WORLD CLASS MAINTENANCE

Infrastructure Maintenance, a Necessity and Opportunity for Europe

TILBURG UNIVERSITY

Contents

Colophon

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Roads, bridges, railways, tunnels, airports, sea and inland ports, locks and other infra assets are crucial to the European economy and thus to our welfare.

This report shows that proper and timely maintenance of these infra assets is vital. It is necessary to ensure availability, which is essential for the transport of goods and people. Proper maintenance extends the lifecycle of infra assets. It saves a lot of money, reduces the use of new materials and thus fits perfectly within the philosophy of the Green Deal.

Maintenance has long been neglected, across Europe, in favour of new construction. Apparently, opening a new tunnel or putting a new road into service appeals more to the imagination than renovating a lock or life-extending maintenance on a motorway, tunnel or bridge.

This report makes it clear that we should not be blinded by new construction. With the latest technological developments in smart maintenance, there are huge opportunities to improve the things we do together. We have to, because many infrastructure assets in the EU are nearing the end of their lifespan and we face a huge task in replacing or maintaining them. The shortage of technicians and the lack of sufficient budget also makes it necessary that asset owners, contractors, service providers, educational and knowledge institutions and governments work together on smart maintenance, or help accelerate its adoption and implementation.

This World Class Maintenance report highlights the importance of good and available infrastructure in a scientifically substantiated way. I highly recommend it and hope it will be applied.

Herald Ruijters
Director Investment, Innovation & Sustainable Transport Directorate-General for Mobility and Transport

Preface

> “What can be done better, smarter and more effectively in the infrastructure sector?”

European infra cannot survive without smart maintenance
If the Morandi Bridge in Genoa that collapsed in 2018 had been equipped with smart sensors, the deadly disaster might not have happened at all, despite overdue maintenance.
If the Merwede bridge in central Netherlands had had sensors, hairline cracks in the structure would have been spotted earlier. The economic consequential damage of around €30 million caused in 2016 by the weeks-long closure would then have been prevented.

Weir De Haandrik in the eastern Netherlands was constructed in 1919 and not designed to meet today’s requirements. Sensors were fitted during a large-scale renovation four years ago. A few days after the sensors were installed, a mechanical component broke down. Thanks to data from the sensors, the asset owner was able to identify the cause and accelerate safety and re-commissioning. The new insights also allowed the asset owner to save a lot of money on renovation costs.

The 5-kilometre-long Zeelandbrug (built in 1965) in the south-western Netherlands is a crucial riverbank connection that in 2023 has to endure a much higher traffic load than it was designed for. That traffic pressure is expected to increase by another factor 4 to 5 in 2025 as the Westerschelde-tunnel becomes toll-free. The toll-free tunnel will create an interesting route for freight traffic between Rotterdam and Antwerp. Meanwhile, sensors have been installed on the bridge that measure vibrations, energy consumption and oil degradation. The data this generates helps to gain insight into the current (safety) status of the bridge. This allows the manager to make more informed decisions regarding safe use, necessary maintenance and timely replacement.

Sufficient and available infrastructure is vital for (the growth of) the EU economy and prosperity. Europe faces a huge task in terms of replacement and maintenance of the existing assets and new construction as part of the TEN-T network. Not only in terms of money, but also in terms of people and materials. So the question ‘what can be done better, smarter and more effectively in the infrastructure sector?’ is a valid one. Smart maintenance is the answer to that question.

Much of Europe’s existing infrastructure is nearing the end of its technical lifespan. One of the questions asset owners struggle with is whether that technical lifespan is correct. Moreover, existing infra assets are often not designed and built for the loads they have to endure today.
Even nowadays, in the year 2023, little or no consideration is given to lifecycle maintenance during construction phase of new assets. The focus is usually on (reducing) construction costs as there are no incentives for designers and builders to optimise maintenance. Furthermore regulations in this area are lacking.

At the same time, many asset owners have less specific technical knowledge than before because many activities are outsourced and because many knowledge holders are leaving their organisation due to an ageing population. Meanwhile, users expect infinite availability.

Monitoring infrastructure with sensors and using that data for maintenance decisions is called smart maintenance, a term in line with the digitisation drive in industry: Industry 4.0. Smart sensors can collect a variety of data from an asset. Experts can use these to make statements about its status. This makes it possible to do the right maintenance at just the right time, and therefore not too late (downtime, risk of accidents) nor too early (capital destruction). By also applying artificial intelligence techniques, a self-learning system is created that predicts ever smarter and better what needs to be done. Maintenance thus becomes condition-based (CBM) instead of preventive and/or corrective. And that means more effective and cheaper.
The attached study shows that by applying CBM, savings of at least 44 billion euros can be realised over the next 20 years. That amount could rise to almost 500 billion euros, depending on the share of investments to which CBM can be applied.

Under the auspices of World Class Maintenance (WCM) in the Netherlands, governments, asset owners, technical service providers and educational and knowledge institutions are working together in a variety of research and innovation projects to further develop smart maintenance applications. This has been happening since 2016 in the WCM Fieldlab CAMINO for the infrastructure sector, in which partners work together in an open innovation setting on real practical cases. The above practical examples of De Haandrik weir and Zeeland Bridge are examples from this Fieldlab.

The necessary joining of forces is thus already taking place in the Netherlands and, as mentioned, is showing valuable results. As a result, Rijkswaterstaat (Ministry of Infrastructure and Water Management) decided to introduce data-driven asset management for its assets. To this end, it entered into a cooperation agreement with five maintenance and management parties that are obliged to share knowledge gained among themselves. This prevents each party from reinventing the wheel for itself and also keeps up the pace. In view of the many obsolete assets, the latter is certainly important.

With the upcoming TEN-T plans, there is a huge opportunity for member states to optimise the construction, maintenance and use of their infrastructure assets at lower cost. It is therefore imperative for Europe to join forces and seize this opportunity.

World Class Maintenance
Prof. Dr. H.A. Akkermans,
Director

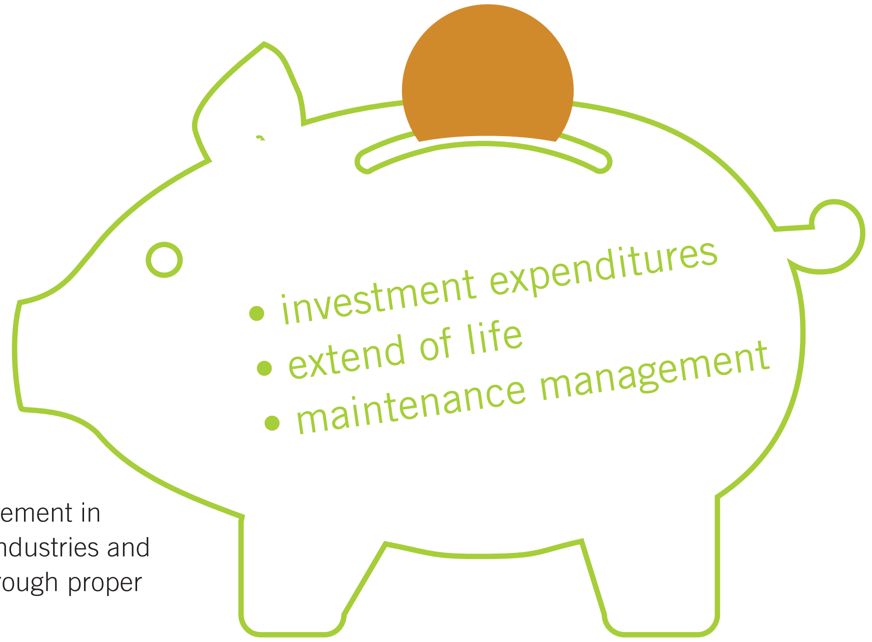
Executive summary

Public investment in the EU has steadily declined from 3.4 % of GDP in the 70s to 2.7 % in 2017 and remains well below its long-term average of 3.1%. The 2008 financial crisis has strengthened the drop in public investment. The decrease in infrastructure investments was even stronger and in 2017 was at only 75% of the precrisis level. The data on average annual spending in 2008-2019 as a percentage of average annual spending in 2000-2007 in Table 1 supports this analysis. [1]Table 1 shows that, apart from inland waterways[2], investments in real terms have gone down considerably after the 2008 crisis. The data on maintenance show a similar pattern. The data are in constant prices, which makes it possible to review the developments in real terms, as well as comparing the development of infrastructure investments and maintenance before and after the 2008 financial crisis.

Over the past decade the government sector accounted for about 80% of the fall in total infrastructure investment in roads, rail, inland waterways, maritime ports, and airports. The costs to the economy of the covid pandemic and the war in the Ukraine will further put a strain on these spendings. A healthy infrastructure is however a must for every modern economy. The annual contribution of infrastructure to the value added of Members between 1995 and 2016 ranges from 11.2% in Germany to 17.3% in Hungary. The contribution decreases as an economy grows and the economic system becomes more complex.

Table 1 Total average annual spending on investment and maintenance as of 2008 compared to before 2008 in constant prices

	road	rail	inland waterways	maritime port	airport
INVESTMENT	70,6 %	91,8 %	105,2 %	64,5 %	67,8 %
data available for	2000-2019	2000-2019	2002-2018	2002-2019	2001-2018
MAINTENANCE	85,0 %	81,6 %	61,2 %	74,1 %	57,2 %
data available for	2000-2019	2000-2019	2002-2018	2004-2019	2000-2018



What is called for is a stronger emphasis on efficient and effective lifetime infrastructure spendings. As already emphasized at the 2014 World Economic Forum, asset management in infrastructure is worse than in other industries and substantial value can be unlocked through proper operation and maintenance.

The best way to unlock the value of maintenance is by condition-based monitoring (CBM), which is based on extensive use of sensors for condition monitoring and data analytics to forecast the effects of wear and tear. These can be implemented during construction or expansion of the infrastructure. For the EU, depending on the share of investments CBM can be applied to the potential savings through longer service lives and improved maintenance through CBM of investments over the period 2020-2040 are most likely €161.2 billion for investments and €38.1 billion on maintenance; but could be as high as €379.7 billion and €90.1 billion respectively. Money that is urgently needed to narrow the gap between actual and needed infrastructure investments after the 2008 financial crisis and realizing the TEN-T goals. Note that this is in constant 2018 prices. With an annual inflation of (say) 2% these amounts increase by some 23%. Money that can be used to narrow the gap between actual and needed infrastructure investments after the 2008 financial crisis.

But this can only be achieved when politicians pay attention to the speedy dissemination and implementation of CBM. In all areas people are already working on identifying CBM opportunities and the implementation thereof, but this is not progressing fast enough. As in many areas of the economy the construction sector is hampered by a lack of skilled labor. This means sharing knowledge between sectors and educating technicians and construction workers to realize CBM's cost saving potentials. What is needed is coordinated cross-sectional action from all areas to reap the benefits of CBM. This points at an important organizational complicating factor for the widespread use of smart infrastructure. It requires the cooperation of operators from different domains of activity, such as ICT and public transport, as well as different levels of government.

But there are also other constraints for a rapid dissemination of CBM technologies. First there is the lack of qualified personnel. Education plays a central role in scaling up the use of new technologies. Data analysts and material experts need to be trained to enhance knowledge creation and the development of new insights. Lack of proper knowledge hinders the spread of CBM in many industries and more emphasis has to be placed on training CBM technicians and educating decision makers about what CBM has to offer. This is also needed to further innovation in, and application of, smart maintenance. This is further hampered by the fact that the construction sector is one of the least innovative sectors, which is at odds with applying the latest technologies.

[1]The table is based on OECD data of Member States for which these data are available.

[2]This is due to a large increase in investments in Italy during the period 2013-2018.

Introduction

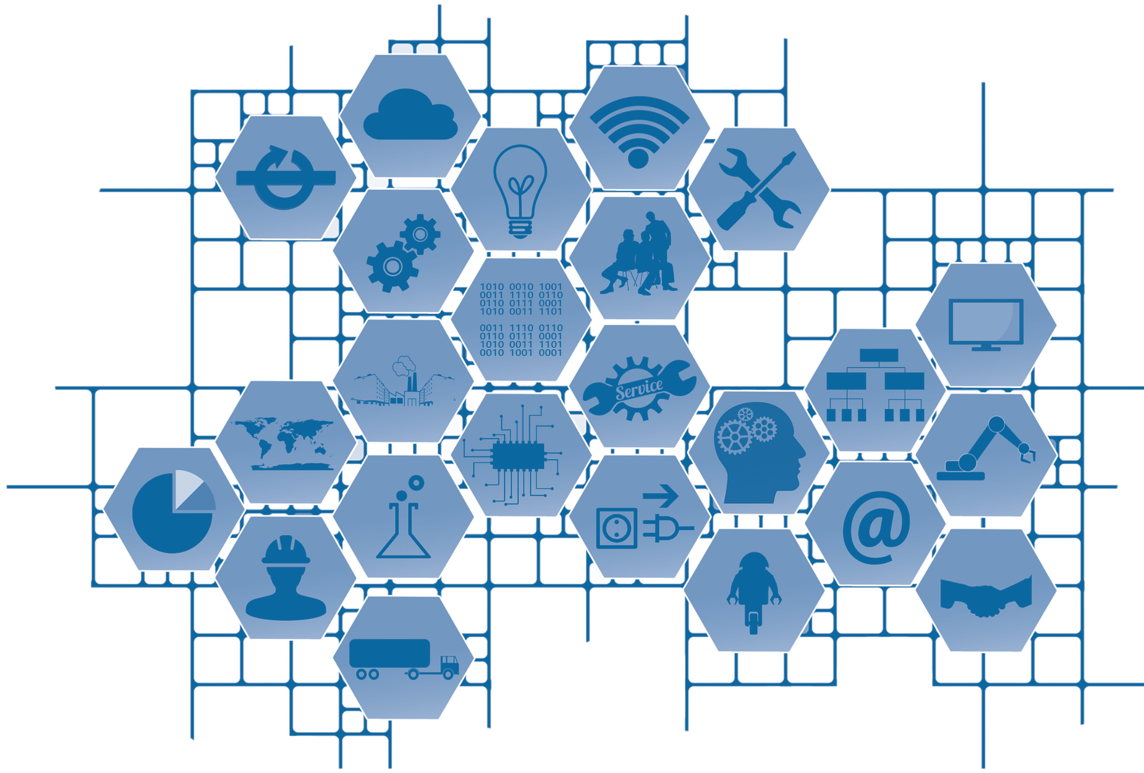
A healthy infrastructure of roads, rail, inland waterways, ports, and airports is the backbone for a sound economic development in the EU. Failing infrastructure immediately affects many other economic activities and often has dire consequences. In the past many infrastructural works were designed without much thought about maintenance. However, infrastructure failure due to lack of maintenance is often very costly. The Dutch Ministry of Infrastructure and Water Management uses as a rule of thumb that in case an asset fails the cost to producers and consumers is ten times that of the cost of repair (Kerkhof, Lamper & Fang, 2018). Furthermore, the different infrastructures are closely connected and dependent on each other; failure to deliver of one affects the performance of the others. This thought is at the core of the EU's Trans-European Transport Network[3] (TEN-T) investment program, the Europe-wide network of connected railway lines, roads, inland waterways, maritime shipping routes, ports, airports and railroad terminals. This demands an approach in which future maintenance of infrastructure gets as much thought as the initial investment, especially since the total maintenance and management costs of infrastructures with lifetimes of 60 years or more are often higher than the initial investment costs.

Smart maintenance through condition monitoring is the way to achieve this goal. Condition monitoring offers ample opportunities to save money when investing in new infrastructure or improving the functionality and/or lifetime of existing ones. But it also saves money due to better planning when renewing parts of existing infrastructure. Condition monitoring uses innovative technology, such as sensor-based applications, and exploits the power (of combinations) of a wide variety of digital technologies. When applied it enables predictive maintenance, also known as condition-based maintenance[4] (CBM) to improve Europe's infrastructure. CBM enables the use of digital twins, a virtual model designed to accurately reflect a physical object, to assess the condition an asset is in. Data analytics, such as artificial intelligence (AI), is used to analyze and interpret the large quantities of data obtained through condition monitoring. CBM makes it possible to better predict when what maintenance is actually needed, this to prevent damage that needs to be corrected or maintaining too early, which both are costly. It also makes it possible to better estimate the remaining service life, to recognize wear and tear early on, and to reduce the risk of failure. This information is also useful for the design of more adequate and easier to maintain future infrastructure investments. CBM leads to more

[3] TEN-T networks consist of nine European corridors that, by 2030, should unite 94 European ports with railway and road connections, 38 key airports with train connections to the major cities, 15,000 kilometers of high-speed trains and 35 cross-border projects to reduce bottlenecks. Also see https://ec.europa.eu/inea/ten-t/ten-t-projects/projects-by-country

[4] Some authors treat predictive maintenance and condition-based maintenance as two separate concepts. This distinction does however make no sense. Both are based on condition monitoring and the use of data analytics to monitor and identify (potential) problems. Since predictive maintenance focuses specifically on predicting future failures, it may be seen as a subset of CBM. CBM is a broader known term (8.8 vs 1.1 million hits on Google search), CBM is a more correct description of the maintenance techniques involved.

[5] This crisis was the result of the bursting of the United States housing bubble, which in its aftermath caused the European debt crisis which had a negative effect on the economy of all MSs and several MSs (Greece, Portugal, Ireland, Spain, and Cyprus) needed support of other eurozone countries, the ECB and the IMF to prevent bankruptcy.



reliable, fact-based decision making resulting in longer service life and lower maintenance costs.

But the use of condition monitoring needs better policy support to speed up its use. Europe's aging and in many places obsolete infrastructure is in urgent need of cost-effective investments and maintenance. Since the 2008 economic crisis[5] spending on infrastructure has gone down in most member states (MSs) leading to investment delays and deferred maintenance. All this requires extra spending. However, with the current crises in mind there will be limited funds to achieve this, so money must be spent wisely.

Already in 2014, a report by the Boston Consulting Group, prepared for World Economic Forum, concluded that asset management in infrastructure is worse than in other industries, with a particular gap in management and control. (WEF, 2014) They conclude that, given the size of our infrastructure stock, substantial value can be unlocked through proper operation and maintenance. This can -among others- be achieved by reconstruction and renewal to prolong its lifetime, and when possible, improving the original performance or capacity through upgrading, but also through improvement of the maintenance strategy.

Although condition monitoring and maintenance is getting attention, this is not going fast enough to reap its benefits to the fullest. CBM as a smart maintenance strategy integrated in future and past investments offers opportunities to improve Europe's infrastructure and at the same time optimizing the use of limited funding. Condition monitoring leads to life-cycle optimization and integrated efficient operations, resulting in improvements in the existing and future infrastructure stock, regarding both safety and serviceability. Although these technologies have been researched substantially, utilizing their potentials is lagging. This document analysis the size as well as the cause of this problem and calls for action to improve this.

This paper is organized as follows. In section 1 economic infrastructure is defined. Section 2 discusses infrastructure's contribution to economic development. Section 3 shows that Europe's infrastructure is lagging its needs. Section 4 analyses expenditures on infrastructure and maintenance. Section 5 reviews what monitoring techniques have to offer. Section 6 discusses savings potentials of CBM. Section 7 reviews future investments for realizing smart maintenance and the potential effects of CBM. Section 8 contains conclusions and recommendations.

1 Infrastructure defined

Infrastructure plays a crucial role in every economy, but there is no agreed-upon definition of infrastructure (Baldwin & Dixon, 2008). The quality of life and well-being depend heavily on the availability of an adequate infrastructure for transport, telecommunication, utilities -water, gas, electricity, waste-, education services, an adequate health system, as well as community services. A useful distinction is that of economic infrastructure (roads and other transportation facilities, power generation and other utilities, and communications systems) as opposed to social infrastructure (schools, hospitals, prisons, etc.).

This study concentrates on investing and maintaining transport infrastructure: road, rail, inland waterways, ports, and airports, which are all part of the economic infrastructure and are essential for connecting markets. The reason for this is that these require large investments and are still mainly done by, or under strict control of, governments, whereas telecommunication and utilities are often owned and operated by private companies.

Another term that is often used is public infrastructure. Originally this term was used for infrastructure investments by the government, covering projects that are generally large capital-intensive investments with several distinctive features. (CEB, 2017 p. 9) It is a non-rival good, which means that consuming its services does not prevent others from consuming these too. It is also often non-excludable meaning that those who do not pay for it can often not be excluded from using it, making it difficult for private investors to make a profit. Furthermore, public infrastructure has significant up-front costs, but benefits take a long time to realize. There are often externalities, for example constructing roads and bridges can have a positive effect on the productivity of companies and households in the region. The social benefits than exceed the possible private returns for a potential provider. Since competition is not possible or too expensive, these investments, done for very long time periods, have the characteristics of a natural monopoly. Infrastructure as such can be defined as a set of fixed structures that have long useful lives, whose creation involves a considerable gestation period, have no good substitutes, and underpin the production of a flow of services for which it is difficult to maintain inventories (Baldwin & Dixon, 2008). What makes it public is that extensive government involvement and regulation is required.

For these investments participation by private investors through public-private partnerships has been on the rise. Public-private partnerships, like toll roads, still represent a relatively small share of the overall investments in infrastructure (Fabre & Straub, 2021). So it is the task of governments to construct and maintain.

All the EU's domestic and international economic activities profit from well-designed and maintained infrastructure systems, but infrastructure as a topic has a disadvantage. When government budgets are tight, spending on infrastructure, and especially on maintaining it, is often postponed. In times of fiscal pressure it is one of the first budget items to be cut. It is also regularly neglected when showing tangible results to a certain section of society is more politically appealing. Furthermore, infrastructure is not the responsibility of one decision maker, but of many: different levels of government as well as private stakeholders. This does not automatically result in an optimal solution. The public only becomes aware of the crucial role of infrastructure when it fails, often after many years of accumulated neglect and deferred maintenance. It is then that politicians act.

Physical systems like bridges, viaducts and tunnels in roads and railways, are in place for a very long time -often 80 years or more-. During such a period there are many technological and other developments that alter our ideas of what services the systems could/should deliver. Not keeping the infrastructure up to date through a lack maintenance, renewal and enhancement puts the entire economy at risk (Weijnen, 2019).
From the above it is evident that investing and maintaining Europe's infrastructure is a challenging task. To complicate matters, infrastructural projects are often characterized by cost and time overruns, and with the increase in cross-border infrastructure dependencies the number of problems is mounting too, notably related to coordination challenges, inconsistent regulatory frameworks across countries, and varied levels of governance and creditworthiness. (IMF, 2020) Nonetheless, as stated by European Investment Bank (EIB) in its 2021 report, maintaining cross-border transport infrastructure is key to ensuring good conditions for economic recovery (EIB, 2022a).

2 Infrastructures' contribution to economic growth

The effect of infrastructure on economic growth has been studied by economists for many years. Melo, Graham& Brage-Ardao (2013) analyzed 563 estimates obtained from 33 studies and conclude that the productivity effect of transport infrastructure varies across main industry groups, tend to be higher for the US economy than for European countries, and are higher for roads compared to other modes of transport.
Bom & Ligthart (2014) analyzed a sample of 578 estimates collected from 68 studies for the period 1983-2008 and found a short run-elasticity of 0.131 and a long run elasticity of 0.170 for core capital investments -which is mainly transport- on the national level. With core capital being about 40% of GDP this implies a marginal return of over 40% on core capital in the long run, which is well above the cost of public capital. The elasticities for investments on the regional level are even higher so from a macroeconomic point of view public investment on the regional level should be encouraged. They argue that public capital is undersupplied in OECD economies. Abiad, Furceri & Topalova (2015) identifying the causal effect of government investment in a sample of 17 OECD economies found that increased public investment raises output, both in the short and long term, and crowds in private investment. A meta-analysis of 78 studies of elasticity of production by Holmgren & Merkel (2017) found that the estimated effect of investing in different kinds of infrastructure varies from insignificant to positive, depending on the type of infrastructure in which the investment is made. Not surprisingly, the vast majority of studies on the contribution of infrastructure to the economy show positive results.

It is evident that without an appropriate infrastructure, policies to enhance economic growth will fail. A problem is that the contribution of infrastructure to value added is not measured directly, but must be approximated. In 2017, on request of NGinfra, a consortium of companies and the Dutch Ministry of Infrastructure and Water Management, Statistics Netherlands analyzed the contribution to value added of infrastructure[6] for a range of countries (Statistics Netherlands, 2019). The average contribution of value added of infrastructure over the period 1995-2016 ranges from 11.2% in Germany to 17.3% in Hungary. The share of infrastructure in the gross value added of the national economy has the tendency to decrease as the economy grows and the economic system becomes more complex.[7]

IMF (2020) states that the effect of public investment on output tends to be significant during recessions and statistically insignificant during expansions. Their analysis suggests that investing in infrastructure would contribute to economic recovery, which is especially true for countries with a smaller capital stock. Furthermore, the better the quality of the infrastructure the larger the response will be. However, in many MSs infrastructure maintenance and investments are under threat.

[6] Infrastructure defined as 'the total of immovable and movable assets and activities that are necessary to ensure the provision of the primary services upon which society and the economy rely'. See Statistics Netherlands (2019) for a concise description of activities included. For this study Mining & Quarrying was excluded.

[7] Note that possible indirect effects of infrastructure investments, which can be positive or negative, are neglected.

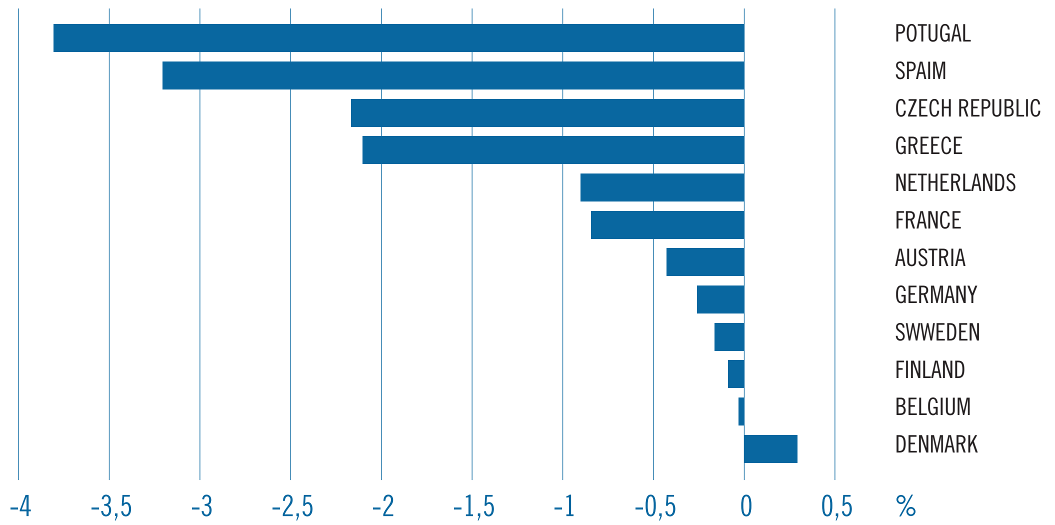
3 EU's infrastructure and maintenance lags need

According to the OECD (2019) public investment in advanced countries has steadily declined from 5% of gross domestic product (GDP) in the 1970s to approximately 3% GDP in 2017. The 2008 crisis has strengthened the drop in public investment, and it was particularly large in the EU; see Figure 1. Between 2008 and 2016 public investment in the EU declined from 3.4 % of GDP to 2.7 % and public investment remains well below its long-term average of 3.1 % of GDP between 1995 and 2017 (Bubbico, Brutscher & Revoltella, 2020). Especially at the subnational level the drop in investments was large, 3.1% per year on average from 2008 to 2016 (OECD, 2019). As Figure 1 shows the changes in government investments vary considerably between MSs[8]. For Portugal and Spain, the decrease was 3.75% and 3.17% respectively, also Chechia and Greece show a decrease of more than 2%. Denmark on the other hand shows a small increase.

The decrease in infrastructure investments was even stronger and in 2017 was at only 75% of the precrisis level. The government sector accounted for about 80% of the fall in total infrastructure investment over the past decade. EU infrastructure investments as a share of GDP after hitting a low of 1.5% of GDP in 2017, started to increase again. However, it reached 1.7% mainly because GDP contracted more than infrastructure investments (EIB, 2022a). The EIB analysis further shows that transport and utilities, including energy, jointly make up some 60% of all infrastructure investment; see Figure 2.

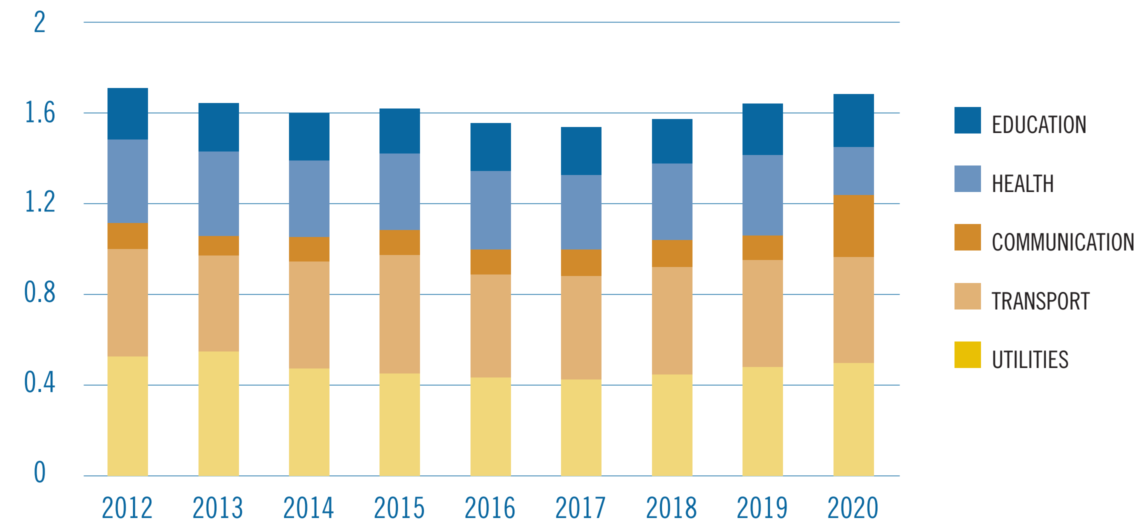
[8] *These data are not available for all MSs.*

Figure 1 **Change in the government investment-to-GDP ratio for various EU-countries between 2016 and the 2008-10 peak, in percent of GDP.**



Source: OECD Economic Outlook 2017, p. 52.

Figure 2 **EU infrastructure investment (% GDP), by economic sector.**



Source: EIB 2022a.

Note: Annual infrastructure investment in the EU by infrastructure asset, as a share of GDP, expressed as a percentage. Relevant data are not published for Belgium, Croatia, Lithuania, Poland and Romania. Where sector-specific data are not yet available, the sector share is assumed to have remained constant. The number of data points for 2020 remains insufficient to provide full confidence.

> "Over the past decades the EU has invested heavily in developing ICT applications to improve its infrastructure and CBM plays an important role in this."

The construction of the EU's transport infrastructure -especially by the EU15- peaked between 1960 and 1980. Although the lifetime of infrastructure is uncertain, there will definitely need to be a peak in construction in the decades between 2040 and 2080. Given the reduction in investments in infrastructure in the EU since the financial crisis there is a strong feeling that this tendency needs to be reversed. The war in the Ukraine and the pandemic add to this through increasing prices in general, and for energy intensive building materials in particular, increasing the gap between infrastructure needs and expenditures.

Central, Eastern and Southeastern European countries (CESEE) were already lagging behind in infrastructure investments and the stock of public capital per capita in CESSEE is only half of that of the EU15[9] (IMF, 2020). CESEE electricity generation is some 50% less and roads and railways normalized for arable land are on average 60% and 40% below the EU15 level. These figures vary considerably between individual countries and EU15. CESEE would need to invest 3%–8% of GDP per year in the next ten years to close 50% of the infrastructure gap relative to EU15 (IMF 2020). The Three Seas Initiative, which covers CESEE-EU and Austria, and focuses on boosting regional connectivity, envisages even larger needs of 8% of GDP (IMF, 2020). The EU wants to develop a level playing field, which can only be reached when sufficient investments are made for CESSEE to catch up. This has worked already to some extend for the CESEE-EU economies, which have reached income levels of about 70 percent of the EU15 level.

Infrastructure and level of government
Apart from these differences between countries with regard to infrastructure maturity, there is another complicating factor. A large part of the infrastructure investment and especially maintenance decisions are taken on the subnational level.

The responsibility for infrastructure expenditures in a country is shared by several levels of government. For the EU28 on average 53.9% of public investments is done by subnational government bodies and of this the majority (44.4%) by municipalities (OECD, 2021). In 2015 the OECD and the EU Committee of the Regions (CoR) conducted a survey of 295 subnational governments (SNGs) and almost all (96%) report having gaps in public investment spending for building new infrastructure (55%) and operation and maintenance (41%). On average around 70% of investment in the EU is allocated to the maintenance and operation of existing infrastructure, and only 30% to new investment. (OECD-CoR, 2016)

Furthermore, the European Investment Bank states that the public sector is slow in adopting the opportunities smart infrastructures have to offer. The integration of monitoring, data analytics and physical assets increases efficiency and reduces unwanted impacts. However, only 17% of EU regions report plans for smart infrastructure investments (EIB, 2019). To improve the governance, professionalism and efficiency of municipal management, there is a tendency to merge municipalities. Larger municipalities are better equipped to deal with problems such as the quality and quantity of municipal infrastructure and services. But the OECD data on subnational governments show that most municipalities are still rather small, making it difficult to acquire the organizational and technical knowledge and skills to deal with what smart infrastructure has to offer.

[9] EU15 includes Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, the Netherlands, Portugal, Spain, Sweden, and for this pre 2020 study also the United Kingdom.

4 Expenditures on Infrastructure and Maintenance

Expenditures on infrastructure comprise four main categories: enhancements, renewal, maintenance, and operation (CE Delft, 2019). Enhancements are expenditures on new infrastructures and expansions of existing infrastructures with respect to its functionality and/or lifetime. The decision to expand -renovate, reconstruct, enlarge- is not dictated by the condition of the asset and increases the performance or capacity of existing fixed assets or significantly extend their previously expected service lives. Renewal is renewing, but not expanding, parts of the infrastructure with a lifetime of more than one year. Maintenance expenditures are expenditures on minor repairs with a lifetime of two years or less that need to be undertaken periodically and these expenditures cannot be avoided, but do not alter the performance or capacity. Operational expenditures are the expenditures for an efficient use of the infrastructure. Together maintenance and operational expenditures are referred to as O&M expenditures.

According to Mahmoodian, Shahrivar, Setunge & Mazaheri (2022) the annual maintenance costs spend on civil infrastructure are 0.4–2% of the construction value. Bleijenberg (2021) uses 2.1% of the infrastructure's replacement value as indication for the annual maintenance costs.

Data on expenditures on infrastructure and its maintenance are not readily available. However, with respect to transport, OECD and the International Transport Forum (ITF) collect data on investment and maintenance of the transport sector (ITF, 2019).[10] OECD/ITF investment expenditures cover expenditures on new infrastructure, expansions and renewal. Maintenance expenditures covers non-capital expenditure to maintain the investments original services and the capacity of the existing infrastructure and related equipment. OECD/ITF's transport infrastructure data on roads, rail, inland waterways, maritime port, and airports include land, permanent way constructions, buildings, bridges, and tunnels, as well as immovable fixtures, fittings and installations connected with them, such as signalization, telecommunications, toll collection installations, etc. These data are available for 2000 till 2020 - albeit only for a limited number of MSs- in current and constant 2015 prices.[11] They are considered to be the most reliable data.

Although these data have limitations, with sufficient care they can be used to check if there is a significant negative trend in the share of the total spendings on infrastructure investments and maintenance in the gross domestic product (GDP). For Austria, Croatia, Estonia, France, Ireland, Italy, Latvia, Lithuania, Poland, Portugal, Romania, and Spain this is the case. Denmark on the other hand shows a significant positive trend. For Malta, Cyprus and the Netherlands, the data on investment and maintenance are missing. For the other MSs the results are insignificant. So the OECD/ITF data support the macro analysis of Section 3.

The data are in constant prices, which makes it possible to review the developments in real terms, as well as comparing the development of infrastructure investments and maintenance before and after the 2008 financial crisis. Table 1 shows that, apart from inland waterways[12], investments in real terms have gone down considerably after the 2008 crisis. The data on maintenance show a similar pattern. Note that infrastructure maintenance only covers maintenance spending financed by public administrations on the preservation of the existing transport network.

Table 1 Total average annual spending on investment and maintenance as of 2008 compared to before 2008 in constant prices

	road	rail	inland waterways	maritime port	airport
INVESTMENT	70,6 %	91,8 %	105,2 %	64,5 %	67,8 %
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MAINTENANCE	85,0 %	81,6 %	61,2 %	74,1 %	57,2 %
data available for	2000-2019	2000-2019	2002-2018	2004-2019	2000-2018

[10] The OECD/ITF data must be interpreted with care due to definition and coverage inconsistencies between countries. Although considered to be the most reliable data on this topic, it is advised to be cautious when making comparisons between countries.

[11] For a complete description of the data and their availability per country see ANNEX 1.

[12] This is due to a large increase in investments in Italy during the period 2013-2018.

This downward trend in infrastructure investment and maintenance, which is in line with the macro analysis above, is extremely worrying. If it continues the European infrastructure for these sectors will not be able to support Europe's position on the international market and MSs will not be able to develop to a level playing field on the internal market.

Since the OECD-ITF data contain data on investment as well as maintenance[13] it is also possible to indicate how much is spent on maintenance compared to investments; see Table 2. Maintenance as a percentage of investment spending is substantial but has gone down in the period after the financial crisis, except for Maritime port. This downward effect is amplified by the fact that investment declined over the same period. The main lesson from Table 2 should be that maintenance spending is substantial and needs as much attention as investment decisions do. Only a lifecycle approach that includes both spending categories will result in optimal spending. As will be shown, condition-based maintenance can help to reach this goal.

However, keep in mind that these are ballpark figures that differ for individual MS and are strongly affected by data availability for the larger economies. However, the analysis supports the findings of Bubbico et al. (2020) that in the wake of the 2008 financial crisis maintenance expenditures went down, due to limited funding rather than reduced maintenance needs.

The analyses above show that the needs for infrastructure investments and maintenance are considerably larger than the actual spending.

[13] *Maintenance expenditure on infrastructure covers non-capital expenditure to maintain the condition and capacity of the existing road infrastructure, but not management and operational expenditures.*

Table 2 Maintenance spending as a percentage of investment spending in constant prices.

road		rail		inland waterways		maritime port		airport	
SHARE	PERIOD	SHARE	PERIOD	SHARE	PERIOD	SHARE	PERIOD	SHARE	PERIOD
52,7 %	2005-2007	83,8 %	2000-2007	62,5 %	2002-2007	48,9 %	2004-2007	71,8 %	2001-2007
57,9 %	2008-2019	69,2 %	2008-2019	47,1 %	2008-2018	64,8 %	2007-2019	55,2%	2008-2018
56,9 %	2005-2019	75,0 %	2000-2019	52,6 %	2002-2018	60,8 %	2004-2019	61,6 %	2001-2018

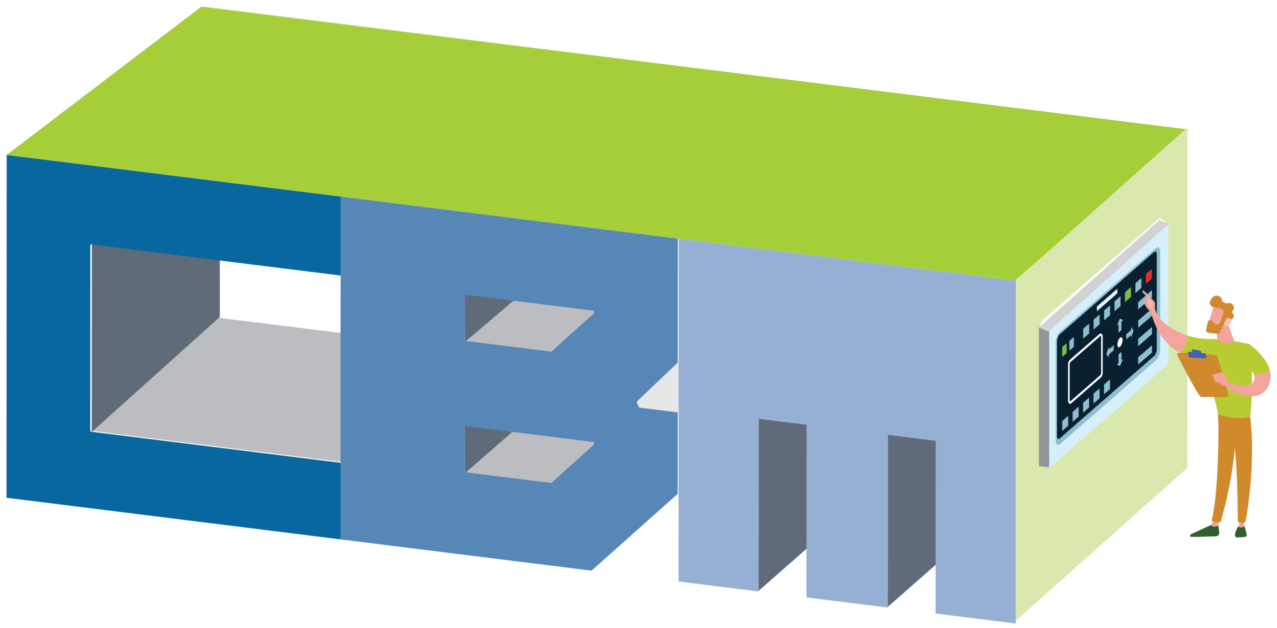
5 Monitoring and Smart Maintenance

ITF (2021) states that in the past many infrastructures were designed without much thought on maintenance requirements. However, with the increased availability of monitoring technologies the role of smart transport infrastructure maintenance has gained importance. There are two main approaches to maintenance: corrective and preventive. Corrective maintenance, also known as reactive maintenance, brings the system back to operation as quickly as possible after a problem occurred. To achieve that the system delivers the agreed upon service levels, preventive maintenance tries to avoid damages by reducing the probability of infrastructure failures (ITF, 2021).

Preventive maintenance can be either based on predetermined rules, better known as time-based maintenance (TBM), or the assessment of the actual condition the infrastructure is in. TBM assumes that failure rates of various parts of an infrastructure can be estimated on historical data. TBM tasks are conducted to delay the deterioration by maintaining the infrastructure according to predetermined periods. However, this can be costly too. Anderson[14] of UNIQUA Analytics states that in manufacturing 30% to 40% of preventive maintenance costs are spent on assets with negligible failure impact.

CBM actions are initiated when analyses of the monitoring data show there is evidence of unusual behaviors. Where TBM maintenance is performed independently of the actual condition of the

[14] *Anderson, D., Reducing the cost of preventive maintenance. UNIQUA Enterprise Analytics. http://www.plant-maintenance.com/articles/PMCostReduction.pdf Accessed on 18-10-2022.*



infrastructure, CBM uses indicative prognostic parameters to detect possible failures before occurrence. In this way unnecessary maintenance tasks can be avoided and therefore reduces maintenance costs. Already in 2010, the U.S. Department of Energy estimated that a proper used predictive maintenance program can save 8% to 12% in maintenance costs over TBM (DoE, 2010).

Exhibit 1: Cars and condition-based maintenance

When a modern car breaks down, the first action of the mechanic is no longer to open the hood, but to read out the data of the cars computer which tells what the problem is and what should be done. But the car also monitors itself and tells the driver what state it is in. The car monitors its condition when operating and indicates what maintenance is needed, the mechanic will then perform the recommended maintenance. But also, when the car fails, the car's performance data are important input for determining the cause of the failure.

Furthermore, the dealer or manufacturer can send messages to the car when needed. Data gathered in this way is also important input for car improvement by the car manufacturer. This interactive feedback loop for control, condition monitoring, maintenance, and performance monitoring, is what condition-based maintenance is about.

Due to the increase in technologies to monitor infrastructure, CBM is, albeit slowly, gaining ground. The data collected and analyzed using appropriate data analytics indicate changes in measurable parameters, which are used to schedule maintenance and prevent failure. 'Maintenance strategies are gradually shifting towards data-driven approaches, exploiting the power of digital technologies, big data analytics and advanced forecasting methodologies.' (ITF, 2021, 9) The objective is predicting irregular behaviors that can affect the performance of the infrastructure assets. Infrastructure systems are becoming more and more closely connected and need each other to function properly, especially using ICT technologies and networks. (See Exhibit 1 for an everyday example.)

We are all familiar with the integration of ICT and goods we use. The use of up-to-date infrastructure is subject to a similar process, but for a much longer period. Infrastructure is in use for many years. Its expected lifetime is based on the expected usage and the corresponding wear and tear. But infrastructure designed for a certain lifespan (say, 80 years) does not necessarily have to be replaced after 80 years, nor does the likelihood of it suddenly failing increase after 80 years. Its condition after 80 years all depends how it was maintained during this long period and on the actual wear and tear due to weather and changing conditions, for example due to climate change. There are plenty of examples one can think of. The 2021 flash floods due to heavy rain in western Germany, Belgium and the Netherlands just as much as the very dry summers in various European countries require rethinking of our water management; increasing sea levels ask for adjustments of dikes; and the high temperatures in the summer affect bridges, roads and railways.

Condition monitoring offers the opportunity to tackle these problems by taking better informed and risk mitigated decisions based on integrated -often real time- measurements of the condition of the infrastructure by its digital twin. For an example see Exhibit 2. Wear and tear can be identified early on, and the systems tell when and what to maintain, when and what to repair and when and what to replace. This increases the lifetime of the infrastructure but also reduces the lifecycle costs; not only for the infrastructure itself, but it also allows companies as well as consumers to be better prepared for the consequences of

About WCM Fieldlab CAMINO

The main objective of the participants in the WCM Fieldlab CAMINO is to achieve one hundred percent predictable maintenance for infra assets. In each case, an asset owner's issue forms the basis for an innovation project. In the 'safe environment' of the Fieldlab, the various parties can experiment and gain new knowledge.

Exhibit 2: CBM and dyke design

During the experiments with the sensors that started in 2007 it was shown that dikes fail later than predicted based on theoretical knowledge (Van Putten, 2013). This showed that TBM was too expensive. Through sensor measurements it was shown that the dike design can be optimized to prevent unnecessary reinforcement. This method has been applied to the Ringdijk in Amsterdam, a typical city dike with little room for improvement. Since 2011, the water pressure in the dike has been continuously measured at various locations using seventeen geobeads. The measurements were used for a new dyke design that was implemented in 2012, when the dyke needed renewal. Instead of the theoretical verge length of twelve meters, it turned out that a verge length of five meters already results in a sufficient safety level. Savings of 60% on materials were realized. On top of that the width of the dike was reduced considerably.

Source: Van Putten (2013)
Image: Amstel Gooi and Vecht Water Board (2017)

maintenance when the actual work is done. Given the fact that the capacity to do these works is limited, the system also allows for better planning of the works. Furthermore, collecting -real time- data increases knowledge about the wear and tear processes of assets. The latter are often known, but not the speed of the processes under various conditions. Of course, there will always be unexpected damaging events requiring more expensive corrective maintenance, but condition monitoring reduces these risks considerably.

The possibilities of various technologies for CBM for infrastructure has been -and is- researched intensely. Wu, Liu, Fu and Xinga (2020) using 166 scientific papers discuss the significant number of innovative sensing systems exploited in civil engineering for monitoring the structural health of bridges, dikes, tunnels, etc. using fiber-optic sensors. These have several advantages, they are small, lightweight, immune to electromagnetic interference and corrosion, and can be embedded. Dua, Duttab, Kurupb, Yub & Wanga (2020) use 144 scientific papers to review the current state-of-the-art applications of fiber optic sensing & monitoring technologies for structural health monitoring of railway infrastructure. These techniques for real time measurement and long-term assessment of structural properties allow for 'early stage' damage detection and characterization, resulting in timely remediation and prevention of catastrophic failures' and enables real-time data collection, inspection and detection of structural degradation. These advantages can be realized through collaborative sensing. He, Shi, Liu, Guo, Chen, & Shi (2022) review collaborative sensing based on the Internet of Things (IoT) for among others smart city, smart grid, smart transportation & smart building. They analyzed 361 scientific papers and show the progress made in smart technologies and its many possibilities in a range of applications. However, these studies do

Exhibit 3: The long way from design to application

Through projects funded by several state and federal administrations the Bridge Engineering Center at Iowa State University began the development of Structural Health Monitoring (SHM) system in 2000. The SHM system provides significant information for assessing bridge condition in real time on

- Identify the percentage of truck events within a driving lane (e.g., the driving lane is typically very large compared to other lanes on a bridge).
- Identify the highest stressed location on a girder (which typically occurs in a driving lane). Inspections can be performed more effectively with these data.
- Identify bridge usage (based on one-minute maximum, minimum, and strain range). These data allow engineers to address fatigue in the bridge, particularly for fracture-critical bridges.
- Identify threshold exceedances, which can show that large strain events do occur with three or more trucks on a bridge at the same time. During construction activity, these can result in closing one of the normal traffic lanes.
- Identify load ratings with the collected data in real time, and the data can show changes in the load rating over time.
- Identify critical areas on the bridge using the long-term data. As an example, the strain data could alert the bridge engineer that a bearing is frozen or partially frozen. Over time, it is possible to create excessive stresses at the abutment.

The current SHM system includes monitoring of more than 15 bridges and will be rolled out to cover many more.

Source: Phares, Freeseman, Greimann & Wipf (2020)

Table 3 **Information technologies classified based on different phases of applications**

Planning and Design	Construction	Maintenance
GIS (Geographic Information System): Site selection, roadside vegetation management, and road investigation.	**BIM:** Information sharing, construction management optimization, schedule monitoring, digital delivery, 3D visualization.	**WSN** (Wireless Sensor Networks): SHM, information collection, quality monitoring and traffic trend forecast.
BIM (Building Information Modelling): Aid decision making, information sharing, collaborative design, 3D visualization and LCM (Life Cycle Management)	**RFID** (Radio-frequency identification): Proximity sensing and safety warning, data collection and material tracking.	**FOS:** SHM (Structural Health Monitoring)
GNSS (Global Navigation Satelite System), **GIS, AR** (Augmented Reality) and **VR** (Virtual Reality): Visualization of underground facilities, investigation of roads.	**CV**: Data collection, visual inspection, quality control, schedule monitoring, efficiency improvement and SHM.	**BIM**: Expansion, update and maintenance, 3D visualization, safety inspection, SHM, asset management and LCM.
CV (Computer Vision): Planning, investigation of road.	**GPS**: Safety warning, material tracking and site management.	**RFID**: Leakage monitoring , object location and proximity sensing.
PPR (Ground-penetrating radar): Exploration of underground structure, investigation of road.	**System information model:** Schedule monitoring.	**Smartphone sensor**: Road detection, track wear assessment, traffic condition detection and vibration monitoring.
	FOS (Fiber Optic Sensing): Strain monitoring.	**MEMS** (microelectro-mechanical system): Assessment performance and condition.
	ICT, AI: Schedule monitoring, site management and communication.	**IoT and smart sensors:** SHM, information collection.
	Satellite remote sensing: Schedule monitoring	**CV**: Data collection, visual inspection, SHM, safety inspection, road extraction and pipeline
		3D printing: Road repair.
		AI, ML (Machine Learning): Passenger flow forecast, infrastructure assessment.
		DAS (Distributed Acoustic Sensing): Earthquake monitoring.
		Big data: Asset management, maintenance of railway condition.
		GPR: Exploration of underground structure.
		GPS: Vibration monitoring.
		GIS: SHM, pavement management and environmental impact assessment.
		Remote sensing: Environmental impact assessment.
		Vehicular sensor networks: Preventing rear-end collisions.

Source: Based on Table 5 in Li et al., 2022

Predictive maintenance for Zeeland Bridge

The Zeelandbrug in the province of Zeeland is a crucial bridge n in the south-western Netherlands. The maintenance of the bridge, which dates back to 1965, is currently done preventively and based on visual inspections. The experience of the technicians involved, who have been involved in bridge maintenance for decades, is decisive. The bridge is starting to age and so the likelihood of breakdowns increases. Meanwhile, experienced technicians are heading towards retirement and new technicians are in short supply.

One bridge section of the bascule bridge (the moveable part of the Zeeland Bridge) has been fitted with vibration and temperature sensors measuring the condition of bearings and oil in 2022. In addition to the data collected, expert knowledge remains necessary to understand the accumulated data and develop a calculation model.

Martijn Hoosemans, team coordinator Programming, Planning and Preparation of the province of Zeeland, owner of the bridge: "We already have the existing data of traffic, weather, energy consumption and movement. We put that data over the sensor data and that should lead to new insights that will help us develop a model that can predict when maintenance is needed. Not too early, but certainly not too late either."

not shed much light on the actual applications of these technologies. So most of studies on smart technologies are limited in scope. Only a few come close to an actual application. One example is the research by the Bridge Engineering Center at Iowa State University; see Exhibit 3.

Li, Guo, Su, Xiao & Tam (2022) provides an overview of advanced information technology applications in civil infrastructure; see Table 3. They identified 204 papers on this topic and analyzed which technologies are used in the three main phases in the lifecycle of a construction project: planning and design, construction, and maintenance. The table shows that there is a wide variety of technologies, especially for maintenance. Unfortunately again almost all papers discuss the *potential* of these technologies and not their use in *practice*.

Over the past decades the EU has invested heavily in developing ICT applications to improve its infrastructure and CBM plays an important role in this. Much has been spent on advancing research on all aspects of transport. Some examples:

- The EU together with local governments subsidized research in innovation capacity in bridge maintenance, inspection, and monito ring in Europe. (Gkoumas, Marques Dos Santos, van Balen, Tsakalidis, Ortega Hortelano, Grosso, Haq, & Pekár, 2019). However, this research (including case studies) has not yet led to wide scale adoption of technologies, especially for smaller structures, where investment in innovative materials and monitoring methods require a budget that is not always available to bridge owners. However, it gradually starts to have an impact. For recent large-scale projects a life-cycle approach has been adopted as of the initial design. For these monitoring and management solutions are included in the design process.
- The Smart Maintenance and the Rail Traveller (SMaRTE) project investigated the applicability of CBM practices from other transportation sectors for rail. Statistical and machine learning techniques for analyzing condition data were developed to detect patterns in the data that predict component failure or degradation, predicting potential failures, allowing sufficient response time before the failure becomes terminal. It was one of a multitude of projects that are part of Shift2Rail, the first European rail initiative to seek focused research and innovation and market-driven solutions. Shift2Rail aims at accelerating the integration of new and advanced technologies into innovative rail product solutions.
- The European Green Deal sets an ambitious target to shift a substantial part of the 75% of inland freight currently carried by road to inland waterways and rail. This requires an increase in the transport capacity of inland waterways, improved management and better connection to rail and road transport facilities. The aim of the NAIADES III project is to move a substantial part of the 75% share of inland freight road transport to inland navigation and rail (EC, 2020). One of the goals of NAIADES III is the roll-out of smart infrastructure, operations and maintenance systems that enable the early detection or prediction of bottlenecks and a return to required service levels with the least possible physical intervention, thereby lowering costs as well as environmental impacts.

All this research has resulted in well-founded knowledge of the potential savings through CBM as well as the organizational changes required for maintenance decisions based on the real-time availability of information. These cyber-physical systems, also referred to as digital twins, are a transformation of passive infrastructure assets into cyber-physical systems in which software-controlled devices interact with the physical world by deploying IoT. A range of different technologies is then used for integral management of all elements the infrastructure to meet the objectives of efficiency, productivity, safety, and sustainability. The potential savings can be huge; potential, because the savings resulting from the application of the many research results lag their potential. As result there are insufficient empirical data on realized savings.

There is one aspect that is at the forefront of condition monitoring in combination with data analytics, the concept of digital twin. The CBM sensor systems are often digital twins of the actual investments that constantly show what is happening. For better decision-making CBM needs a network infrastructure to send real time information from an asset to its digital counterparts and vice versa. Digital twins will be used to make better decisions for sustainability also (Muench, Stoermer, Jensen, Asikainen, Salvi, & Scapolo, 2022). The technologies used for CBM and those to enhance sustainability can clearly profit from each other and implementation of both face the same problems.

An important organizational complicating factor for the widespread use of smart infrastructure remains that this often requires the cooperation of operators from different domains of activity, such as ICT and public transport, as well as different levels of government.

Algorithm optimises water flows, maintenance and energy consumption

In this pilot project, the municipality of Almelo worked in a CAMINO field lab on a self-learning real-time control system (RTC) for its sewer system. Almelo did this together with the nearby Vechtstroom Water Board, research institute Deltares and some market parties.

The aim was to improve the control of the sewerage system. The real-time control system controls the installations in the sewer system, such as weir pits (gates) and pumps. The weir spits and pumps are equipped with sensors for this purpose. When it rains hard, the system receives commands to direct the water in a certain direction, or directions, to prevent flooding and sewer overflow.

By making the system self-learning with artificial intelligence, commands towards pumping stations and/or underground gates can cause the water to go faster and in a different direction. The algorithm should ensure optimisation of water flows, maintenance and energy consumption.

The test site in Almelo lasted several years. Step by step, the RTC system was further improved. The result achieved could only be realised through cooperation in the open innovation setting of the WCM Fieldlab CAMINO test site.

6 Potential savings through CBM

The application of CBM has the potential to lower the lifecycle cost, i.e. enhancement and renewal costs as well as management and maintenance costs, and to distribute the spending on infrastructure more evenly in time. Because of the amount of timely information due to CBM, maintenance is done only when and where necessary. This extends the life of assets because wear and tear is proactively and timely detected and prevented at an early stage. Condition monitoring also enables better control of the maintenance work already done, leading to better quality. The monitoring information is also used to avoid unnecessary maintenance activities, which is the case when corrective or time-based maintenance is applied. The costs per activity go down also because CBM, due to early warnings, allows for clustering and better planning of maintenance activities. CBM's more precise and timely information results in better focused and better quality of maintenance. This reduces degradation and increases our knowledge of the degradation processes. This allows for risk-based decision making through which not only maintenance, but also enhancement and renewal decisions can be better prioritized. This improved planning will lengthen the lifetime of the investments and reduce the number of unanticipated failures of which the consequences are normally more expensive. Unanticipated failures need repair on top of what has already been planned and, since capacity is limited, result in time overruns elsewhere also. CBM also adds to our knowledge of the wear and tear processes of assets, helping to better understand the speed of these processes. The latter can be used to improve condition monitoring and prioritizing maintenance and replacement. The knowledge of the system also reduces the need for renewal because CBM focusses on what is really needed. As a result, the focus on CBM from the start of an investment will increase its useful lifetime and reduce its financial burden.

All this results in increased availability of civil works, which has a positive effect on its users -consumers as well as enterprises. But they will also be better prepared when planned maintenance will reduce an infrastructure's capacity because they get warned early on and are better able to anticipate the effect it will have on their activities and thus minimize economic losses.

The question is how much can be saved by a condition-based maintenance strategy compared to other types of monitoring? Unfortunately, the majority of the research on CBM concentrates on potential savings in existing manufacturing firms. Less is known about the potential for investments in infrastructure.

First of all, the increase in lifetime due to investing in CBM will result in substantial savings. Kerkhof, Lamper & Fang (2018), using several references as well as discussions with practitioners from Deltares[15] and the Dutch Ministry of Infrastructure and Water Management, estimate that a lifetime increase of 12.5% to 25% for new investments and expansions is realistic when compared to corrective maintenance. This increase in lifetime makes it possible to better spread investment decisions over time and reduces the funds needed. Unfortunately there are no actual data on lifetime increases due to CBM. Senseye[16], a Siemens business, states that for manufacturing predictive maintenance technologies have extended asset lifespans by as much as 50%. Using survey data, PWC found support for an increase in lifetime of 20% (PWC, 2018). Most of the mentions of improvement are with respect to a decrease in downtime. The US Department of Energy mentions a reduction in downtime for energy systems of 35%-45% compared to corrective maintenance (DoE, 2010). Deloitte (2017) mentions an increase in uptime for manufacturing of 10%-20% and McKinsey (2018) estimates the potential increase in availability in the heavy industries at 5%-15%. Furthermore, McKinsey (2017) expects that 15-25% efficiency gains from CBM for the railway sector. McKinsey (2020a), discussing the opportunities of CBM for distributed fixed assets, state that advanced companies have realized a 20–50% decrease in downtime. Unfortunately these studies do not mention to which maintenance

[15] *eltares an independent Dutch institute for applied research working on future deltas, sustainable deltas, safe deltas and resilient infrastructure.*

[16] *https://www.senseye.io/hubfs/_Downloads/Senseye-Challenges-of-Sustainability.pdf*

strategy these results have been compared, but most likely a mix of strategies since companies hardly ever use only one strategy for the mix of assets they operate.

However, monitoring comes at a cost. For all enhancements, CBM will increase the investment cost for monitoring equipment and training of personnel by 5% at most. Kerkhof, Lamper & Fang combine these ranges. The 12.5% savings in investment expenditure due to a longer lifetime combined with an extra cost of 5% for monitoring results in a cost decrease of at least 7.5% and it might be as high as 25%; on average the savings on investment expenditure for new assets will be about 17%.

For expansion and renewal of infrastructure, CBM has an additional advantage because these can be better targeted. Instead of the entire asset, only those parts that really need to be replaced are actually replaced. However, it is unknown how much exactly can be saved. Based on a few promising examples Kerkhof et al. (2018) give a guestimate of 5-15% -which they call conservative- for savings on expenditure for the expansion of assets. The increase in lifetime (12.5%-25%) also applies to expansions and renewal. Combined with the extra cost for monitoring (0%-5%), potential savings ranging from 13% to 36% are possible compared to corrective maintenance.

To what extend the potential savings on enhancements can be realized depends on the number of assets that qualify for condition monitoring. These figures are not known. For the Netherlands Bleijenberg (2021) estimates the value of civil infrastructures[17] at €318 billion, based on a concise review of the number of works throughout the country. About €73 billion (23% of the total)) are infrastructural and hydraulic structures such as (movable) bridges, tunnels and subways, pumping stations, etc. the majority of which certainly qualifies for monitoring. However, with the latest developments in monitoring systems (see Table 3) also roads, rail- and waterways offer ample opportunities. For example, smart road maintenance systems monitor and inspect road conditions. Data analytics in combination with the IoT is used to check the progress of wear and tear and suggest improvements (Muchhala, Avisha, Dhamnaskar & Doshi, 2021). Kerkhof et al. (2018) assume that condition monitoring can be applied to no less than 75% of the infrastructure portfolio.

Maintenance

By replacing corrective and periodic maintenance through maintenance when needed, considerable cost savings can be achieved. The information obtained through condition monitoring makes it possible to reduce the amount of maintenance work through a better focus on what to work on, do the work when needed, and improve the asset timely, resulting in reduced wear and tear. The maintenance cost will also decrease for several other reasons. Wear and tear is identified early on so it can be remedied when needed, reducing the need for more expensive maintenance. For example, if road maintenance is neglected too long the costs of necessary repairs or renewals increase 3 to 6 times (EC, 2019). Furthermore, failures occur far less often. The available information using sensors allows for better and earlier diagnoses of potential problems. This allows for better planning of maintenance in time and better use of scarce capacity. However, not all unplanned maintenance can be prevented. Unfortunately, there are no rigorous research results on the long-term effects of CBM. What is available are estimates based on surveys and

[17] *This includes roads, railways, dykes, waterways, sewerage and all associated infrastructural and hydraulic structures, such as bridges, tunnels, locks and dams. This civil infrastructure is almost entirely owned and managed by government bodies – municipalities, provinces, water boards, RWS and ProRail – and semi-public bodies, especially Amsterdam Airport Schiphol and the ports.*

Exhibit 4:
Potential savings on replacing the Dutch infrastructural and hydraulic structures

Bloksma & Westerberg (2021) took stock of the Dutch infrastructural and hydraulic structures. These include roads, railways, dykes, waterways, sewerage, and all associated infrastructural and hydraulic structures, such as bridges, tunnels, locks and dams. This infrastructure is almost entirely owned by public and semi-public bodies.

Using Netherlands Statistics data on publicly owned civil infrastructure Bleijenberg (2021) estimates the replacement value of infrastructural and hydraulic structures at € 318 billion and the average technical service life at 80 years. The annual replacement and renewal costs on average are thus €4 billion, which is in stark contrast to the estimated €1.2 to €1.5 billion actually spent in the period 2017-2019 (Bleijenberg, 2021). The annual maintenance costs are estimated at almost €7 billion, 2.1% of the replacement value.

There are no exact data on when the infrastructure was constructed, but the investments started to take off in 1960-70, with a peak in 1970-80 and stayed rather high thereafter. This implies that, if an 80-year of service life is used, by the end of the century the entire €318 billion stock has to be replaced. The cost of this will rise from €1 billion annually now to €3 to €4 billion for the period 2040-2050 and €4 to €6 billion by the end of the century (Bleijenberg, 2021).

We do not know to which share of the investments CBM applies, but the minimum was estimated at 23% and the maximum at 75%. Furthermore, there is uncertainty about the potential savings on enhancements, which range from 7.5% to 25%. The table below shows the range of potential savings due to applying CBM throughout the lifecycle of the infrastructural and hydraulic structures, and the figures show that these are substantial ranging from at least €5.5 billion to a potential €59.6 billion, but savings in the range €11.9 to €38.8 billion are more likely.

Percentage potential savings on enhancements	Investment share to which the savings could apply		
	Min 23%	Max 75%	Average 49%
	Potential savings in billion €		
Max 25%	17,9	59,6	38,8
Min 7,5%	5,5	18,3	11,9
Average 16,0%	11,7	39,0	25,3

However, CBM is a lifetime approach. If it is assumed that there will be a smooth growth of the replacement and renewal costs from €1 billion now to €6 billion annually in 2100, CBM will lead to a reduction in maintenance costs of these new investments. CBM's potential savings on maintenance range from 7% to 23%. Taking into account the investment shares to which the savings would apply, these are in the range €2.1 billion to €11.6 billion, which is substantial also. On average the potential savings are €33 billion, a bit more than 10% of the total enhancement costs.

Potential savings on maintenance in percentages		
Min 7%	Max 23%	Average 15%
Potential savings on maintenance in billion €		
1.1	11.6	7.6

These results are in current prices; inflation will increase these considerably.

expert opinions. Most studies focus on improvements of availability and costs. Already in 1978 Nowlan & Heap estimate the reduction in maintenance activities at 30%. In 2010 the US Department of Energy estimates that a well-designed CBM program could save 8-12% in costs over preventive maintenance and 30-40% over corrective maintenance (DoE, 2010). Jardine and Tsang (2013) mention a decrease of 50% in maintenance activities for manufacturing and utilities, and cost reductions in the range of 30-40% for the utility sector. In a study on the effect of the IoT, McKinsey (2015) estimates cost savings for equipment in the range of 10-40%, a reduction of equipment downtime by up to 50% and reductions in capital investment by 3-5% by extending its useful life. McKinsey (2018) estimates the potential for reduction in maintenance costs for the heavy industry at 18-25%. In 2017 the Deloitte Analytics Institute found an increase in uptime of 10-20% and a decrease in maintenance costs of 5-10% (Deloitte, 2017). McKinsey estimates potential efficiency gains in the rail sector to be around 15-25%. (McKinsey, 2017) In later rail infrastructure research, the savings in maintenance and replacement costs of a combination of advanced analytics and a condition-based strategy are estimated as high as 25% (McKinsey, 2020b). Based on a survey of 67 companies in Belgium, Germany and The Netherlands that implemented smart maintenance or at least executed a pilot, PwC found, on top of the lifetime extension of 20% mentioned earlier, support for uptime improvement of 9%, cost reduction of 12%, and a reduction of safety, health, environment & quality risks of 14% (PWC, 2018). Kerkhof, Lamper & Fang (2018) estimate that CBM cost savings compared to corrective maintenance are in the range of 17-43%, on average 30%. McKinsey (2020a) states that advanced companies have realized a 20-30% decrease in maintenance costs. These results are supported by a comparison of CBM and TBM by de Jonge, Teunter & Tinga (2017). They show that for realistic preventive maintenance, CBM has substantial cost benefits over TBM. However, depending on industry and asset type, there are still substantial opportunities for improvement. For transport infrastructure it is reasonable to assume savings on maintenance in the range of 7-23% are realistic.

The above shows that savings due to CBM are substantial. The value of the Dutch civil infrastructure is estimated at €318 billion (Bleijenberg, 2021) and most of it has to be replaced by the end of the century. Exhibit 4 shows that by applying CBM where possible and under reasonable assumptions, savings till the end of the century in the range of €11.9 billion up to €38.8 billion on investments and between €2.4 and €11.6 billion on maintenance are possible. This is in line with the findings by others. For example, Morimoto (2010) analyzes a smart infrastructure sensor system developed jointly by Cambridge University in the United Kingdom and Massachusetts Institute of Technology in the United States for the British water pipeline system. She estimates the net present value of savings till 2056 if this smart maintenance system were used to avoid disruption and damage costs (including water loss) due to water pipe bursts, as well as by reducing annual operating and maintenance costs to be US$ 23.7 billion.

The above shows that applying CBM, starting in the design phase, has the potential to substantially reduce both capital expenditures and maintenance expenditures, thus reducing the lifecycle cost of assets.

More effective maintenance of tunnels

Road tunnels are equipped with installations to ensure tunnel safety. Those installations generate data that are used for that purpose. Tunnel maintenance largely depends on visual inspections. Authorities and service providers have been working together in four tunnel projects since last year to use existing data for more efficient and better management and maintenance.

Initial results from these projects show that inspections can be much more effective, allowing better planning of the deployment of already scarce technicians. At the same time, the quality of inspections improves considerably.

7 Potentials for Realizing Smart Maintenance in the EU

The goal of all the efforts to develop and further the knowledge on infrastructure within the EU is among others the development of the Trans-European Transport Network. Supported by traffic management systems TEN-T will provide integrated and intermodal long-distance, high-speed routes. One objective is to close gaps, remove bottlenecks and technical barriers, as well as to strengthen social, economic and territorial cohesion in the EU. The TEN-T policy supports the application of innovation, new technologies and digital solutions to all modes of transport. Other objectives are reduced environmental impact of transport, enhanced energy efficiency and increased safety, which can be achieved by utilizing the digital twins CBM has to offer.

Much has been achieved already. However, with respect to maintenance the European Court of Auditors conclude that insufficient maintenance by MSs puts the state of the core road network at risk in the medium to long term because of steadily decreasing maintenance budgets. These budgets should increase with the increasing length of infrastructure and ageing of crucial links. The European Court of Auditors calls for measures to enhance MSs long-term maintenance planning (European Court of Auditors 2020a). In their evaluation of eight flagship projects they urge that it should be verified that 'the beneficiary has the necessary financial resources and mechanisms to cover operation and maintenance costs and ensure their financial sustainability' (European Court of Auditors, 2020b). This calls for more emphasis on maintenance in the many planned investment projects. This calls for action in the near future as once more significant resources are allocated to expanding Europe's infrastructure.

Expanding Europe's infrastructure

The Connecting Europe Facility (CEF) is used for financial support of TEN-T investments. During 2014-2020 CEF Transport allocated €24 billion to support the enhancement of sustainable transport infrastructure projects in order to modernize the Trans-European Transport network. For 2021-2027€25.81 billion is available for transport. These funds are used to support investments by MSs. However, within the EU'S 2021-2027 long term budget of €1.211trilion in combination with the €806.9 billion of the Next Generation EU recovery package there are many more programs that offer infrastructure investment opportunities, such as the European Regional Development Fund (ERDF) of €217.09 billion, the Cohesion Fund (CF) €48.03 billion and the European Territorial Cooperation goal (ETC) €8.96 billion; parts of these funds are transferred to CEF (EU, 2021).

Although these figures are impressive and the Junker Plan has shown that EU seed money can mobilize significant funds, as was shown above for many years the total investment needs for infrastructure in Europe have been much higher than the actual spending. The European Investment Bank estimates that the average annual investments in transport and water infrastructure needed over the period 2014-2020 were as much as €298 billion annually, but on average only €128 billion was spend by the EU28 over the period 2007-2013 (EIB, 2016). CE Delft (2019) estimates the total infrastructure costs for road, rail and inland waterway transport in the EU28 in 2016 amount to €267 billion. These are all average annual amounts. As discussed above the reduction of investments and maintenance due to the various crises has continued, so substantial extra funding is needed to keep the infrastructure as it is. But given the TEN-T goals also additional funding is needed.

There is one additional problem for funding infrastructure investments. In the past the processes of privatization, liberalization and globalization attracted institutional investors such as pension funds, insurers, and sovereign wealth funds. Infrastructure offered private investors low-maintenance, low competition investments with predictable risk and stable long term cash flows, enabling liability matching and inflation hedging. (OECD, 2014) However, conditions are changing due to the energy transition, changes in mobility, and digitization. As a result infrastructure investments have become less attractive to investors and the expected IRR has declined by 20-40% over the past 10 years (McKinsey, 2022a).

The lack of sufficient investments by all parties -government and private- in combination with the series of crises since 2008 will put much strain on infrastructure investments and maintenance. The conclusion can only be that whatever funding is available, it has to be used as efficient as possible and in for many investments CBM is what is needed to achieve this.
Almost all MSs have formulated investment plans for civil engineering works to utilize the EU's Recovery and Resilience Facility[18] (RRF) funds; see Exhibit 5 for a few examples. Please notice that maintenance is mentioned only once. The RRF is very helpful in accommodating these plans; its contribution often results in an investment of 4 to 5 times the size of the RRF contribution.

A survey by the European Construction Observatory[19] shows that these investment plans

[18] The aim of the Recovery and Resilience Facility (RRF) is to mitigate the economic and social impact of the coronavirus pandemic and make European economies and societies more sustainable, resilient and better prepared for the challenges and opportunities of the green and digital transitions.

[19] https://single-market-economy.ec.europa.eu/sectors/construction/observatory/country-fact-sheets_en.

face three major challenges to realize these. First, almost all mention that the construction sector has an on-going shortage of skilled workers and has problems to mitigate these on short notice. Second, late payments are a major concern and have become worse during the COVID-19 pandemic. The resulting cashflow issues are transferred further upstream through the supply chain. Finally and perhaps the most challenging is the lack of innovation by the construction sector as well as its inability to implement digital technologies and innovations. This is confirmed by the EIB 2022 survey, which shows that construction and infrastructure are the two least innovative sectors. (EIB, 2022b)

Given the wide range of plans for infrastructure investments in all transport modes as well as the dire need to enhance and renew existing infrastructure, there are ample opportunities to improve maintenance of Europe's infrastructure.

EU's CBM savings Potential

For the Netherlands a concise estimate of the

Exhibit 5: Some short- and medium-term plans for infrastructure investments

- Germany has earmarked €269.6 billion for the 2030 Federal Transport Infrastructure Plan, a plan to modernize 2,000 bridges before 2030, and renew 2,000 km of railway track and 2,000 turnouts. In addition, a railway line between Dresden and Prague will also be built in cooperation with the Czech Republic, including two tunnels: the Central Bohemian Highlands tunnel with a length of about 18 km and the Erzegebirge/Krušnohorský tunnel with a length of at least 26 km, of which 11.7 km will be built on Czech territory. From 2021 onwards the German government plans to raise €1.0 billion of federal funding per year to expand local public transport infrastructure, which is expected to increase to €2.0 billion per year by 2025.
- France is investing €17.8 billion in renovating and improving its transport infrastructure and at the same time make it more sustainable. France also intends to further its high-speed rail infrastructure. Intended projects are the modernization of the Montpellier - Perpignan and the Marseille - Nice line. France also considers new additions; the €26.0 billion greenfield Turin-Lyon project, the Toulouse -Bordeaux line and the Normandy-Paris line.
- Hungary plans to extend its motorways to the state borders and connecting regional centers to the high-speed road network. Hungary earmarked €723.0 million for extending the capacity of the Budapest suburban rail network, committed €57.0 million towards eliminating rail bottlenecks on the TEN-T corridor, and €86.0 million for deploying central traffic management on TEN-T railway lines.
- In 2021 Italy allocated €28.3 billion to high-speed railways and road maintenance 4.0, and €3.7 billion in intermodal transport and integrated logistics. The construction of various lines such as the Naples-Bari and the Brescia-Verona-Padua railway and the Tortona-Genoa high speed railway are continued. Furthermore, €1.6 billion has been allocated to road maintenance.
- In Latvia as well as Lithuania investments are made to augment the cross-border Rail Baltica project, which intends to connect Finland and the Baltic states via Poland via highspeed rail with the rest of Europe.
- Under the National Road and Motorway Construction Programme 2014-2023 Poland intended to build 3,263 km of roads and Poland intends to continue its challenging investment program. Poland intends to spend €64 billion until 2030 on pre-planned road projects with a combined length of more than 3,700 km.
- Slovakia, with support of the EIB, is investing in motorways that are part of TEN-T. The government also committed to invest €2.9 billion in road improvement in the Upper Nitra coal mining region.

Based on the European Construction Observatory - country fact sheets. Consulted at 16-11-2022.

Figure 3 Potential savings of applying CBM

POTENTIAL SAVINGS

Minimum	Avarage	Maximum
€ 44.2 billion	€ 204,6 billion	€ 482,2 billion
Of which	Of which	Of which
€ 35.9 billion on investment	€ 165,6 billion on investment	€ 389,9 billion on investment
€ 8.3 billion on maintenance	€ 39,0 billion on maintenance	€ 92,3 billion on maintenance

SAVINGS IN REST EU AND CESEE-EU

EU-rest	Maximum	Avarage	Minimum
Total	36.2	167.7	395.2
Investments	29.4	135.7	319.5
Manitenance	6.8	32.0	75.7
CESEE-EU			
Total	8.0	36.9	87.0
Investments	6.5	29.9	70.4
Manitenance	1.5	7.0	16.7

Total investment 2020-2040

€ 2.079 billion

Remark: Minimum, average and maximum is based on what part of the infrastructure capital stock qualifies for CBM investments (range is from 23-75%) and how much can be saved on maintenance annually (range is from 7-23%)

value of the stock of civil infrastructures is available, which was used to indicate what CBM has to offer financially over the lifetime of its replacements compared to other maintenance policies; see Exhibit 4. Unfortunately these data are not available for the other MSs, so how to indicate potential savings for the whole of the EU? Fortunately, the IMF publishes data on the value of the general government[20] capital stocks for MSs and their GDP (IMF, 2021). From this the ratios of general government capital stock and GDP can be calculated for each MS, which vary considerably. Unfortunately it is not known how much of the general government capital stock is inland infrastructure. What is known is that the share of Dutch civil infrastructure (€318 billion) in IMFs general government capital stock for the Netherlands (€497 billion) for 2018 is 64%. This is used to approximate the share of infrastructure in the general government capital stock for the other MSs.

The effect of applying CBM is a long term one and for that reason the period 2020-2040 is chosen to analyze the savings potential of CBM for the period most affected by current policy decisions. What is needed is a scenario of economic growth for this period, which is difficult given the current turmoil due to the war in the Ukraine and the effects of Covid. Although it has its drawbacks, the OECD's

[20] General government consists of central, state and local governments and the social security funds controlled by these units.

[21] https://data.oecd.org/gdp/real-gdp-long-term-forecast.htm

real GDP long-term forecast[21] is used for this. For the period 2020-2030 economic growth is on average 2.7% for CESEE-EU[22] and 1.9% for the rest of the EU; weighted with the real GDP of 2018. For the period 2031-2040 these growth figures are 1% for both.

However, as mentioned above CESEE-EU infrastructure still has to catch up with the rest of the EU, which is supported by the difference between the average general government capital stock for CESEE-EU (45,5%) and the rest of the EU (58,2%) for the period 2000-2019; weighted with the total real GDP. The goal is to abolish this gap. To achieve this, extra investments in infrastructure of 0.8% of GDP for CESEE-EU are needed for the period 2020-2030. Furthermore, it is assumed that the average lifetime of infrastructure is 80 years, which is reasonable given the spread of service lives for various structures.[23] This implies that on average 1.25% must be replaced annually.

The potential savings through better utilizing investments for the period 2020-2040 range from €35.9 billion to €389.9 billion but are most likely €165.6 billion, depending on the share of investments in transport that are suited for CBM -23%, 75% and 49% respectively; see Figure 3 for more details. The savings on maintenance due to CBM in enhancements will be in the range of €8.3 billion to €92.3 billion, but most likely about €39.0 billion. These maintenance benefits of CBM will increase considerably after 2040 because of the fact that these benefits are realized over the total lifetime. Note that these savings are in constant 2018 prices. With an annual inflation of (say) 2% these amounts increase by some 23%. These figures assume that CBM is applied from 2020 onwards whenever feasible and are a good indication of what CBM has to offer.

These are only the direct effects. There are also cost for the rest of society when infrastructure fails or more importantly is insufficient. For example, the cost of congestion for EU inefficiencies in urban mobility cost an estimated €110 billion per year; more than 1% of the EU's GDP. Unfortunately there are not many data on this subject. However, the American Society of Civil Engineers regularly analyzes the cost of inadequate and insufficient investments in infrastructure, taking into account interdependencies, and estimate a loss of $10 trillion in GDP and a decline of more than $23 trillion in business productivity cumulatively for the U.S. over the next two decades if the growing gap in the investments needed for bridges, roads, airports, power grid, water supplies, and more is not addressed properly (ASCE, 2021) This despite the fact that the U.S. is quite high on the 2019 ranking of countries according to their quality of infrastructure[24], well above the weighted average quality ranking for the EU. With the investment gap mentioned above in mind, it is clear that the EU's investments in infrastructure also need an extra impulse, both in money and quality.

[22] Here CESEE-EU comprises Bulgaria, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovak Republic and Slovenia. Rets EU comprises Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, The Netherlands, Portugal, Spain and Sweden.

[23] Bloksma and Westenberg (2021): movable bridges 70 years, fixed concrete bridges 120, fixed steel bridges 80, fixed wood bridges 40, tunnels, subways and culverts 100, sheet piling 60, locks 80, pumping stations, jetties, quays, dams and overpasses 50.

[24] https://www.statista.com/statistics/264753/ranking-of-countries-according-to-the-general-quality-of-infrastructure/

Data-driven asset management in testing site Eefde lock.

In this project, asset owner Rijkswaterstaat and various market parties worked together to develop new ways of smart maintenance and condition monitoring for the management and maintenance of a lock complex.

Three ways of monitoring were used in the living lab. Energy consumption at component level, vibration, noise and moisture and corrosion monitoring. To these were added control data from the lock machinery. Data from the adjacent renovated lock chamber were also added. That was special, because this data came from two competing contractors. Meanwhile, the pilot project has been completed and all lessons learned have been recorded.

This project was one of the first living labs with predictable maintenance for Rijkswaterstaat. The results of the project in Eefde contributed to the decision of Rijkswaterstaat and the ministry to fully commit to data-driven asset management and smart maintenance for all its objects.

8 Conclusions & Recommendations

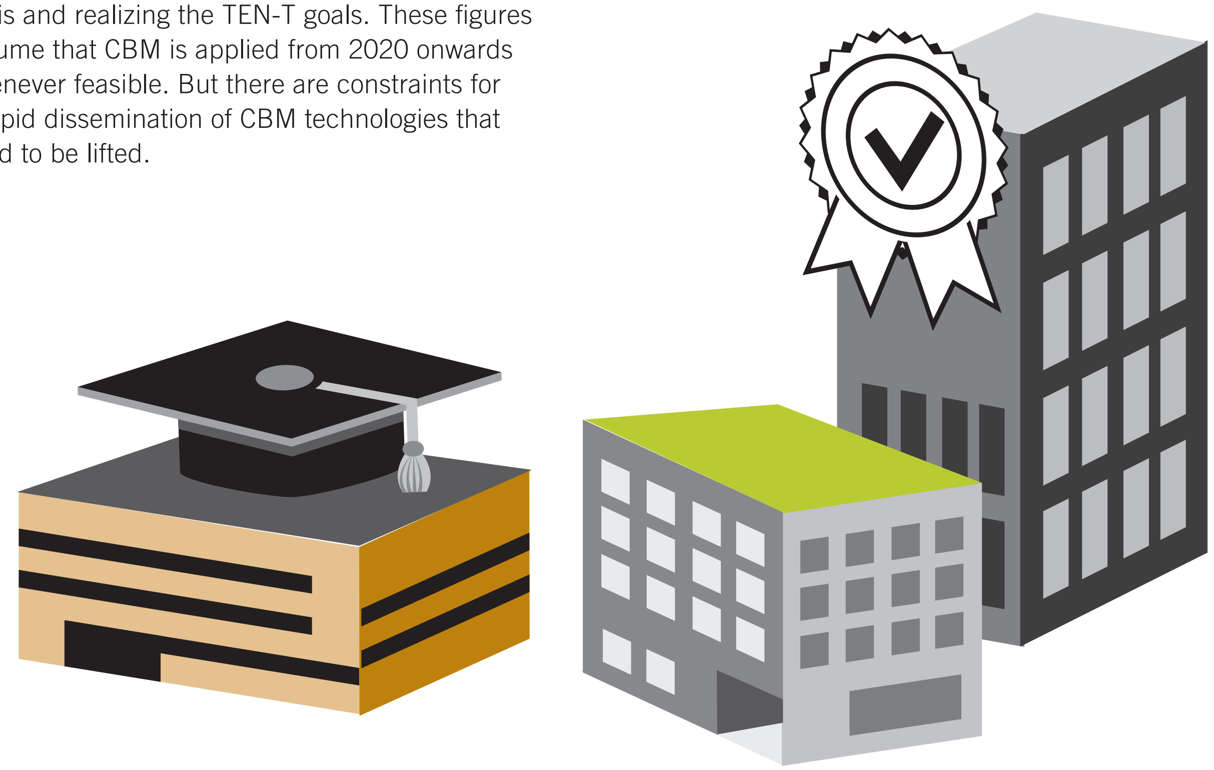
Well designed and sufficient infrastructure is a necessary condition for economic progress. Its contribution to gross value added is substantial. However, since the financial crisis of 2008 and the crises that followed in its wake, infrastructure has suffered and is not at par with the EU's economic needs. EU's infrastructure needs additional investments to maintain the current level of services. The TEN-T program needs to speed up to meet the goals set for 2030 and to narrow the gap between transport infrastructure in CESEE-EU and the rest of the EU. This is needed to further the internal market and even more so to be competitive in the international markets.

In the past maintenance of existing infrastructure has been neglected, not only after construction, but also in the design stage. What is needed is a lifecycle approach where the total costs are considered. It is then that smart maintenance like CBM will prove its worth. CBM technologies for all aspects of infrastructure maintenance have been developed and many with the help of substantial EU funding. The lifetime savings of these technologies substantially outweigh the initial increase in investments in sensor-based systems and the analytic tools needed to realize these. Furthermore, widespread application will enhance the development of the technologies leading to lower maintenance costs, but also to lower investment costs due to a better understanding of the wear and tear of the various assets. Most infrastructure investments have a long lifetime, which with well-designed expansions can be over a century. Not considering the opportunities CBM has to offer early on in the design process is difficult to correct once the investment is finalized. A lifecycle cost approach based on a lifecycle analysis of investments and smart maintenance from the start would be an excellent solution to minimizing overall expenditure. In addition, the cost of innovative technology has dramatically decreased over the past several years. In summary, the opportunity for investing in CBM has never been better.

The most important advantage of speeding up integrating CBM in Europe's transport infrastructure is the large potential for financial gain. Given the current political situation there is a lack of funds and CBM offers the opportunity to better utilize these in the long run. Depending on the share of investments CBM can be applied to the potential savings through longer service lives and improved maintenance through CBM of investments over the period 2020-2040 are most likely €165.6 billion for investments and €39.0 billion on maintenance, but could be as high as €389.9 billion and €92.3 respectively. Money that is urgently needed to narrow the gap between actual and needed infrastructure investments after the 2008 financial crisis and realizing the TEN-T goals. These figures assume that CBM is applied from 2020 onwards whenever feasible. But there are constraints for a rapid dissemination of CBM technologies that need to be lifted.

First there is the lack of qualified personnel. Education plays a central role in scaling up the use of new technologies. Data analysts and material experts need to be trained to enhance knowledge creation and the development of new insights. Lack of proper knowledge hinders the spread of CBM in many industries and more emphasis has to be placed on training CBM technicians and educating decision makers about what CBM has to offer. This is also needed to further innovation in, and application of, smart maintenance. This is further hampered by the fact that the construction sector is one of the least innovative sectors, which is at odds with applying the latest technologies.

An important organizational complicating factor for the widespread use of smart infrastructure is that this often requires the cooperation of operators from different domains of activity, such as ICT and transport, as well as different levels of government. Governments play an important, if not decisive, role in decisions on investing in civil infrastructure. The EU has a network of funding policies to stimulate central as well as local governments to take the correct decisions on these matters, calling upon the wide variety of results from the many research programs funded by these

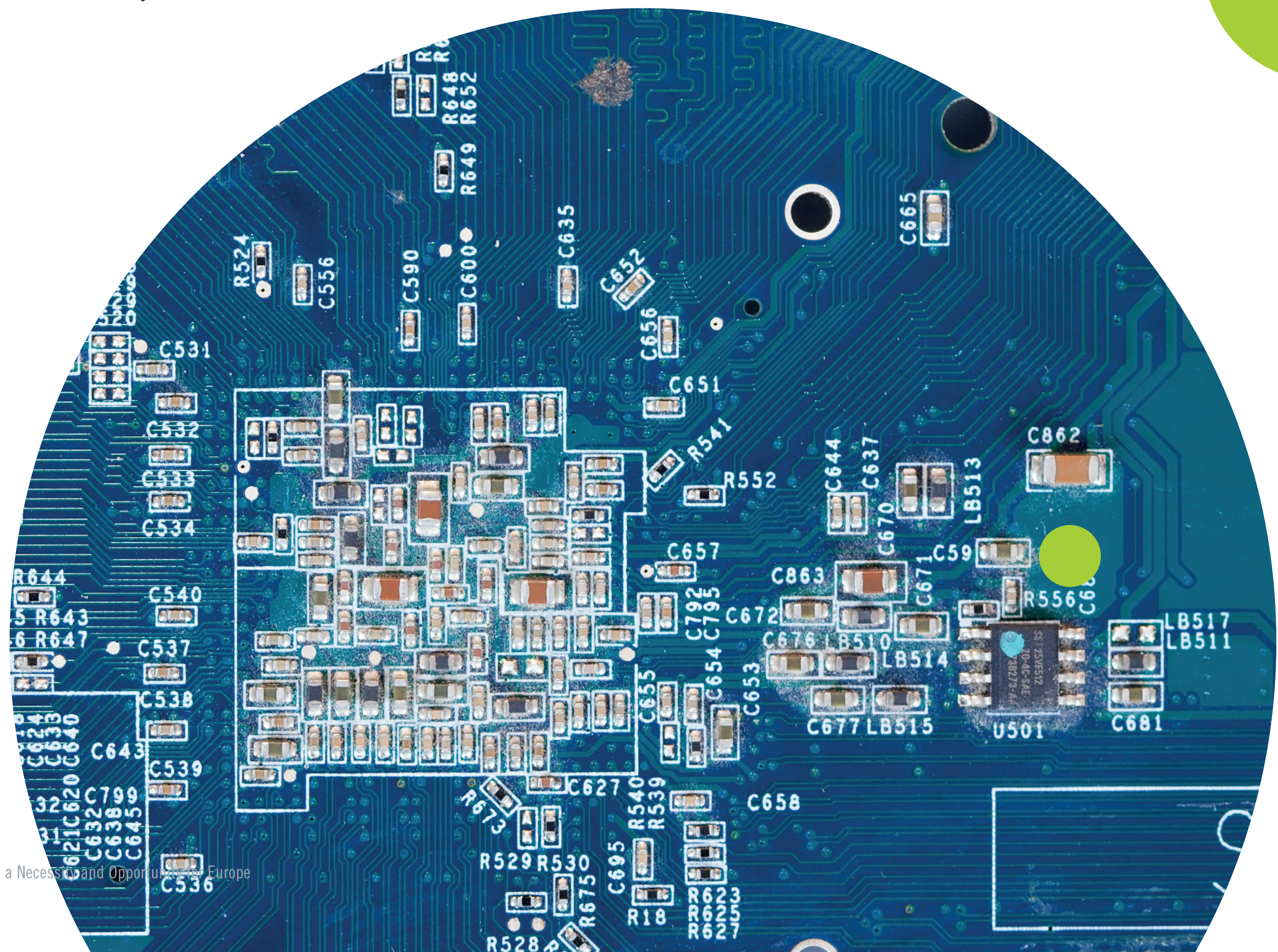


governments and the EU. The many digital solutions and analytic tools developed over the past decades should be used as leverage to speed up the use of CBM as part of the many new infrastructure investments and expansions needed in the near as well as the long-term future. This will have a substantial positive effect on the efficient use of infrastructure funding.

The widespread use of CBM and data analytics will also speed up the improvement of the many smart maintenance technologies that have been developed so far. This will also increase our empirical knowledge of wear and tear processes in infrastructure. This knowledge will help to further the technical efficiency of investments, and thus increase their safety and lower their financial burden.

The technologies applied in large scale infrastructure projects cover many areas -as was the case for research-, therefore cross-sectoral consortia are needed to guarantee appropriate application and improvement of smart maintenance technologies. This will complicate matters during construction, but it is a necessity especially in support of the green deal.

This has an additional advantage. Currently Europe is still lagging on value creation and growth in ICT. ICT is a transverse technology that has a strong link with other innovation topics and the World Economic Forum estimates that digitally enabled platform business models will be responsible for 70% of new value created over the next decade. Speeding up the dissemination and improvement of smart maintenance will undoubtedly help Europe to close the gap with its competitors. It will also strengthen the international exposure of the industries involved.



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Annex 1

OECD/ITF (2019) investment and maintenance data defined

https://ec.europa.eu/eurostat/web/transport/data/database

Roads

- Investment expenditure on roads covers capital expenditure on new road infrastructure or extension of existing roads, including reconstruction, renewal (major substitution work on the existing infrastructure which does not change its overall performance) and upgrades (major modification work improving the original performance or capacity of the infrastructure). Infrastructure includes land, permanent way constructions, buildings, bridges, and tunnels, as well as immovable fixtures, fittings and installations connected with them (signalization, telecommunications, toll collection installations, etc.) as opposed to road vehicles.
- Maintenance expenditure on road infrastructure covers non-capital expenditure to maintain the condition and capacity of the existing road infrastructure. This includes surface maintenance, patching and running repairs (work relating to roughness of carriageway's wearing course, roadsides, etc.).

Railways

- Investment expenditure on railways covers capital expenditure on new railway infrastructure or extension of existing railways, including reconstruction, renewal (major substitution work on the existing infrastructure which does not change its overall performance) and upgrades (major modification work improving the original performance or capacity of the infrastructure). Infrastructure includes land, permanent way constructions, buildings, bridges and tunnels, as well as immovable fixtures, fittings and installations connected with them (signalization, telecommunications, catenaries, electricity sub-stations, etc.) as opposed to rolling stock.
- Maintenance expenditure on railway infrastructure covers non-capital expenditure to maintain the original condition and capacity of the existing railway infrastructure.

Inland Waterways

- Investment expenditure on inland waterways covers Capital expenditure on new inland waterways infrastructure or extension of existing inland waterways, including reconstruction, renewal (major substitution work on the existing infrastructure which does not change its overall performance) and upgrades (major modification work improving the original performance or capacity of the infrastructure) renewal and upgrades or major repairs (repairs improving the original performance or capacity of the infrastructure). Infrastructure includes land, channels and permanent way constructions, buildings, navigation locks, mooring equipment, toll collection installations, as well as immovable fixtures, fittings and installations connected with them (signalization, telecommunications, etc.) as opposed to IWT vessels.
- Maintenance expenditure on inland waterways covers non-capital expenditure to maintain the original condition and capacity of the existing IWT infrastructure.

Port infrastructure

- Investment expenditure on port infrastructure covers capital expenditure on new construction (including new maritime ports) or extension of existing maritime port, including reconstruction, renewal (major substitution work on the existing infrastructure which does not change its overall performance) and upgrades (major modification work improving the original performance or capacity of the infrastructure). Infrastructure includes land and port approach canals, port facilities machinery and equipment, office and storage buildings, port repair facilities, navigation aids and services, hinterland links, as well as immovable fixtures, fittings and installations connected with them (signalization, telecommunications, etc.).
- Maintenance expenditure on port infrastructure covers non-capital expenditure to maintain the original condition and capacity of the existing port infrastructure and related equipment.

Airport infrastructure

- Investment expenditure on airport infrastructure covers capital expenditure on new construction (including new airports) or extension of existing airports infrastructure, including reconstruction, renewal (major substitution work on the existing infrastructure which does not change its overall performance) and upgrades (major modification work improving the original performance or capacity of the infrastructure). Infrastructure includes land, airport facilities and associated equipment, office and storage buildings, air navigation systems as well as immovable fixtures, fittings and installations connected with them (signalization, telecommunications, etc.).
- Maintenance expenditure on airport infrastructure covers non-capital expenditure to maintain the original airport services and the capacity of the existing infrastructure and related equipment.

The table below shows for which MSs these data are available.

Table 1 Data availability on maintenance and investment in current and constant prices

	road		rail		inland waterways		maritime port		airport	
Country	Maint.	Invest.	Maint.	Invest.	Maint.	Invest.	Maint.	Invest.	Maint.	Invest.
Austria	1	1	1	1						
Belgium	1	1		1	1	1		1		1
Bulgaria		1	1	1			1	1	1	1
Croatia	1	1	1	1					1	1
Czech Republic	1	1	1	1	1	1			1	1
Denmark										
Estonia	1	1		1				1		1
Finland	1	1	1	1	1	1	1	1	1	1
France	1	1	1	1	1	1	1	1		1
Germany		1		1	1	1		1		1
Greece		1		1				1		1
Hungary		1	1	1						
Ireland	1	1		1				1		1
Italy	1	1	1	1	1	1	1	1	1	1
Latvia	1	1	1	1	1	1				1
Lithuania	1	1	1	1	1	1	1	1	1	1
Luxembourg	1	1	1	1	1	1			1	1
Malta										
Netherlands										
Poland	1	1	1	1		1			1	1
Portugal				1		1				1
Romania		1								
Slovak Republic		1			1	1			1	
Slovenia	1	1	1	1			1	1		1
Spain		1		1			1	1		1
Sweden	1	1	1	1			1	1	1	1
Total	15	22	14	21	10	12	8	13	10	19

Afterword

This report does not just highlight the importance of infrastructure to EU economies. It also outlines the problems facing the infrastructure sector: overdue maintenance, too little attention at the design stage for maintenance that needs to take place during its lifetime, insufficient available budgets, too few qualified staff and, last but not least, no consideration from policymakers.

The report shows that CBM contributes to higher availability of infra assets and a longer lifespan. All that at a lower cost: the minimum saving is €44 billion euros and could reach 500 billion over the next 20 years. To get close to the latter amount, constraints preventing rapid diffusion of CBM technologies must be removed as soon as possible.

Education plays a central role in this. Data analysts and experts on the matter must be trained to promote knowledge creation and the development of new insights. More emphasis should be placed on training CBM technicians and teaching decision-makers about what CBM has to offer. This is also needed to take innovation and application of smart maintenance further.

The construction sector is not known as an early adaptor of new technologies. It is therefore important to join forces at European level and work together to stimulate and implement smart maintenance in the infrastructure sector. The expertise that has now been built up in the Netherlands provides an excellent base from which to coordinate contacts with other centres of excellence in Europe to ensure and accelerate the necessary knowledge building and transfer.

> “CBM contributes to higher availability of infra assets and a longer lifespan.”

Tilburg University

World Class Maintenance