemed particularly relevant and interesting:

i. Universal Cost models for sewerage networks;
ii. Unmanned Autonomous Vechicles (UAV) applications for inspection of streets and bridges;
iii. AI applications in water networks.

In early 2023, a round of focus group discussions (FGD) were held with a handful of practitioners and experts in the partner network around these three specific areas of knowledge transfer, to assess them from a practical viewpoint. See Appendix 1 for the list of participants in the Focus Group Discussions, and Appendix 2 for the questions that guided these facilitated discussions.

2.2 Theorising knowledge diffusion

When analysing the potential of transferring knowledge from the railway sector to roads and water infrastructure, it is crucial to have an idea of how such transfer happens, and what makes the case for a successful process. The innovation literature is vast, and here we will only sketch a basic model we believe to be useful for the purpose of our analysis.

For decades, Rogers' theory of diffusion has been very influential in a variety of societal sectors[5]. Essentially, the spread of ideas and innovations are here believed to largely be a social phenomenon, where gradually more people adopt the new idea through a sequence of different archetype users, starting with the "innovators" and "early adopters", through "early and late majorities" and finally, "laggards"[6]. The idea of innovation diffusion has been very useful to understand e.g. the dynamics of market penetration of a new consumer product, or the cultural uptake of values and ideas.

However, for the purpose of our study, which deals with short-term transfer of knowledge from one large technical system to another, Rogers' diffusion theory needs to be complemented. A more detailed analysis is needed, and the diffusion processes must be put into context. Firstly, the innovation developed in one sector has to correspond to a need in the other sector; there needs to be a problem that the innovation can solve. Secondly, a successful uptake is more

[5] Rogers 1962
[6] A useful overview of Rogers' theory and its significance is found in this Wikipedia article

likely to happen if the innovation is aligned with the overall structure of the 'new' sector, if it fits in the ecosystem.

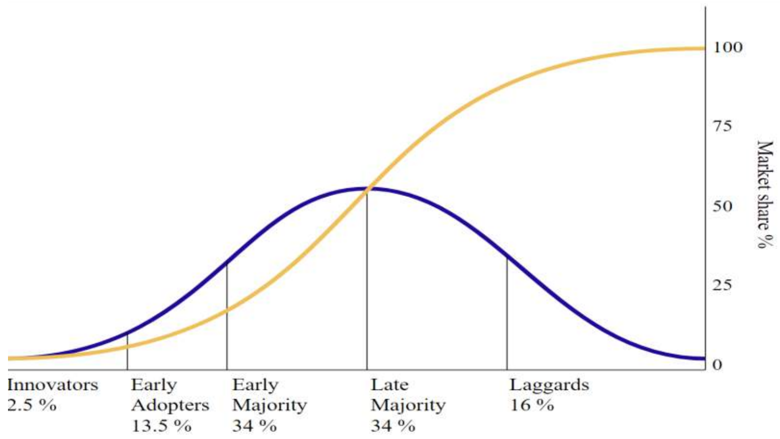

Fig.1. Based on Rogers, E. (1962) Diffusion of innovations. Free Press, London, NY, USA., Public Domain, https://commons.wikimedia.org/w/index.php?curid=18525407

Here it will be useful to borrow some concepts from the emerging and influential Sustainability Transition (ST) literature. The ST literature suggests that large technological systems evolve through an interplay between quick local innovation activity in "niches", the slower system level referred to as "regimes", and the backdrop of a social and material environment called the "landscape", which is changing over long periods of time (see Fig.2 below)[7].

The uptake of an innovation in a technological system thus depends not only on its performance per se, but also on how well it is "aligned", and to what extent it can be assimilated and move from the isolated niche level to the much larger regime level[8].

There can also be instances where transfer of innovations from one technological domain to another happens even where there is a poor fit with the existing regime. This can result in dramatic changes, often referred to as "radical" or "disruptive" innovation. A good example of disruptive innovation in recent times is the introduction of ICT into the media industry, which has completely changed the production, distribution, and user experience of for example music and film in a very short time, along with the corporate structure[9]. Historically, there have been plenty of these technology-driven game changers, for example introduction of steam engines into shipping business, agriculture, and manufacture industry[10]. We will mostly assess the transfer of knowledge and innovation in its more conservative form of gradual diffusion, but will also consider disruptive elements.

[7] Geels 2002; 2004.
[8] For a fuller discussion of the concept of "alignment", see Blomkvist et al 2020; Nilsson and Blomkvist 2021.
[9] Markard 2011; Christensen et al 2015
[10] Landes 1969

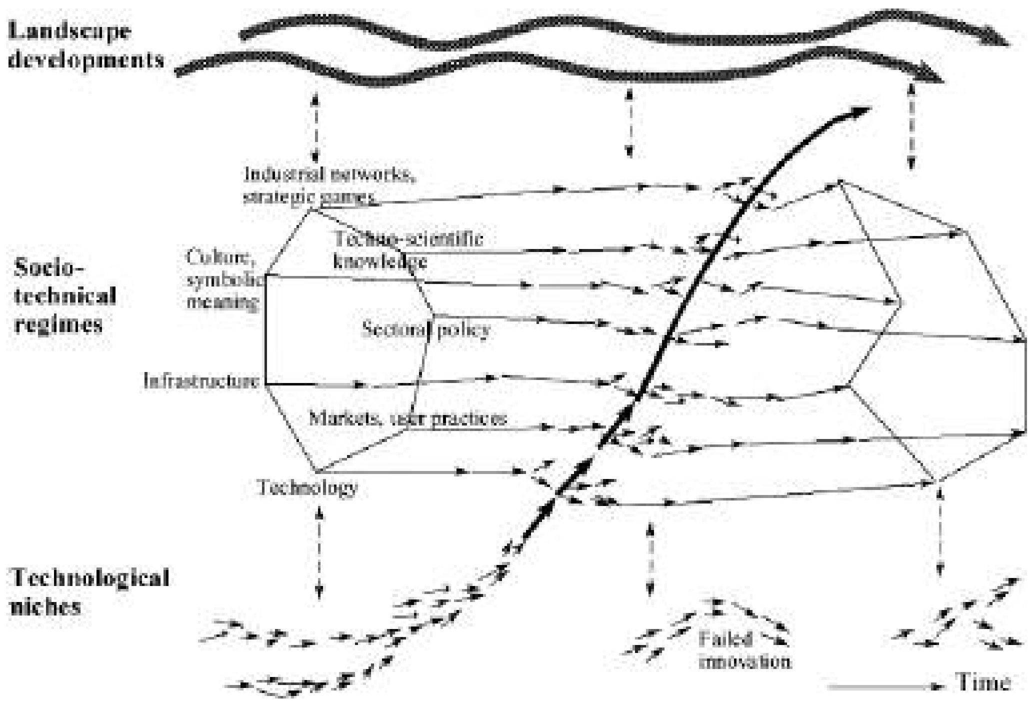

Fig. 2. From Geels (2002). Illustration of socio-technical transition taking place at the three levels niche, regime and landscape.

The main take-away from this short theoretic foray is thus, that to assess the potential of knowledge transfer from European railroads to water, sewerage and roads in Sweden, we should both look for similar problem-sets, and assess similarities (and differences) in the wider ecosystem of institutions, structures and actors into which the innovation need to fit.

3 Unpacking the Shift2Rail innovation arena

3.1 Overview of S2R

Shift2Rail started in 2014 as a European Commission Joint Undertaking to strengthen the European transport system through enhanced and improved rail transport. At the same time also the competitiveness of European Rail industry shall be further enhanced. In 2011, the European Commission adopted a Transport White Paper to set the EU on a path for a more competitive and resource-efficient transport system.[11]

The Transport White Paper sets out a number of goals, including a tripled length of high-speed rail network by 2030, connecting all core network airports to the rail network, and almost doubling the freight volumes by 2050. It also underscores the necessity of establishing a Single European Railway Area (SERA) in order to achieve a modal shift from road towards more sustainable modes of transport such as rail. In effect, this would put all rail operators in the EU under a common framework of rules and regulations.[12]

[11] https://ec.europa.eu/transport/themes/european-strategies/white-paper-2011_en
[12] S2R 2015

Shift2Rail (S2R) is a research and development initiative that supports the transformation of the European rail system towards a single railway area in line with the White Paper. More specifically, S2R has as its objectives to accomplish:

- A 50 % reduction of the life-cycle cost of the railway transport system (i.e. costs of building, operating, maintaining and renewing infrastructure and rolling stock),
- a 100 % increase in the capacity of the railway transport system,
- a 50 % increase in the reliability and punctuality of rail services (measured as a 50 % decrease in unreliability and late arrivals).

The budget for S2R stands at 967 M€ from EU including 517 M€ as in-kind contributions from participants. In addition to the EC, there are 8 so called founding members and 19 associate members to the Joint Undertaking from industry and national rail authorities, including the Swedish Transport Agency, Trafikverket.[13]

S2R is a large and diverse programme carried out by hundreds of organisations in parallel Projects, Work Areas and Technology Demonstrators. The entire programme is divided into seven Innovation Programmes (IPs), including one cross-cutting and one for disruptive technologies and future studies (see Table 1).

Table 1. The structure of innovations in S2R

The Innovation Programmes (IP) in S2R	***R&D target areas***
IP1 – Cost-efficient and reliable trains, including high capacity trains and high speed trains	Concentrates on the rolling stock, i.e. development and design of new vehicles. Also contains instrumentation, sensors, fault detection and prediction of vehicles.
IP2 – Advanced Traffic Management & Control Systems	Communication systems and positioning, automatic train operation, management and optimisation of traffic flows. IP2 also has components of cyber-security to ensure safety and integrity of traffic control.
IP3 – Cost Efficient and Reliable High Capacity Infrastructure	Use and management of the fixed infrastructure assets, such as railroad tracks, bridges, tunnels, switch systems, and stations. LCC aspects in design and material choice, intelligent, risk-based and predictive maintenance, new inspection and status prediction methods, and energy efficiency, are important areas of work in this IP.
IP4 – IT Solutions for Attractive Railway Services	Focuses on the customer experience side. This includes new digital ticket sales interfaces, data-enhanced customer relations and inter-modality, entertainment, and ways of capturing and visualising user value.
IP5 – Technologies for Sustainable and Attractive European Rail Freight	Strengthening rail services for freight to re-capture lost or new markets and adapting the services to modern logistics demands. Focuses on inter-operability, inter-

[13] S2R 2020

	modality, reliability and in general, the offer to the freight customer.
Cross-cutting IP themes and activities	Activities that support the formation of a joint European rail service area, and in particular Technical Specifications for Interoperability (TSI). This pertains to testing requirements, standards, performance measurements, joint energy and sustainability assessments, human resource development, divided into 6 Work Areas (WA)
IP X – Disruptive innovations	Innovations that are not endogenous to the railways systems technology domain but that could become disruptive game changers, like IOT, AI, and Blockchain technology.

S2R thus provides a comprehensive and system-oriented package of knowledge development along the value chain from infrastructure owners, service operators, technology suppliers to customers, set within its broader political and societal context.

Our objective is to assess potential innovation diffusion to the area of water supply, sewerage and city streets, and in particular those that centrally placed regime actors like municipalities (or their suppliers) can adopt. As outlined in the previous section, we want to focus on railway innovations targeting problem-sets that are relatively similar to those experienced in the municipal infrastructure sector. Solutions regarding vehicles (IP1) or freight and logistics (IP5) could obviously be relevant for car and truck manufacturers, as well as urban freight companies. However, we here focus on the infrastructure owners and in particular local governments. Therefore, we have concentrated our search to particularly relevant interventions in the IP 3 on infrastructure assets, plus the cross-cutting themes which have a more general bearing on the regime level and the innovation ecosystem. We will return briefly to the other areas in the discussion.

3.2 Towards Cost Efficient and Reliable Infrastructure

The IP3 “Cost Efficient and Reliable High Capacity Infrastructure” is implemented through a set of Technology Demonstrators and carried out through 12 R&D Projects, some of which are linked to each other. The most relevant projects, with accessible outputs in terms of technical reports and/or scientific publications, are listed below in Table 2.

In essence, the aim of Innovation Programme 3 is to develop new methods and tools for ensuring a safe and cost-efficient rail infrastructure in its very physical sense. Central to all of the Technology Demonstrators (TD) is that they rely on data-driven methods to assess and predict the status of assets, and to optimise their use and technical lifespan in order to reduce environmental impact, lower costs, and reduce risk at operational, tactical and strategic level. Below we provide a summary of four relevant Technology Demonstrators (TD) and the type of solutions currently being developed through them[14].

[14] The information is compiled from S2R 2020, Annual report for 2019, where relevant, additional reports and publications are indicated.

3.2.1 Bridges and tunnels

The **TD3.5 Proactive Bridge and Tunnel Assessment, Repair and Upgrade Demonstrator** provides improved inspection methods and repair techniques for reducing costs, improving quality and extending the service life of existing structures. The demonstrator includes innovations in a range of areas:

- Autonomous image-based tunnel inspection system using high definition images paired with precise positioning, LIDAR scanning and software for automatic anomaly detection.
- Optical measurement methods using ground based and un-manned aerial vehicle (UAV), enabling image-based technologies for digital twins, detection of damage and identification and tracking of changes in geometry and structural behaviour of bridges.
- Enhancement of old masonry arch bridges using concrete liners, cross ties and fibre reinforced polymer plates.
- Fibre optical distributed sensors in laboratory and operational environment as part of a tunnel health monitoring system solution.
- New materials for drainage pipes in Tunnels.
- Monitoring of fatigue consumption of bridges and prototype demonstration using sensor installation on a bridge and development of algorithms for data analytics.
- The systematic use of BIM for monitoring conditions of bridges and tunnels.
- Noise monitoring on real metallic bridges and development of fatigue capacity of metallic bridges along with prototype for underwater monitoring of scour.

Published results and reports on tunnels and bridges are found under the IN2TRACK and Asset4Rail project websites.

3.2.2 Information management systems

The **TD3.6: Dynamic Railway Information Management System (DRIMS)** defines an innovative system for the management, processing and analysis of data. As an information system, it is linked to both TD3.7 (monitoring) and TD 3.8 (asset management) and has been developed for long-term as well as short-term asset management decisions, i.e. addressing both strategic and tactical needs of the infrastructure owner. The DRIMS demonstrator includes features such as:

- Anomaly detection system prototypes for a wide variety of railway assets, including analysis of assets degradation and malfunction and prototype tests of data-driven models proven through use cases.
- Explorative studies of Process Mining (workflow and event analysis). A conclusion is that in the railway asset management domain, process mining is currently not capable of providing high quality results due to low quality of process-related event logs.
- Development and testing of ten different predictive models for varying infrastructure applications[15]
- Data model prototypes through the usage of a CDM data model structure, data exchange formats (JSON, XML and HDF5) and open data message protocols.
- Improving prediction accuracy through operator interactions with the IT-systems.

[15] ARIMA models used to predict switches failures; Support Vector Regression models and Moving Average models to predict track circuits failures; Precipitation Compensation Algorithm to manage weather-related false alarms; bridges degradation and intervention costs predictions; Bayesian estimation with particle filter, SVM regression, Random Forest regression to predict track geometry degradations; Cox modelling and Breiman permutation to predict fasteners anomalies and the time between earthworks status changes; predictive model for rail defects; ANOVA models and Markov-based degradation models to predict earthworks degradations.

- Metrics for prediction performance assessment.
- Smart contracts via block-chain technology, Proof of Concept development.

Results and reports on the information management system are developed and published through the IN2DREAMS and In2Smart (stage 1 and 2) projects.

3.2.3 Measuring and monitoring

The **TD3.7 Railway Integrated Measuring and Monitoring System (RIMMS)** involves developing techniques to capture information relevant for assessing the current status of infrastructure assets, as input to the DRIMS (T3.6). Analysis of the information cascades further into asset management activities developed within TD3.8 (see below). The innovation activity includes areas such as:

- Testing Unmanned Aerial Vehicle (UAV) and robots for inspection, and associated regulations and standards.
- On-board vehicle prototypes for monitoring of track and switch systems.
- Tests of sensor technology for wheel-to-rail monitoring.
- Architecture for extraction of data from signaling systems, including hazard analysis and a Proof of Concept lab demonstrator.
- Monitoring solutions for rolling stock impact on infrastructure in several use cases.
- Wayside Monitoring system based on machine vision to detect defects and perform measurements on the rolling stock.

The progress and achievements under TD3.7 are mainly found in the Asset4Rail, In2Smart and MOMIT projects.

3.2.4 Asset management system

The purpose of the **TD3.8 Intelligent Asset Management Strategies (IAMS)** is to pave the way for a whole-system approach of asset management employing data from TD3.7 and TD3.6. This includes translating long-term decisions (strategic asset management) into annual plans and day-to-day execution of the maintenance activities (tactical and operational asset management). A number of IAMS use cases have been developed:

- Prototype for managing uncertainties of Life-Cycle Cost (LCC) models in medium to long-term planning of asset interventions, allowing optional distributions of costs rather than point estimates.
- Strategic IAMS model for managing effect of earthworks degradation through optimal intervention schemes under budget and resource constraints, based on strategic KPIs.
- Improving robustness of maintenance task planning, by combining status assessment with risk assessment of failure of other assets, and the effect of intervention duration on the computed plan.
- Autonomous Rail Vehicle prototype to enable automated robotic Inspection and Maintenance, using a modular design with open system architecture, plug-and-play interchangeable robotic tool and equipment sets.

The research and development activities for intelligent asset management under TD3.8 are carried out in the In2Rail and In2Smart projects and publications are found on the respective websites.

Table 2. Projects in IP3 of relevance to our study

IP3 PROJECT	KEY AREAS
ASSETS4RAIL	bridges and tunnels, data representation, Asset specific Information Model (AIM), Building Information Modelling (BIM), sensor and system testing, wayside monitoring stations
IN2DREAMS	smart sensors, open data collection, data management, DRIMS
IN2RAIL	integrated asset monitoring, self diagnostic, new materials, data from low-cost, low-maintenance sensors; standardised approach to information management, standardised interfaces, forecast network asset statuses, uncertainties from heterogeneous data sources,
IN2SMART	systems to collect, process and aggregate a set of heterogeneous railway asset status data, data diagnostic collection techniques, data management, data mining and data analytics, standard open interfaces, analytic tools to automatic detect anomalies and predict railway assets decay, Decision making, maintenance strategies and execution procedures
IN2TRACK	switch & crossings and track systems, extending the life of bridges and tunnel assets through new approaches to maintaining, repairing and upgrading these structures
MOMIT	remote sensing, platform independent tools for data analysis and decision making, operational criteria for unmanned technology
S-CODE	radically new concepts for switches and crossings for higher capacity, reliability and safety, including architectural requirements

3.3 Cross-cutting themes

The future development of railroads (or any large technical system) depends highly on factors that are not endemic to the sector itself, such as governance frameworks and political climate, user preferences, environmental factors, knowledge and competence, etc. There are also unknown factors at play, for example, if there are innovations and technologies that radically change the future conditions for the infrastructure system.

These cross-cutting themes pan out over a vast canvas divided into Work Areas (WAs):

- **Long-term needs and socio economic research** (WA1). The first phase focused on customer needs and mobility behaviour while a second phase concentrates on customer requirements and scenarios for the railway freight sector. Results from socio-economic research are presented in the IMPACT-1, IMPACT-2 and NEAR2050 projects.
- **Key Performance Indicators** (WA2) is a methods-oriented area which seeks to capture the impacts of the programmes TDs in order to assess how they contribute to the key targets of Shift2Rail and the European Transport policy. Extensive groundwork to establish state of the art in a range of railways sub-sectors is presented in the projects Roll2Rail and IMPACT-2.
- **Safety, Standardisation and Smart Maintenance** is the focus of Work Area 3, expected to facilitate the integrative process towards a Single European Rail Area. This includes a Rail Safety Framework (WA3.1) which integrates risk assessment across infrastructure asset categories. This work included machine learning models built to automatically identify any change in asset conditions and plan preventive maintenance

activities in a timely manner. The Safety framework is documented in the projects GoSafeRail and Plasa. Standardization activities (WA3.2) migrate results into regulatory documents through pre-standardisation processes with the relevant standardisation bodies, presented in IMPACT-2. The Common Smart Maintenance Concept (WA3.3.) with common principles for cyber physical data models as well as requirements on data standards, is developed in IMPACT-2 and SMARTE.

- **Smart Mobility** (WA4) aims to enable railway stakeholders to make the best decisions for the overall system, for example concerning schedules and the availability of rolling stock and staff, based on up-to-date operational data, taking into account all essential information. Details and publications are found under the Roll2Rail, GoSafeRail and Plasa projects.
- **Energy and Sustainability** is the focus of WA5, which also includes research on noise and vibrations in the projects FINE1 and FINE2.
- **Human Capital** is a key area analysed in WA6, including the impact of innovations from S2R on the human factor in the rail system. Generally, greater emphasis on IT-qualifications, data processing and analysis can be expected, as well as a shift from individual work to a multi-disciplinary approach/cooperative work, e.g. with IT experts, technicians, engineers working together. This requires advanced social skills to be able to work well with other professions and take their perspective into account. Results are published in the Human Capital Report series.
- **Disruptive Innovation and Exploratory Research** in IP X include topics that are deemed to have potential for railway systems in the more long term. This involves Blockchain methods (B4CM project), technology transition and future studies (FlexRail), a novel European rail system architecture (LinX4Rails), system integration of Artifical Intelligence (RAILS); and more.

In all, it is obvious that there is a very wide set of knowledge and applications being developed in the Shift2Rail programme even within our restricted scope. An impressive amount of R&D activity has already taken place in areas of automated inspection, data management and analysis for condition-based maintenance, asset management and decision support, as well as more conceptual work on system architectures, standards and definitions. Considering that municipal infrastructure owners, researchers and industrial partners now are actively pursuing R&D agendas around “smart” maintenance and asset management, such as in MIM programme, we hold no doubt that S2R could provide a gold mine of ideas, knowledge and applications. However, technology transfer is not a straightforward process of “copy and paste”. In the next section, we analyse more closely the transfer potential from S2R into the areas of municipal water, sewerage and city streets.

4 Transfer potential

After outlining the main areas of innovation and knowledge production in the S2R programme, we now turn to analysing the transfer potential to the arena of municipal infrastructure in Sweden, using the theoretical concepts outlined in section two. Similar problem sets and a good fit in the sector ecosystem will be two guiding criteria. We will also relate our observations from S2R to the programme structure of MISTRA InfraMaint, simply because our programme may have a critical catalytic role in the actual transfer process. The programme today includes over 50 public and private organisations in Sweden and indirectly connects to all municipal water providers through the programme partner Svenskt Vatten. Hence, the programme has the ability to create momentum and mobilise the important “early adopters” for digital technologies within municipal infrastructure.

First, we start by categorising our most pertinent observations on knowledge and innovations that could respond to similar problem-sets in municipal infrastructure, sorted into the three broad programme areas of MIM, namely i) Decision-support; ii) Organisation and iii) Competence. After that, we discuss aspects of system-fit by comparing the sectors in terms of system structure and organisation.

4.1 Relevance for Decision-support

Below we list key R&D topics and their associated S2R projects, and assess what kind of application they could have in municipal infrastructure in general, an in MIM specifically.

S2R topic	S2R project(s)	Potential municipal application	Current MIM area/project
Autonomous image-based tunnel inspection	IN2TRACK, Asset4Rail	Inspection of bridges, tunnels, pipes, reservoirs, road surface	1.1, 1.3
Optical measurement using UAV	IN2TRACK, Asset4Rail	External inspection of bridges, reservoirs, road surface	1.1, 1.3
Fibre optical distributed sensors	IN2TRACK, Asset4Rail	Monitoring of large structures e.g. bridges, tunnels, reservoirs, arenas	1.2, 1.7, 1.8
Monitoring of fatigue consumption of bridges using sensors	IN2TRACK, Asset4Rail	Monitoring of large structures e.g. bridges, tunnels, reservoirs, arenas	1.1, 1.3
Use of BIM for monitoring conditions	IN2TRACK, Asset4Rail	Monitoring conditions of structures and pipes	1.2, 1.7, 1.8, 1.10
Development and testing of ten different predictive models	IN2DREAMS, In2Smart	Failure prediction and risk-based condition assessment on piped networks, roads and bridges	1.1, 1.5, 1.6, 1.7, 1.8, 1.9, 1.13
Data model prototypes using CDM data structure and open formats	IN2DREAMS, In2Smart	Developing coherent and suitable format for datasets for the municipal infra sector	All comp. 1 projects
Improving prediction accuracy through operator interactions with the IT-systems	IN2DREAMS, In2Smart	Automated condition assessment for sewer inspection (currently done manually by operators)	1.1, 1.6, 1.7
Metrics for prediction performance assessment.	IN2DREAMS, In2Smart	Benchmarking and standard indicators for performance assessment in municipalities	Comp.1
UAV and robots for inspection, and associated regulations and standards.	Asset4Rail, In2Smart, MOMIT	Drone inspection of sewers, tunnels, bridges, and water reservoirs	1.1, 1.6, 1.7
On-board vehicle prototypes for monitoring of track, and tests of sensor technology for wheel-to-rail monitoring	Asset4Rail, In2Smart, MOMIT	Road condition monitoring using sensors in vehicles (cars, buses, trucks)	Comp 1 – new area to include vehicle fleet
Prototype of asset management system for managing uncertainties of LCC models	In2Rail, In2Smart	Strategic Asset management models in water, sewerage and roads	All Comp. 1

Improving robustness of maintenance task planning, by combining status assessment with risk assessment	In2Rail, In2Smart	Strategic Asset management models in water, sewerage and roads	All Comp. 1

There are numerous innovations around smart decision-support in the S2R programme that could hold great potential for transfer and application in the area of municipal water, sewerage and roads. Particularly interesting areas are condition assessment of large infrastructure components such as bridges, pipes and tunnels. Today much of this work is done in municipal infrastructure sectors by ocular inspection or filming, followed by time-consuming manual assessment. In S2R much R&D effort is spent developing various unmanned vehicle inspection techniques (e.g. drones and robots) and automated image interpretation. More and better data could be acquired using unmanned inspection and automated image analysis, and technologies for doing this would largely be the same for municipal infrastructure[16].

Another area of great interest for transferring knowledge relates to models and systems for data exchange, models for failure and condition prediction, and how to manage uncertainty in data-driven decision making. While the assets and organisations will be different, to a large extent the mathematical algorithms will be the same. The S2R has reportedly already evaluated ten different models for asset condition and failure prediction. Hence, it will be a matter of combining the right maths with the organisational and material context. S2R can offer a vast pool of applications and knowledge, that can be recombined for the municipal infra sector.

Finally, the railway arena can offer inspiration for developing an entirely new way of working with data collection by integrating the vehicles into the picture. In S2R, substantial effort on R&D goes into vehicle sensor technology under concepts like "wheel to rail". Here, close collaboration with rail vehicle manufacturers has led to data generation by the users of the infrastructure, vital for assessing the condition of not just the vehicles but also the rails, switches, power supply etc. Vibration and sound monitoring is common, but also other types of sensors, like heat anomalies etc. This is so far largely unchartered terrain for municipal infrastructure owners, but could become an important R&D area in the road sector up ahead, considering the high level of instrumentation and sensing abilities of a modern car, bus or truck (see Fig.3). One concern, however, is that ownership of the collected data needs to be properly considered in processes with user-generated data[17].

[16] Interview with Prof. Raied Karoumi 2021-07-02
[17] Interview with Prof. Mats Berg, KTH. 2021-06-23

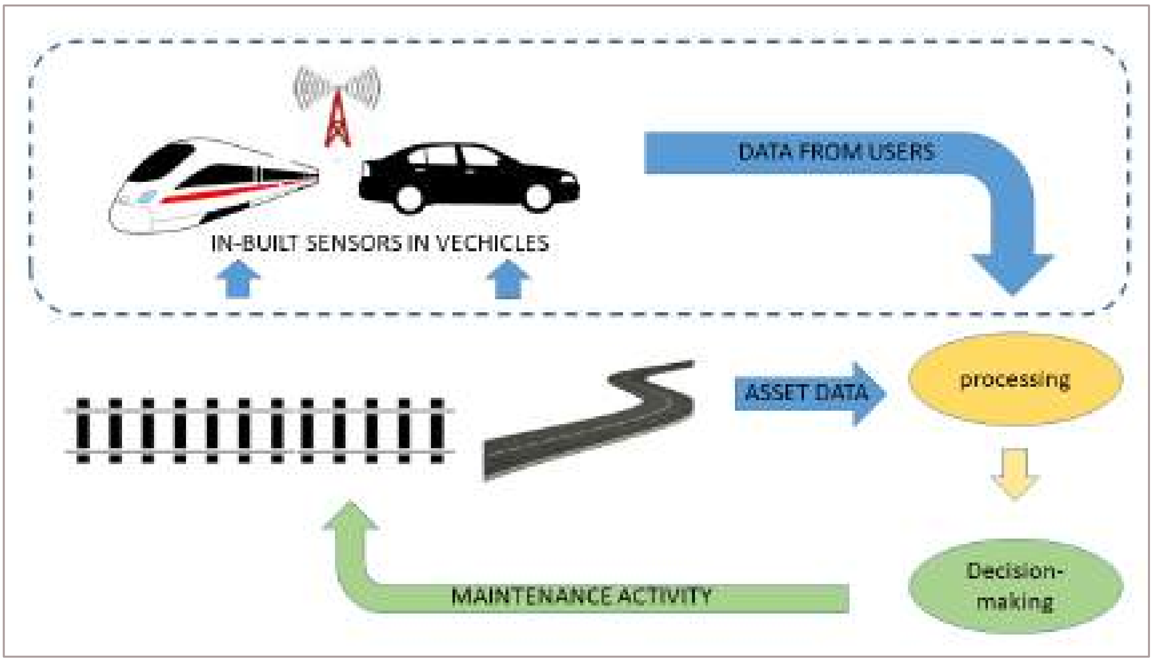

Fig. 3. Conceptual illustration of how involving the users, like vehicle manufacturers and transport companies, can unlock a vast new stream of data for infrastructure owners.

4.2 Relevance for Organisation

Obviously, the municipal infrastructure sector in Sweden differs quite substantially from the European rails sector from an organisational point of view, which we will return to in section 4.4. Nevertheless, below we have identified a number of R&D activities or “organisational innovations” that will be interesting to consider further.

Topic	S2R project(s)	Potential municipal application	MIM Compt. /project
Concept of a Universal Cost Model to promote spread of innovations in rail sector	Roll2Rail, NEXTGEAR	Valuation of costs across users, owners, and external costs, over entire life cycle enabling comparison and prioritisation	1.10, 1.11 Comp. 2
Smart contracts via block-chain technology	IN2DREAMS, In2Smart, B4CM	Improved contract management for maintenance tasks involving entrepreneurs, partners or users	2.2
Roadmap for Standardisation	IMPACT-2	Setting standards for improved markets for tech suppliers, facilitating data exchange and sector performance monitoring	2.3, 2.4
Common Smart Maintenance Concept (sector-wide principles for cyber physical data models and data standards)	IMPACT-2, SMARTE	Reducing fragmentation in R&D, competence development in the sector and facilitating data exchange	All Comp. 2
Explorative future studies and Disruptive technology	B4CM, FlexRail,	Understanding long-term trends in municipal	Comp 2

	Linx4Rails, NEAR2050	infrastructure and its organisation	

Of particular interest is to note the large amount of work being done to foster a common European railways system. This entails substantial R&D activities, coupled with policy integration, aimed at achieving higher levels of standardisation, not just for technology but not least for the economic valuation models (Life Cycle Cost) and for data compatibility. This is natural for a highly inter-connected physical network infrastructure to enable goods and people to travel in a seam-less fashion across continents. Municipal infrastructures are local to their physical coverage, but they depend on a highly connected and globalised market of technology suppliers and competence. In a small country like Sweden, with 290 municipalities with a median population of 15,000, it is not economically feasible to develop site-specific solutions for smart asset management in each and every of these places. Standardisation can create a much greater market for developers, also facilitating exchange of data and competence within the market as well as benchmarking performance. Here, inspiration and learning from S2R could be very useful, including looking at the Common Smart Maintenance Concept and the RoadMap for Standardisation (see Fig.4 below). A similar sector-wide approach for standardisation could be spearheaded by MIM programme along with key institutional actors. Moreover, inspiration could be sought in the ambitious approach for studying future scenarios and disruptive technologies in projects like NEAR2050 (societal megatrends) and B4CM (blockchain technology).

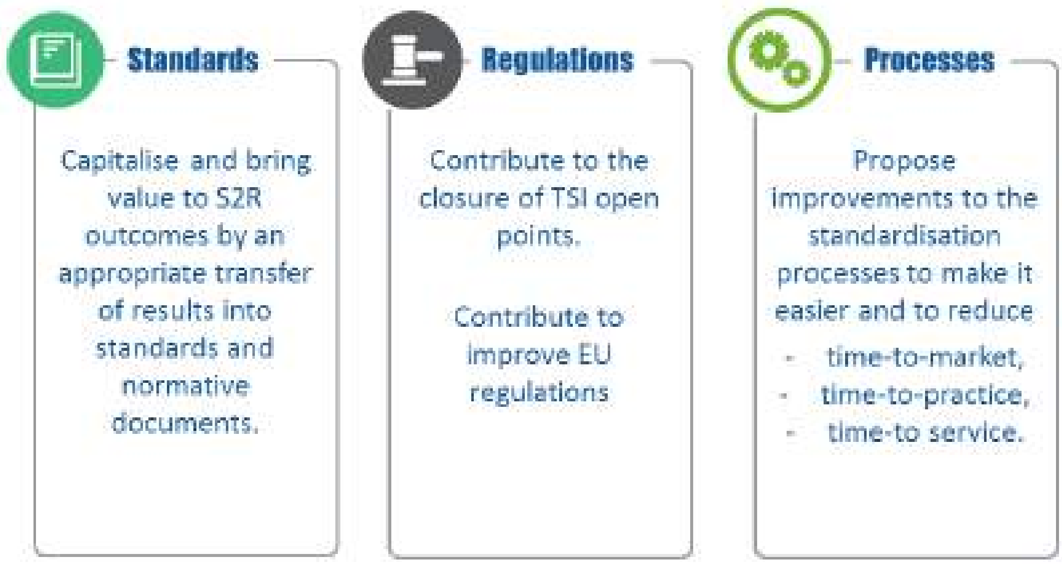

Fig. 4. Illustration showing how R&D results can influence institutional framework in the railways sector. From Report "Deliverable D 5.1. Global Roadmap Standardisation", project IMPACT-2

4.3 Relevance for Competence

The amount of work in S2R dedicated to development of competence and human resources is fairly small compared to the R&D activity devoted to issues of technical and economic nature. However, the S2R established a useful basis for analysis and strategic considerations through a number of cross-country studies performed by TNO, the Netherlands Organisation for applied scientific research. The results were published as the Human Capital Report series. Again, while European railways and Swedish municipal roads and water sectors are different, the approach of making a thorough analysis of the current and future workforce, skills needs, and the attractiveness of the sector, should serve as a role model for how municipalities could map strategies for competence development. Of interest to MIM, one of the reports points to the need of mobilising a more full-bodied approach to human capital development, taking into account all the four areas of the *skills ecosystem*:

i. the demand for skills (recruiting function of companies);
ii. the supply of skills (labour market: from schools, from competitors, from other sectors);
iii. the development of skills, and:
iv. the deployment of skills (quality of work).[18]

Typically, employers tend to over-emphasise the supply of skills and particularly the role of conventional education institutions (college/universities). However, more effort needs to be placed on on-the-job training, workforce transfer, and strategic demand-side development; identifying what skills organisations will need, not today; but tomorrow.

In addition, the efforts towards standardisation and sector-wide harmonized concepts noted in the previous sections also support a larger and more dynamic competence base. As an example, professionals in the Swedish water sector now have to learn new methods and tools for data management and decision-making every time they shift jobs. One water utility has reported having five (5) different SCADA systems for data collection and operational control of assets, within the same company[19].

4.4 Comparing rail, city streets and water

As noted earlier, to analyse possibilities to transfer knowledge and innovation from the European railway sector to Swedish municipal water and roads sector, it is important to understand differences between institutional and organisational structures. We here attempt to outline, in an admittedly sketchy fashion, some features of the respective systems that will be important to take note of in the context of knowledge transfer.

4.4.1 System characterisation

Railways, roads or streets, as well as piped water and sewerage are all networked technological systems. Essentially, a network is a system consisting of a number of “nodes” that are connected through “links”[20]. In railways, the links are the rails connecting the stations (the nodes), which typically are located in places of economic, demographic or military significance. Similarly, roads connect cities, villages, factories, harbours etc and in the cities the streets make up a fine mesh, connecting most parts of the city. Water and sewerage pipes also form dense grids in the cities, connecting producers of fresh water with the consumers, and connecting the water consumers with the wastewater treatment facilities. Moreover, railways, road networks, and water infrastructure are all classical examples of large technical systems that are capital-intensive, typical natural monopolies, durable and very slow to change[21]. From a system architectural point of view, these systems thus seem very similar at first glance. But as soon as we start categorising them according to the flow within the networks, we see very important differences. Networks can be either distributive (distributing goods or services to consumers), accumulative (collecting goods) or communicative (two-way flow of goods and services)[22]. Roads and railways are both communicative networks, but water

[18] Dhondt et al 2019
[19] Pers .comm. Swedish water Utility CEO, 2020-04-22.
[20] Jonsson 2000
[21] Kaijser 2003; Markard 2011
[22] Jonsson 2000

networks are distributive. Sewerage networks, on the other hand, are accumulative (see Fig. 5).

The three types of flows obviously will shape the design process immensely, but also have operational considerations. For example, in an accumulative network such as sewer systems, the system operator will have more difficulties in controlling the inflow, which happens at the many nodes (and yes, households tend to flush all kinds of things down the toilet).

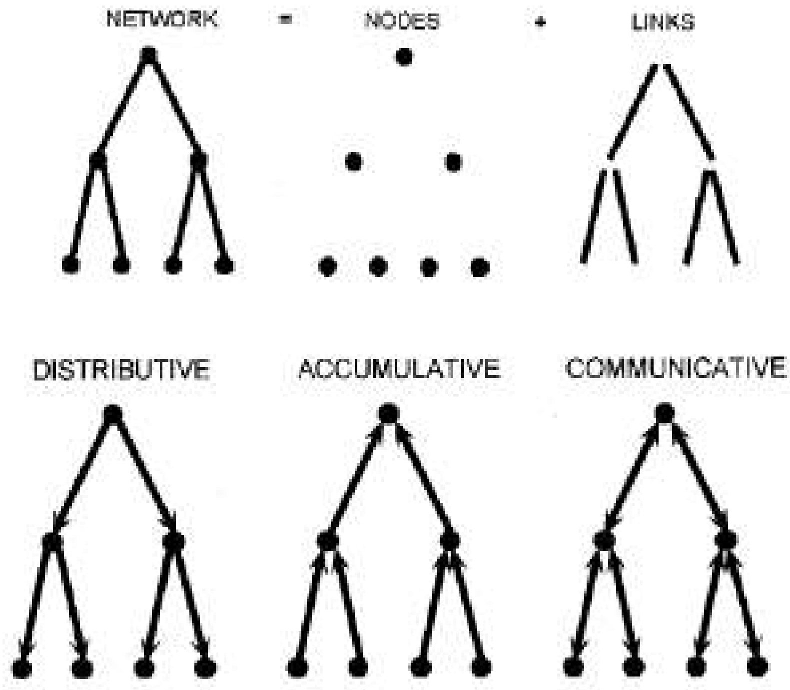

Fig. 5. All networks consist of a system of nodes connected by links through which goods and services flow. Networks can be of distributive, accumulative or communicate type, depending on the direction of these flows. From Daniel Jonsson (2000).

Another thing that sets the systems apart on a conceptual level, is to what extent the systems are "tightly coupled", meaning that the infrastructure can only be used in a very a specific and pre-determined way[23]. The railways is a tightly coupled system since it can only be used by vehicles (trains) that are built for this purpose, and according to very specific technical standards. Water and sewerage are also relatively tightly coupled, with a low degree of use flexibility. Roads and city streets on the other hand, can be used by virtually any mode of transport, from pedestrians and cyclists to the latest high-tech self-driving cars. Municipal streets are therefore loosely coupled systems. How tightly coupled the system is makes a huge difference, since it will dictate to what extent the infrastructure owner also must control its use, operation and maintenance.

Finally, the geographies also differ for obvious reasons. Railway systems span and connect countries over vast distances, while city streets and water networks have local, sometimes regional, geographic coverage. The European Commission awards the development of a common EU rail system vast economic and political significance and sees the railways as an instrument for economic integration. It is hard to see how the same kind of political momentum in EU could be mobilised around infrastructure of local nature.

[23] Hughes 1983

4.4.2 Ownership and operations

The railway sector has typically been developed, owned and protected by national governments for over 150 years[24]. For a long time, both the infrastructures as well as the transport services were under government-owned monopoly companies throughout Europe. Even today, large national parastatals dominate much of the rail transportation, even though rail transport now is open for competition from private or public enterprises[25]. The fixed infrastructures (rails, bridges, stations, switches, signal systems etc) are still owned and managed by national authorities, like Trafikverket in Sweden, but they have to serve a growing number of commercial operators.

City streets and water infrastructures, on the other hand, are owned entirely by municipalities in Sweden. These municipalities are very different in size, economy, and geography but have identical responsibilities as inscribed in law, such as VA-tjänstlagen (law on water and sewerage services). The law, since 2007 explicitly forbids private ownership of water and wastewater services, which must be offered on not-for-profit basis. In many places, municipalities have incorporated water utilities as limited companies, but they have to be fully controlled and owned by the municipalities. In some regions, municipalities have formed joint utilities to benefit from economies of scale, or to manage regional water resources jointly. Nevertheless, many municipalities – especially the smaller ones - face increasing challenges in terms of capacity, scale, finance and competence[26]. In comparison to railways, the municipal infrastructure appears as much more fragmented, with many small and public actors with limited capacity. In railways, the tight coupling combined with the market liberalisation over the past decades, have resulted in R&D collaboration between fixed asset owners (like Trafikverket), transport companies, and large vehicle manufacturers[27]. In comparison, water utilities have no private operators to collaborate with when innovating, as all operations are in-house.

Summing up the comparison of sectors, we can see important similarities as well as differences. They are all networks of great importance for society, they are century-old systems and they share many technical and economic features. On the other hand, they exhibit different types of flow architecture, they vary wildly in geographic scope, and perhaps most importantly, are populated by very different actor-sets. In railways we find strong national asset owners and many large private companies involved both in transport operations and in the vehicle industry. The water and city streets sectors tend to be more fragmented with many small municipalities and fewer commercial actors.

4.5 Knowledge transfer in practice

In this section we discuss practical cases where knowledge from the rail sector is deemed particularly relevant for transfer to municipal infrastructure sectors, or in some cases, where this is already happening. The purpose is to look at the potential of knowledge transfer from a practical angle, and to shed some light on the transfer process and the maturity of the Swedish municipal sector. Below, we have selected tangible outputs from the S2R domain and we discuss how they are applied, or how they could be applied, to WSS and/or street management. In the conceptual framework presented above in section 2, these specialised applications could be said to form "niches" which has to fit into the "regimes" of municipalities. In addition, we have interviewed (through Focus Group Discussions, FDGs) individuals from

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[24] Kaijser 1994
[25] The Economist, 2021-11-13
[26] Bennich, Engwall and Nilsson (2023)
[27] Interviews with R. Karoumi and with M. Berg.

municipalities, private sector and academia to get a better and more grounded picture of their potential value for different users as well as what it would entail to put this into practical use.

4.5.1 Universal cost models

Infrastructures are designed for specific purposes but can still have different uses and users. Sewerage pipes transport wastewater from households, as well as industrial and hospital waste, rainwater, snowmelt and groundwater. Roads are used by trucks, cars, bikes and pedestrians which all bring different loads and wear on the transport infrastructure. Likewise, railways are used for a range of vehicles and transport services, interacting and affecting the rail system in various ways. Each of these uses are associated with certain benefits, but also with costs for maintenance and re-investment. Ultimately, these costs have to be borne by the customers and therefore the asset manager (e.g. a public railways agency) needs to distribute the costs fairly among the operators and users. In the Shift2Rail programme, considerable research efforts have been devoted to determining infrastructure-related costs for different uses and establish a universal cost model (UCM), applicable across the European railways network.

One study presents a model for "marginal cost per damage unit" based on observations on 143 rail sections and computer simulations to inform the pricing system in a fully integrated European transport network[28]. Another study explores lifecycle costs of the infrastructure wear, in particular ballast-beds, the rails, switches, and crossings. Simulations are used to evaluate the technical performance and wear under different conditions, and to calculate economic cost. This also includes the cost of "downtime" i.e. periods when certain infrastructure is not in operation, due to breakdown or closure for repair[29]. The UCM was expanded in a third study to include not just wear from vehicle usage, but energy, CO2 emissions and noise effects. This study also evaluates the benefits a Condition-Based Maintenance approach[30].

A similar approach could be interesting for sewerage services. Users already have individual service agreements, and the tariff could be more directly related to wear and operational costs, using a marginal cost model. For instance, the cost of infiltration and inflow (in Swedish; ovidkommande vatten) is of interest for municipalities, but also extreme temperature, chemicals and hazardous waste from industries. Moreover, wastewater is increasingly used as a heat source for property owners using heat pumps, which can have negative effects on the wastewater system[31]. There are external costs from capacity overload, sewer overflow, and basement flooding, as well as internal costs, electricity and pumping, increased treatment cost and material deterioration from different kinds of discharge streams[32]. In MISTRA InfraMaint, some aspects of this are being explored in project 1.6.b.

From a practical point of view, however, the Focus Group Discussion revealed that there seems to be relatively small potential for developing UCMs for sewerage services, at least in the short term. Sewerage operators (municipalities) are generally concerned about - for instance - the infiltration and inflow water, but rarely from an economic cost point of view for the sewer system itself. Mostly, it is the effects caused downstream in wastewater treatment plants or due to sewer overflow and basement flooding that cause concern. Currently, the tariff systems and the legislation are not designed in such a way that the price can easily be differentiated between different uses. To be able to differentiate pricing against the customers, a lot more data collection and measuring would have to take place to be able to justify price

[28] Smith et al, 2021
[29] Bertolin et al, 2021
[30] Casanueva et al, 2021
[31] Nilsson et al, in review; Arnell et al, 2021
[32] Saletti et al, 2023

differences from a legal viewpoint. To manage a more data-driven cost model, the municipalities need to ramp up their ability for measuring, data management, and smart decision-making to a completely new level, and the incentives for doing so are presently not enough. As one of the respondents put it, the water utilities need to build a new data infrastructure on top of the old, piped infrastructure which would require substantial organisational innovation. Currently the water utilities find themselves "stuck in the Death Valley of innovation"; not yet able to take the leap to become a data-driven service sector. A conclusion from this FGD is that it is necessary to demonstrate the real benefits of data-driven pricing and planning in order to convince municipalities, and that the business models, organisation and regulation also need to be developed.

4.5.2 Unmanned Autonomous Vehicles (UAV) for inspection

Bridges and tunnels are critical structures for transport systems and their status and condition is also a vital safety concern. The costs for maintenance and inspection therefore must be balanced with as accurate as possible estimation of failure risks. However, inspection is costly and interferes with the normal operation, and Shift2Rail has therefore developed methods for non-intrusive inspection and monitoring of their status. Comprehensive data on useful indicators, such as cracks, movement, vegetation, signs of scouring, sound, water pressure and many more, are available. Moreover, new non-intrusive technologies such as Unmanned Autonomous Vehicles (UAVs), noise detection, laser scanning, image and radar analysis have been mapped and tested, along with methods for data and reliability analysis using e.g. Building Information Modelling, BIM[33]. This knowledge is useful for municipalities, water provider associations or regional authorities, who own and manage tunnels and bridges - along with other structures such as water towers, reservoirs, or harbour structures.

One promising and fast-growing area is that of UAVs or drones. In a study by Riquelme et al (2020) different aerial drones platforms, for inspection of rail infrastructure were tested, including key specifications (e.g. payload capacity, battery, range) and challenges with standards and safety requirements documented. Anti-collision equipment, pilot skills, camera requirements etc were also evaluated against economic performance. Another study reported on tests in Poland to inspect railway sidings and signal installations, check-lists and pre-flight planning scenarios were proposed[34]. This could be useful for drone operators across application areas even in a rapidly advancing technological area like UAVs.

Some knowledge has already found its way into Sweden's municipalities, thanks to Mistra InfraMaint. Project 1.1.b builds on knowledge and applications developed in Shift2Rail using UAV inspection of bridges along with automated image analysis of early indicators on municipal infrastructure in Stockholm. The purpose is to spearhead condition-based maintenance (CBM) approaches at Trafikkontoret in City of Stockholm (City street administration). On the whole there may be interesting prospects in this field.

From the focus group discussion, it appears that Sweden seems to be lagging behind other European countries when it comes to the use of UAVs. For inspection of street surfaces, however, various types of automated inspection takes place, for example using LIDAR-scanners mounted on cars. These services are commercially developed and are regularly procured by municipalities. For inspection of bridges, there has been some development thanks to early initiatives from Trafikverket on digital asset management for bridge infrastructures (BATMAN). UAV-based services are available commercially, but mainly for documentation and seldom used for any more sophisticated analyses. Data formats are to a

[33] Hermosilla et al, 2019
[34] Kochan et al, 2018

large degree standardised. However, the huge amounts of data generated by image and scanning technologies was reported as a barrier due to difficulties in storing and retrieving these data-sets for long-term condition assessment. To get a more wide-spread use of UAVs for Swedish municipal infrastructure, the FDG participants were unanimous that a variety of actors can have important roles to play; suppliers and consultants, municipalities, universities, funders like Vinnova, but also non-traditional actors like ICT-companies (Amazon, Google, IBM) and science-parks and incubators. Development of UAV applications needs to be done by private sector and universities but in collaboration with municipalities, and SKR (the Swedish Association of Local Authorities and Regions) should have a stronger coordination function for technical issues. There is need for more tests and practical development to show the way, but also to develop the quality of actor collaboration. Municipalities can improve their capabilities as professional clients and for adopting new technology, universities need to strengthen their capacity for transdisciplinary work, consultants can be more active in knowledge circulation between sectors, for example.

4.5.3 Artificial Intelligence for managing water networks

Feeding large data amounts into computer algorithms to recognize patterns and to detect anomalies is increasingly being applied in a range of fields. Typically, such applications of "machine learning" are used to assess condition status or to predict malfunctions and failure in infrastructure such as railways. In a side project to Shift2Rail, research was carried out to use data from movement detectors in bridges to detect risk of failure using an Artificial Neural Network[35]. These methods have already been carried over into the water sector by developing a use case on data from Uppsala Vatten, a water utility in Sweden, in the Mistra InfraMaint project 1.1a[36]. Around the same time, another ANN application was developed internally in one of the Swedish water utilities (SVOA in Stockholm) to detect and predict water leakages. This has later spread to other utilities through a national network[37].

Methods and experience of machine learning or other AI applications in the railways sector have thus already proven themselves to be of high relevance for the municipal infrastructure sector. But the examples prompt us to reflect on how innovation diffusion takes place, and how knowledge is managed, within the respective sectors. The municipal water sector is characterised by a non-commercial and non-competitive arena which could be favourable for open innovation and sharing of knowledge. On the other hand, market fragmentation and lack of political and consumer awareness may be disadvantages from an innovation perspective[38]. In the water sector examples above, individuals or not-for-profit networks have typically been instrumental to introduce and implement innovative digital technologies. New techniques such as ANN have great potential for municipal infrastructure but the innovation ecosystem may need strengthening through capacity building, harmonisation and standards, which could make it more interesting for commercial developers and consultants.

From the implementation side it is obvious that ANN applications to water networks management are only in its infancy in Sweden. While not necessarily representative of the situation in other countries, the participants in the Focus Group Discussion all expressed that the number of applications in Sweden is still small and mainly directed to relatively simple functions, such as anomaly detection. ANN applications are also to a relatively small degree used to inform decision making. Barriers identified included lack of development capacity and competence among the municipal water utilities, as well as of data fragmentation which creates

[35] Leander, 2018
[36] Meydani, 2022
[37] Sörensen & Nilsson, 2021
[38] Bennich, 2022

"lock-in" of data and of applications. It is hard for developers and private suppliers to develop applications when all the potential customers work in their own unique way and have different data formats. While there is an ambition to "work smarter" among municipalities, the incentives are not strong for change as the leadership typically prioritises conventional expansion and operation rather than innovation in the management of existing assets. The Swedish water sector, one participant pointed out, is perhaps too happy about the current state of affairs and not really interested in change. In order to unlock the potential of ANN (or other data-driven applications) the participants emphasised that more sector collaboration is needed to spearhead development of useful and tested applications. Funders like Vinnova and umbrella organisations like Svenskt Vatten should have important roles in pulling actors together instead of working alone. They also stressed that there is need for organisational innovation and that municipal water actors could get inspiration from other sectors, to learn from different organisational cultures and how they work with competence management.

5 Conclusions

The European railways sector is in a stage of renewal and change, where the EU-funded Shift2Rail programme (S2R) supports a dynamic and active innovation ecosystem. In this study, we have identified new knowledge and innovations within S2R that could potentially be beneficial for the municipalities in Sweden, for managing and maintaining their infrastructures, such as city streets, water and sewerage. There are lessons to be learnt in all three areas of work for MISTRA InfraMaint (decision support, organisation and competence) but some innovations and knowledge are more likely than others to be transferrable.

The innovations that may be directly applicable (or require minor adaptations) we believe are found in areas where the technical systems face similar types of management challenges and where components are physically similar, such as bridges, tunnels and other large structures. Here, S2R innovations and knowledge are deemed particularly useful for applications such as:

- UAV inspection;
- Image data analysis,
- Fibre optical methods;
- Vibration sensing and modelling;
- Data management including BIM, and:
- Prediction and condition assessment based on AI / ANN.

Numerous results from S2R can be useful but will require careful adaption, or can serve mainly as inspiration. This includes innovations like:

- Universal cost models and sector-wide KPI:s;
- Common Smart Maintenance Concept;
- Standardised Data and System requirements;
- Instrumentation of vehicles and users to generate new data streams;
- Future studies and exploration of disruptive technologies like BlockChain, and:
- Sector-wide analysis of Human Capital development needs.

On an overall level, we see important differences between the respective sectors that are likely to affect the transferability of knowledge. The most noteworthy is that the actor-sets differ substantially between railways and municipal infrastructure, where the latter exhibit fragmentation with many small units and few industrial partners. Hence, in order to take advantage of knowledge transfer from S2R or from other sectors, **the municipal sector should strive to create a stronger innovation ecosystem at national level**. Important lessons from S2R would be to initiate national processes of **standardisation, to harmonize data formats, system requirements, and joint concept definitions**. In addition, both municipal actors and the MISTRA InfraMaint should also strive to increase **dialogue and collaboration with technology suppliers and consultants** in R&D. In combination with transfer of knowledge, this can help in creating a more robust and dynamic innovation ecosystem around management of city streets, water and wastewater infrastructure. Sector umbrella organisations like Svenskt Vatten or SKR will have to assume key roles in this consolidation process of the sector.

Another key message is that to succeed with knowledge transfer, technical innovations need to be matched with reforms to **improve organisational cultures and competence**. The dialogue and interaction we have had with sector professionals in this project was relatively limited and we are careful not to base too far-reaching conclusions on this. Nevertheless, incentives and "landscape pressure" is crucial for innovation. It could well be that many municipal decision-makers are still to be convinced about the real benefit of working with data-driven, "smart", asset management. We believe that to get to the next level, the municipal infrastructure sector in Sweden will have to take a serious look not just at technological innovations, but at their own needs of organisational and institutional development.

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Appendix 1. People interviewed

Mats Berg, KTH

Raied Karoumi, KTH

FGD on Universal Cost Models:

Glen Nivert, Göteborg Stad, VA och Kretslopp (municipal water department)

Andreas Lindhe, Chalmers tekniska högskola (university)

FGD on UAV inspection:

Anna Wenman, Stockholms stad, Trafikkontoret (municipal streets department)

John Leander, KTH (university)

Juan Avendano, KTH and Tyréns (consulting company)

FGD on AI applications for water networks:

Marinette Hagman, DHI Sverige AB (consulting company)

Tommy Giertz, Stockholm Vatten och Avfall AB (water utility)

Simon Granath, VA-Syd (water utility)

Appendix 2. Questions for the Focus Group Discussions

(translated from Swedish by the authors)

FGD on AI and water

1. Most agree that AI applications in VA have great potential. But to what extent is it used practically today in VA operations in Sweden in your opinion?

2. What are the biggest barriers to AI applications being developed, deployed and used?

3. Who are the most important players in accelerating the pace of innovation in this area? (e.g. VA principals, consultants, technology suppliers, trade associations, etc.)

4. How can the water sector absorb knowledge and solutions from other sectors, such as road, railway, industry etc.?

FDG on UAV applications in municipal street management

1. Most agree that UAV applications in street and bridges managaemtnhave great potential. But to what extent is it used practically today in Sweden in your opinion?

2. What are the biggest barriers to UAV applications being developed, deployed and used?

3. Who are the most important players in accelerating the pace of innovation in this area? (e.g. VA principals, consultants, technology suppliers, trade associations, etc.)

4. How can a municipal technical sector (like streets) absorb knowledge and solutions from other sectors, such as water, railway, industry etc.?

FDG on Universal Cost models

1. Different functions and use of a sewer network entail different costs and risks. To what extent do the WSS utilties in Sweden know the costs of, for example, stormwater and infiltration?

2. What would motivate better knowledge of various costs and risks on the user side?

3. What are the biggest barriers for the municipal utilities to use more advanced methods (eg sensors, modelling, AI) to assess these costs and risks?

4. What possibilities does the WSS utility have to differentiate pricing based on use?

5. What advantages or difficulties do you see in developing uniform cost models for the Swedish wastewater sector?

6. Who are the most important players in accelerating the pace of innovation in this area (e.g. municipalities / utilties, consultants, technology suppliers, trade associations)?