TOWARDS NETWORKS OF PREDICTIVE TWINS IN THE BUILT ENVIRONMENT

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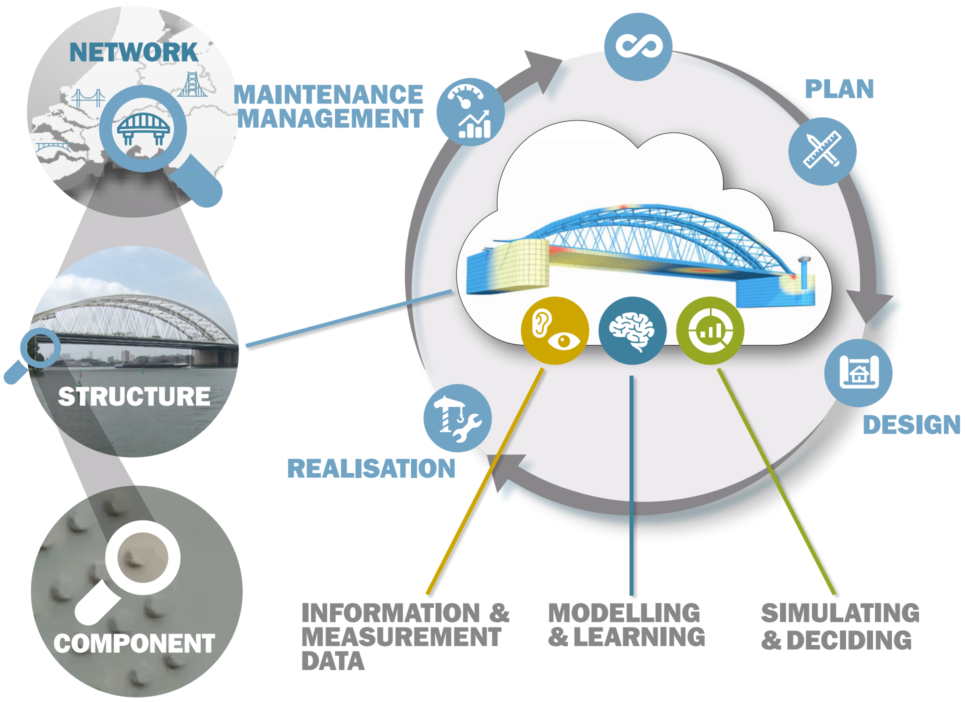
INTRODUCTION

The construction and infrastructure sector faces enormous challenges, such as the eve of a major replacement and renovation task for existing civil infrastructure.[1] The sector is also moving towards circular construction (goal: circular by 2050) and the existing built environment must be energy-neutral by 2050.[2]

A widely supported view is that these challenges and the associated adaptations to the built environment can only be realised through the intensive use of advanced digital solutions.[3] These make it possible to increase the productivity of the sector and to innovate much faster.

But how are digital solutions really going to make a difference to these challenges? TNO sees a crucial role for predictive digital twins, or **'predictive twins'**.[4] These are predictive digital replicas of physical structures such as bridges, tunnels, homes and offices. With these twins, the future behaviour and use of structures and networks of structures can be predicted and influenced. This step towards predictive twins is crucial for proactive decision-making on structures and networks of structures based on data, learning predictive models and simulations.



In the opinion of TNO, predictive twins can contribute to these challenges in various ways:

- Predictive twins will be used in the *replacement and renovation* of existing civil infrastructure in order to predict the expected technical lifespans of civil structures and networks of civil structures in an efficient and cost-effective manner. Among other things, this will take into account the ageing of structures and changing future (traffic) loads. With these insights, maintenance, renovation and replacement can be optimised at the structure and network level.
- In the transition to a *circular construction sector*, predictive twins can serve not only as a materials passport for structures but also as an important tool for monitoring and forecasting the technical lifespan and quality of construction components. The supply and demand of circular building components and materials can therefore be better matched during the design and realisation phases of new circular structures. The behaviour and technical lifespan of circular building components and materials in new circular structures can thus also be better demonstrated, giving an important boost to circular construction.

– As part of the *energy transition* of existing structures, predictive twins will be used to optimise energy consumption at a building and neighbourhood level. By monitoring, predicting and influencing this energy consumption, it will be possible to better coordinate energy demand and supply at a neighbourhood level, whereby large investments to strengthen the energy grid can be avoided as much as possible. At the same time, the effectiveness of renovation concepts which have been developed can be evaluated in practice and, based on these experiences, the energy performance of new structures can be better predicted and optimised.

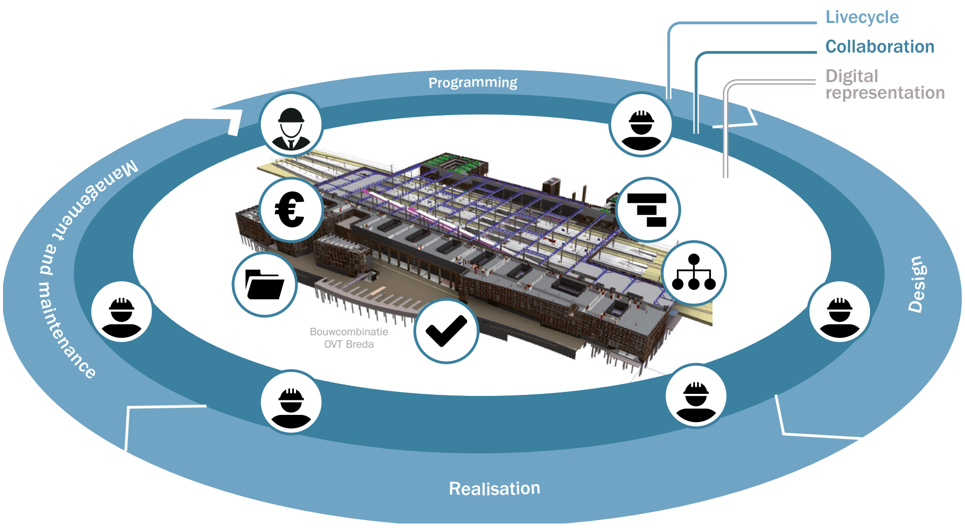
This position paper elaborates on what TNO understands by predictive twins and why these are important. We also discuss the steps that TNO is taking in the development of predictive twins and the important preconditions that TNO sees in terms of making the broad deployment and usage of predictive twins feasible and affordable.

“PREDICTIVE TWINS ARE SELF-LEARNING DIGITAL REPLICAS WHICH CAN PREDICT AND INFLUENCE THE FUTURE BEHAVIOUR AND USE OF STRUCTURES.”

BIM AS A STEPPING STONE TO PREDICTIVE TWINS

At first glance, predictive twins appear to have many similarities with Building Information Models (BIM). These can be seen as a digital representation of the physical and functional characteristics of a structure.[5] The developments surrounding BIM which have taken place in the construction and infrastructure sector over the last 20 years are indeed an important stepping stone towards working with predictive twins.[6] Which BIM developments that have taken place in recent decades are relevant to predictive twins?

Since the beginning of this century, we have seen more and more applications of BIM, which involves working with 3D models consisting of 3D objects and the associated information regarding those objects.[7] All kinds of parties are actively working on the introduction and application of BIM, ranging from architects and engineering firms, construction companies and subcontractors to suppliers, clients and managers.[8] As a result, a great deal of experience has been gained in working and collaborating with BIM. This applies in particular to the design phase of construction projects. The use of BIM is more limited in the realisation phase of projects, and this is even more the case in the management and maintenance phase.[9] However, an increasing amount of attention is being paid to the use of BIM as a building and materials passport for decisions on dismantling and reuse.[10]



Based on: Bruggen Bouwen met ICT (Building Bridges with ICT) (Adriaanse 2014).[11]

It is not surprising that the use of BIM is lagging behind in the management and maintenance phase of construction works. After all, this phase must be fuelled by BIM data from the design and realisation phases. A lot of structures were built many years ago and BIM data from the design and realisation phases is often not available for these.

The method by which BIM is applied is also undergoing changes. Initially, BIM was mainly about creating 3D models of structures. Nowadays, we see that 3D models and 3D objects are becoming less central to BIM development. It is increasingly about 'linking' all kinds of data which is recorded in all sorts of data sources during the lifecycle of structures, including 3D models.[12] This includes requirements, specifications, cost figures, environmental data and management and maintenance data. In this way, all kinds of combinations of data are created which can be of value to parties in the construction and infrastructure sector at any given point during the lifecycle of structures.

As a result of this development – the combination of datasets recorded by several parties – the term ‘Building Information Model’ is starting to become confusing.[12] After all, a Building Information Model is often associated with a 3D model. For this reason, more and more people are discussing 'Building Information Management': the object-oriented recording, sharing and management of construction information throughout the entire lifecycle of structures.

With the introduction of BIM, information on structures is becoming increasingly accurate throughout their lifecycle. This information - often 'static' for the manager - is being recorded and reused in an ever more structured manner.

Although this development has a very positive impact on the design and realisation phases within the sector[13], application in other phases also has its limitations. For example, it is good for asset owners and managers to know what data on a structure has been recorded in the past and it is important that this data can easily be accessed. But what is the current and expected condition of a structure (such as a bridge or a building)? How is this structure used now and how is it expected to be used in the future? The BIM development which has been outlined only provides a limited answer to these questions.

"BIM ONLY GIVES A LIMITED PICTURE OF THE ACTUAL AND EXPECTED BEHAVIOUR AND USE OF A STRUCTURE."

EVER MORE MEASUREMENT DATA

In recent years, more and more ‘dynamic’ measurement data has become available on both the condition and use of structures. This is an important addition to the more ‘static’ data previously mentioned, making it easier to assess the current condition and use of structures.

In the context of *bridges*, for example, an increasing amount of dynamic measurement data is becoming available on traffic loads, deformations and crack formation due to degradation. This data can be combined with other (more static) available data, such as the construction of the structure, dimensions of components and types of material used – data that has often been recorded via BIM in constructions realised in recent years. The same applies to *buildings*: via building management systems, energy meters and additional sensor networks, dynamic measurement data is increasingly being obtained on the energy performance of installations, user behaviour and weather conditions, among other things. This information can also be combined with BIM data on the number of rooms and their contents, for instance.

This static and dynamic data is available in an increasing number of situations and is useful for analysing the condition and use of structures. However, the availability of this data is still insufficient in common situations. An asset owner or manager wants to be able to make predictions about the future condition and use of the structures for which they are responsible. For example, how long can a structure or component of a structure last? How is the structure expected to be used in the future and what are the consequences of this? And how can one optimise the specific structure and a network of structures on the basis of these insights?

There is a need for a decision-support system that can predict the use and condition of structures and networks of structures. This will make it possible to optimise decisions not only on the use of structures but also on the maintenance, renovation and replacement of structures.

This brings us to the crucial digitalisation step that TNO expects the construction and infrastructure sector to take: *the step towards networks of predictive twins in the built environment*.

TNO'S PREDICTIVE TWIN VISION

TNO sees a crucial role for predictive twins of structures in predicting and influencing the future behaviour and use of structures and networks of structures. But what do we actually mean by predictive twins?

A predictive twin is a predictive digital replica of a physical structure, such as a building or a bridge. Together with the predictive twins of other structures, a network of predictive twins can be created, such as of a neighbourhood or of the bridges in a traffic network. A predictive twin is connected to its physical twin, allowing it to follow, assess and ultimately learn from the information it receives. The predictive twin can be used to make all kinds of simulations and predictions regarding the future behaviour and use of the physical twin during the lifecycle of structures. With the help of these insights, the predictive twin can propose decisions or even make its own decisions and carry out actions relating to the physical twin.[14]

If we look more specifically at predictive twins, we can see that they consist of separate components that TNO has actively been working on for many years. We want to integrate the following components in predictive twins[15]:

Information & measurement data This component concerns the 'eyes and ears' of predictive twins. A predictive twin is fed with both static and dynamic data. This data often comes from different parties and has a varying level of quality. Managing large datasets, and structuring and combining the datasets of these parties, in predictive twins is a major challenge. National and international standards for information capture and sharing are needed to combine the datasets of parties involved in the lifecycle of structures in a predictive twin. In the context of BIM (particularly in the sense of Building Information Management), this need has already been felt strongly. This is why TNO has been contributing to the development of national and international standards for information capture and sharing in the sector for many years. Because a predictive twin can connect both BIM data and dynamic measurement data, the need for these standards plays an even stronger role here.

Modelling & learning This concerns the intelligence of a predictive twin. Predictive models are part of a predictive twin and these models learn on the basis of the data (confidential or otherwise) with which the predictive twin is fed. For years, TNO has been actively working on the development of theoretical, physical and probabilistic models for prediction in practice and is increasingly combining these models with data and machine learning applications in order to improve the accuracy of predictive models, reduce the calculation time of models and allow models to learn from specific situations.[16]

Simulating & deciding With this component, future situations can be simulated at the level of structures and networks of structures, allowing predictions to be made and possible 'what if' scenarios to be assessed. TNO deals with questions such as: "what are the consequences of new innovative transport systems such as truck platooning (in which trucks travel on the road network in 'trains') for the traffic load and therefore for the technical lifespan of bridges?", "what effects does the changing behaviour of residents (e.g. due to COVID-19) have on the energy consumption of homes and neighbourhoods?" and "how can we limit the need to strengthen grids when making buildings more sustainable?" Predictive twins not only provide insights but can also carry out actions in some situations, such as changing the start times of the cooling and heating of buildings.

TNO is taking steps in various domains through the development of predictive twins and networks of predictive twins. Two examples are explained in the remainder of this position paper. The first example deals with the use of predictive twins to predict the expected traffic load on Dutch road infrastructure and the (associated) technical lifespan of bridges and bridge networks. The second example deals with the use of predictive twins to predict the energy performance of buildings and to match energy supply and demand at the building and neighbourhood levels. Both examples discuss the steps that TNO is taking now and, through this, the future that is being targeted and the impact that will be achieved.

“A PREDICTIVE TWIN INTEGRATES THREE COMPONENTS THAT TNO HAS ACTIVELY BEEN WORKING ON FOR MANY YEARS: INFORMATION & MEASUREMENT DATA, PREDICTIVE MODELS AND SIMULATIONS.”

REPLACEMENT AND RENOVATION OF CIVIL INFRASTRUCTURE AND CIRCULAR CONSTRUCTION

Situation:
Over the coming years, the infrastructure sector will have to deal with a huge replacement and renovation task for civil infrastructure. A major challenge lies with bridges and viaducts. The Netherlands has a total of approximately 53,000 bridges and viaducts.[17] Many of these civil structures were built after the Second World War - with construction peaks in the 1960s and 1970s - and will be nearing the end of their design lifespan over the next few decades.

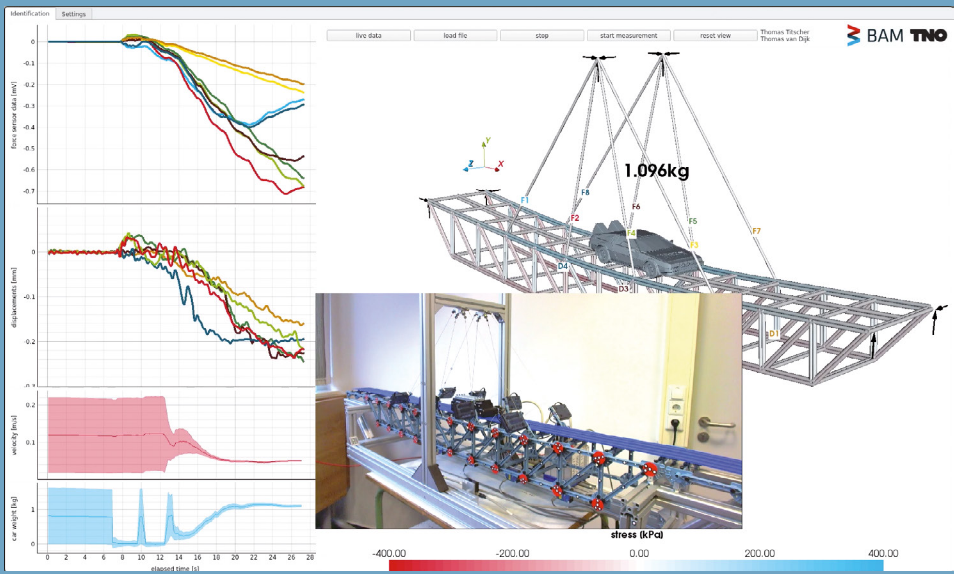
Renovating and replacing these structures costs many billions of euros and also causes a great deal of traffic disruption. However, there are often still reserves in the load-bearing capacity, meaning that the actual technical lifespan can be longer than the design lifespan. So, what is the right time for maintenance, renovation or replacement? Renovating or replacing too early is expensive and unsustainable, but taking action too late is clearly also undesirable. And if replacement or renovation is indeed chosen, can components and materials be reused in new circular constructions?

An important question for parties in the infrastructure sector - such as asset owners and managers - is therefore: how do I make optimal decisions about the maintenance, renovation and replacement of civil structures while accounting for assessment criteria such as structural safety, traffic disruption, sustainability (including circularity) and costs?

Current methods for the assessment of bridges and viaducts - based on inspections, 'quick scan' calculations and extensive assessments with measurements and finite element models - provide only global insights into the technical lifespan or are very labour-intensive and costly to carry out (and therefore not widely applicable). There is a need for new methods that provide the necessary insights into the technical lifespan of bridges and viaducts in a cost-effective manner.

Predictive twins of road infrastructure and (networks of) bridges and viaducts:
TNO focuses on the creation of predictive twins to make the necessary predictions regarding the technical lifespan of bridges and viaducts with limited costs and effort. To this end, two types of self-learning predictive twins are being developed: (1) a predictive twin of a road network that predicts the expected traffic load at each point in the road network based on available data on traffic intensity and measured loads and (2) predictive twins of bridges and viaducts that predict the technical lifespan of these structures. Within this, traffic loads on a road network will affect the technical lifespan of bridges and viaducts.

These twins answer questions such as: “what traffic loads are expected at which points in the traffic network, such as specific bridges?”, “what is the expected technical lifespan of a bridge and can specific parts of a bridge still be used?” and “how can I best optimise the replacement and renovation of a network of bridges and viaducts, taking into account criteria such as structural safety and traffic disruption?”



Development of a predictive twin of a bridge at a scale level. The twin learns from the real-time information obtained from the load and speed of the vehicle. Developed in collaboration with the German knowledge institution BAM.

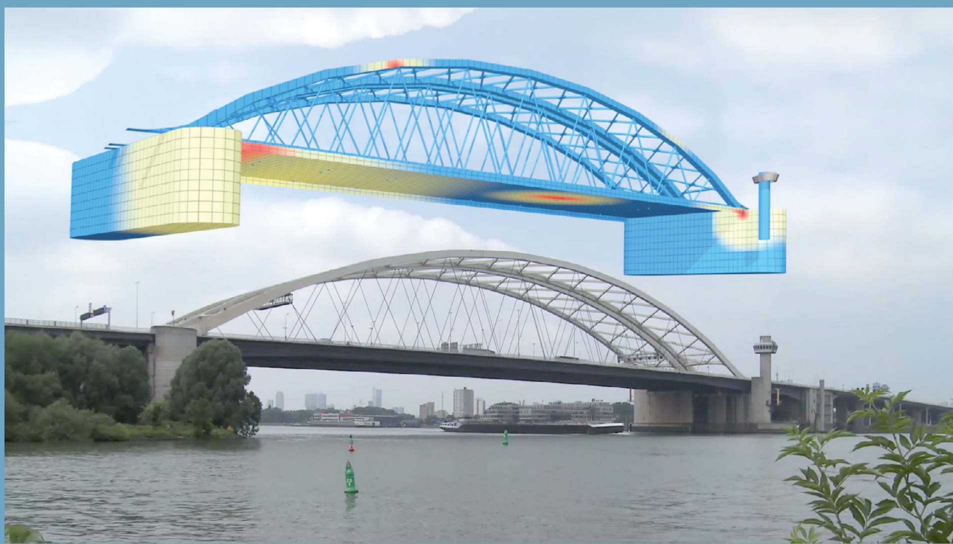
In 2019 and 2020, TNO developed several building blocks for predictive twins and translated them into cases such as the IJssel bridge and the Merwede bridge. Together with the German knowledge institute BAM (Bundesanstalt für Materialforschung und -prüfung), a predictive twin was also developed of a bridge at a scale level.

In 2021, TNO will focus on testing and demonstrating both types of predictive twins in practical situations, including field labs of specific bridges. The predictive twin technology for traffic loads (type 1) will then be ready for further development in collaboration with Rijkswaterstaat, provinces and municipalities for integration within their road, bridge and viaduct management and maintenance systems. For predictive twins of bridges and viaducts (type 2), TNO aims to have a toolbox in place by 2022 with which predictive twins can be created efficiently. This toolbox will contain methods and techniques for the development of the various components of a predictive twin:

- **Information & measurement data:** methods to collect the necessary data on bridges and viaducts with as few measurements as possible. These methods also focus on combining measurement data with other available information (such as BIM information that can be used in a predictive twin).
- **Modelling & learning:** models that predict the forces in structures and indicate how damage occurs and progresses in those structures. These models learn on the basis of data received on the physical twin. An important step that is now being worked on is to initially develop 'simple' predictive models of civil structures. These models will then learn in specific practical situations on the basis of information received from the physical twin, such as from sensors. The belief is that the predictions of these models will eventually be as accurate as the predictions that would otherwise have been obtained from much more complex and costly models.
- **Simulating & deciding:** methods to efficiently carry out simulations and scenario analyses. For example, what is the effect of new transport innovations (such as truck platooning) on the technical lifespan of bridges?

Impact:
Networks of predictive twins of bridges and viaducts are crucial to the replacement and renovation task for civil infrastructure as they:

- make it possible to better optimise the maintenance, renovation and replacement of bridges and viaducts. This results in:
  - fewer incidents with existing civil structures due to better forecasting.
  - cost reductions through later and better optimised replacement and renovation.
  - a reduction in traffic disruption through optimisation within a network of predictive twins.
- make it possible to make better integrated assessments of the replacement and renovation of bridges and viaducts on the basis of criteria such as structural safety, traffic disruption, sustainability and costs.
- can offer designers of new (circular) structures insights into the availability, quality and technical lifespan of components in existing structures.

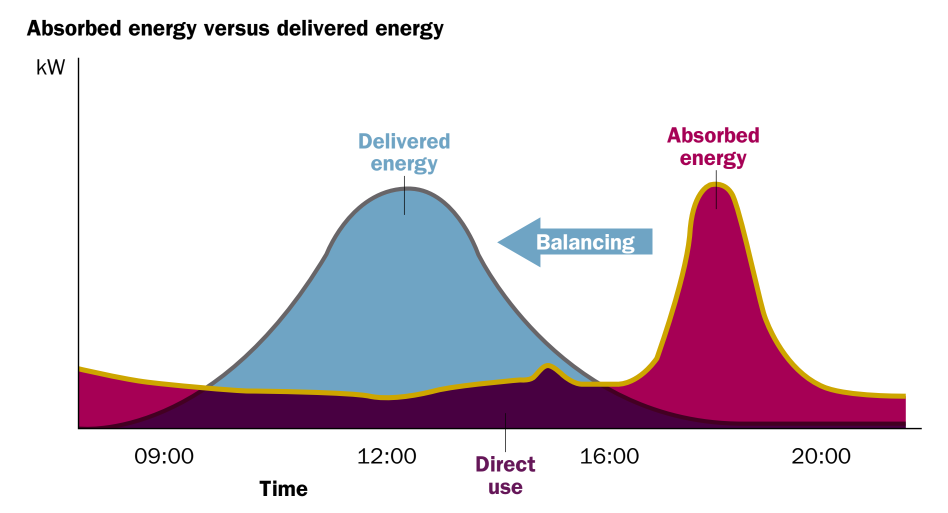


ENERGY TRANSITION IN THE BUILT ENVIRONMENT (BUILDINGS AND NEIGHBOURHOODS)

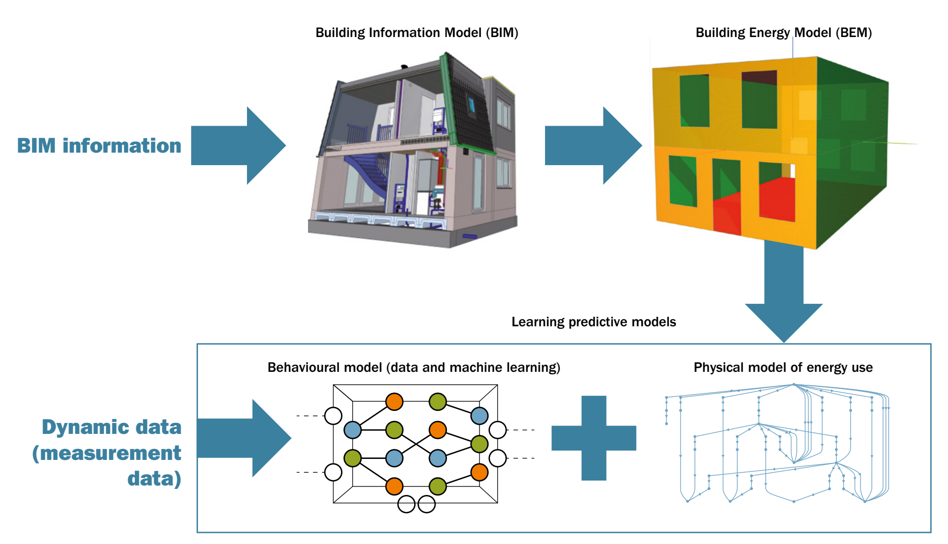
Situation:
By 2050, the entire built environment must be energy-neutral. Furthermore, all homes and utility buildings need to shift from natural gas to sustainable energy sourcesby that same year. The ability to predict the energy performance of buildings and to match energy supply and demand to the building and neighbourhood level are of great importance for various reasons.

Firstly, there is a great need to understand the effectiveness of new energy and renovation concepts for buildings. The achievement of a high energy performance in buildings depends heavily on the interactions between the building, the user, the building installation and the environment. Intended energy performance is often not achieved due to buildings and installations being used differently than what was conceived during the design phase or due to a lack of continuous management of installations. Since a disappointing energy performance is a dead end for the energy transition, it is essential to be able to guarantee the intended building performance not only in terms of energy but also in comfort and indoor air quality.

Secondly, the energy transition leads to both increased peaks in energy demand (e.g. through the application of electric heat pumps in buildings and the increase in charging stations for electric vehicles) and increased peaks in decentralised energy supply (e.g. through solar panels). This will result in peak loads in energy demand and supply and therefore in bottlenecks at the energy network level. There is a need for solutions that predict and optimise energy consumption at the building level, but also – more importantly – are able to balance energy supply and demand at a neighbourhood level. This can be done, for example, by starting up the heat pumps for heating and domestic hot water in buildings sooner or later, thereby reducing the peak demand for energy.[18] By reducing peaks in energy demand and supply, costly investments in strengthening the energy network can be avoided as much as possible.



Predictive twins of buildings and neighbourhoods:
TNO is focusing on the creation of predictive twins of buildings and neighbourhoods. These will monitor, predict and influence the energy consumption at both levels, thereby allowing energy use to be optimised and energy supply and demand to be better matched.



From Building Information Model (BIM) to learning predictive models.

By 2022, TNO wants to have developed a basic methodology for the integrated measurement and prediction of energy performance at a building and neighbourhood level with networks of predictive twins.
The basic methodology focuses on the various components of predictive twins, as explained in the main text:

- **Information & measurement data:** developing methods to collect relevant input for a predictive twin with a limited number of measurements and to make maximum use of captured static information (such as BIM). In any case, energy data is required. This data can be enriched with data from intermediate meters, thermostats, installations and smart sensor networks

- **Modelling & learning:** TNO is developing predictive models based on physics and machine learning techniques. Well-known relationships (such as heat transfer in relation to the insulation of walls and facades) are described in physical models. Whenever mechanisms are unknown (particularly in regard to human behaviour), models are developed based on dynamic data, knowledge of human-technology interaction and machine learning techniques. In order to guarantee the privacy of building users, the dynamic measurement data does not leave the building. Models are trained locally within the building. Only the model parameters that are needed to carry out analyses at a neighbourhood level leave the building.
- **Simulating & deciding:** developing methods for making decisions (automated or otherwise) on physical twins and performing 'what if' analyses regarding future performance at a building and neighbourhood level. Simulations can be carried out in the use phase but also in the design phase. Together with partners, TNO is developing methods to predict and simulate energy consumption and the quality of the indoor environment in the design phase of housing projects and then to monitor and analyse these in the usage phase.[19] Methods are also being developed to influence the settings of installations and the use of energy, such as by planning the charging of electric cars and the use of heat pumps.

In recent years, the necessary steps have already been taken towards the development of the basic methodology. In 2019, for example, predictive twins that could approximate actual energy performance were developed for a number of homes. These were new-build and renovated homes. Building models were developed for a number of very low-energy homes owned by BAM and Van Wijnen, which were calibrated with energy and installation data. In addition, a living lab has been set up with Strukton to which a predictive twin has been linked. As a result, it is possible to make better predictions of both energy consumption and indoor temperatures. Building concepts can be improved on the basis of these insights. Previously, the behaviour of occupants had only been included in predictive models to a limited extent, but this turned out to be a highly decisive factor in making the right predictions.

In 2020, predictive models were developed for various building types and more extensive use has been made of machine learning in the predictive models in order to take better account of user behaviour and the privacy and security of building data, among other things. The use of BIM information that becomes available during the lifecycle of buildings in order to make better predictions has also been investigated and tested in practical situations. In addition, there have been investigations into how a step can be taken towards scalable predictive twins in order to predict energy performance at the building level and thus balance energy supply and demand at the neighbourhood level.

Impact:
Networks of predictive twins are crucial in realising the energy transition in the built environment, as they:
- provide insights into the effectiveness of energy and renovation concepts in terms of energy, comfort and indoor air quality.
- predict building performance in terms of energy, comfort and indoor air quality. Better forecasting of energy performance is essential for performance contracts.
- are an important means of matching energy supply and demand at a building and neighbourhood level.

These examples show that predictive twins contribute significantly to the data-based optimisation of decisions on civil infrastructure and buildings. This has great added value for the challenges facing the construction and infrastructure sector, such as the replacement and renovation of existing civil infrastructure, the transition to circular construction and making the existing built environment energy-neutral.

PRECONDITIONS FOR THE DEVELOPMENT AND USE OF PREDICTIVE TWINS

TNO is currently gaining experience with the development and use of (components of) predictive twins in various domains. On the basis of these experiences, we see five important challenges:

1. EFFICIENT (RE)USABLE AND LEARNING PREDICTIVE TWIN SOLUTIONS

In order to make predictive twins usable in practice, it is important that they are created efficiently while also providing sufficiently reliable forecasts. If predictive twins are very expensive, the wide application of this technology will not be possible. TNO is therefore actively developing methods, techniques and toolsets in order to create predictive twins efficiently and to test their usability in field labs. For example, TNO is now working on a method to develop a predictive twin of a large bridge in a short period of time. This twin will then learn on the basis of monitoring data. The hypothesis is that the development time for the necessary predictive models can thereby be reduced from one year to one week. This would be a major breakthrough for the broad applicability of predictive twins of bridges.

2. FIT FOR PURPOSE

Although predictive twins will bring significant added value to the construction and infrastructure sector, there is also a risk that technological solutions will be too broad for the needs of specific situations. We are constantly asking ourselves questions such as: does every type of structure need the same advanced predictive twin with corresponding accurate predictive models and detailed datasets? It is therefore important to clarify which forms of predictive twin exist and in which situations in the sector they are useful and cost-effective.

3. CONNECTING KNOWLEDGE DOMAINS

Predictive twins can only be developed when experts from different disciplines collaborate. The domain/professional knowledge of experts in areas such as civil engineering and building physics should be combined with the knowledge of experts in information modelling, monitoring systems, human-technology interaction and machine learning. Only by allowing experts from these knowledge domains to work together in a targeted manner can the necessary predictive twins be developed.

4. STRUCTURING AND CONNECTING SOURCES OF INFORMATION

In a predictive twin, data comes together from different information sources that generally have varying levels of quality. This concerns static and dynamic information that often originates with different parties. Dealing with information of a varying quality level and the unambiguous recording, structuring, sharing and linking of information was already a challenge in the context of BIM development and is at least as important for predictive twin development. Determining and implementing national and international agreements and standards at a sector level[20] is very important for predictive twins.[21]

5. MANY (COLLABORATING) PARTIES WITH THEIR OWN INTERESTS AND NEEDS

The construction and infrastructure sector has traditionally been fragmented and divided across many parties ranging from architectural and engineering firms, construction companies and subcontractors to suppliers, clients and managers. Each of these parties operates on the basis of different interests and has different needs and working methods in regard to predictive twins. How does a network of predictive twins fit in with these interests, needs and working methods? What use scenarios are there for these parties? And how does a predictive twin facilitate collaboration between these parties in the fragmented construction industry? Together with practical parties, the development of predictive twin use scenarios (and associated benefits) for parties in the construction and infrastructure sectors, as well as the demonstration of these use scenarios in field labs, are important for accelerating practical implementation over the coming years.

CONCLUSION

Over the coming years, the construction and infrastructure sector will take a step towards networks of predictive twins in the built environment. This step is crucial for more data-driven and proactive decision-making on structures and networks of structures.
These predictive twins are a necessary tool for the realisation of important societal challenges facing the construction and infrastructure sector. TNO is currently taking important steps towards the outlined view of the future and is actively working on conditions for the successful development and application of predictive twins. Together with practical and knowledge partners, TNO will continue to do this over the coming years in order to make the step towards feasible and affordable networks of predictive twins.

“TNO IS DEVELOPING METHODS AND TECHNIQUES TO CREATE PREDICTIVE TWINS OF STRUCTURES AND NETWORKS OF STRUCTURES WITH LIMITED RESOURCES.”

FINAL NOTES

1 See, for example, the letter to the House of Representatives on the approach to preserving national infrastructure for the coming years, dated 19 June 2020 https://www.rijksoverheid.nl/ ministeries/ministerie-van-infrastructuur-en-waterstaat/documenten/kamerstukken/2020/06/19/aanpak-instandhouding-rijksinfrastructuur).

2 See, for example, the Construction Agenda (De Bouwagenda, www.debouwagenda.com) and the Climate Agreement presented on 28 June 2019 (www.klimaatakkoord.nl). The Concrete Agreement (Het Betonakkord) even has the objective of 100% high-quality reuse of freed-up concrete by 2030 (www.betonakkoord.nl).

3 See, for example:
- EIB (2020). Monitoring Bouwagenda; De voortgang in de periode 2017 t/m 2019 (Construction Agenda Monitoring; Progress over the period 2017 to 2019). Economisch Instituut voor de Bouw (Economic Institute for Construction), Amsterdam.
- DigitaliDealGO (2020). Werken aan de digitale transformatie van onze gebouwde omgeving (Working on the digital transformation of our built environment) (Update DigiDealGO March 2020). DigiDealGO.

4 TNO uses the term predictive twins here. These are digital twins that focus specifically on making predictions regarding the use and functioning of buildings. Predictive twins are therefore part of a digital twin. For a further explanation of digital twins for the construction and infrastructure sector, see (for example):
- Bolton, A., Butler, L., Dabson, I., Enzer, M., Evans, M., Fenemore, T., ... & Pawsey, N. (2018). The Gemini Principles. https://doi.org/10.17863/CAM.32260.
- Brilakis, I., Pan, Y., Borrmann, A., Mayer, H., Rhein, F., Vos, C., ... & Wagner, S. (2020). Built Environment Digital Twinning; Report of the International Workshop on Built Environment Digital Twinning presented by TUM Institute for Advanced Study and Siemens AG. https://publications.cms.bgu.tum.de/reports/2020_Brilakis_BuiltEnvDT.pdf.

5 NBIMS (2007). United States National Building Information Modeling Standard; Version 1 – Part 1: Overview, Principles, and Methodologies. National Institute of Building Sciences.

6 See, for example:
- Boje, C., Guerriero, A., Kubicki, S., & Rezgui, Y. (2020). Towards a semantic Construction Digital Twin: Directions for future research. Automation in Construction, 114, 103179.
- Ding, K., Shi, H., Hui, J., Liu, Y., Zhu, B., Zhang, F., & Cao, W. (2018). Smart steel bridge construction enabled by BIM and Internet of Things in industry 4.0: A framework. In 2018 IEEE 15th International Conference on Networking, Sensing and Control (ICNSC) (pp. 1-5). IEEE.

7 Adriaanse, A. M. (2014). Bruggen bouwen met ICT (Building bridges with ICT). Enschede: University of Twente.

8 However, there is a difference here in the 'BIM maturity' of these types of parties. See, for example:
- Siebelink, S., Adriaanse, A., & Voordijk, H. (2014). BIM-Maturity Sectoranalyse - 2014: Een beeld van de BIM-ontwikkeling in deelsectoren van de bouw- en GWW-sector (BIM Maturity Sector Analysis - 2014: A picture of BIM development in subsectors of the construction and GWW sector) (https://www.bouwinformatieraad.nl/main.php?cat_id=6&mode=download_cat).
- Siebelink, S., Adriaanse, A., & Voordijk, H. Enquête BIM-maturity 2016: Sectorrapportage (Survey on BIM Maturity 2016: Sector reporting) (https://www.bouwinformatieraad.nl/main.php?cat_id=6&mode=download_cat).

9 Adriaanse, A. M. (2014). Bruggen bouwen met ICT (Building bridges with ICT). Enschede: University of Twente.

10 See, for example:
- Honic, M., Kovacic, I., Sibenik, G., & Rechberger, H. (2019). Data- and stakeholder manage- ment framework for the implementation of BIM-based Material Passports. Journal of building engineering, 23, 341-350.
- Van den Berg, M. C. (2019). Managing Circular Building Projects. Enschede: University of Twente.

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12 Luiten, B., Böhms, M., Alsem, D., & O'Keeffe, A. (2019). Asset information management using Linked Data for the life-cycle of Roads. Delft: CRC Press/Balkema.

13 ING (2018). ConTech: Technologie in de bouw Bouw digitaliseert volop maar industrialiseert nauwelijks (ConTech: Technology in the construction industry is digitising a lot but hardly ever industrialises). ING Economics Department, Amsterdam.

14 See also, for example, the Digital Twins sub-programme of the BTIC Knowledge and Innovation Programme Digitalisation (https://btic.nu/wp-content/uploads/2020/05/Digitalisering- DigitalTwins_Kennis-en-innovatieprogramma_BTIC.pdf).

15 TNO uses this three-part division. For a similar classification, see:
- Ye, C., Butler, L., Bartek, C., Iangurazov, M., Lu, Q., Gregory, A., Girolami, M. & Middleton, C. (2019). A Digital Twin of Bridges for Structural Health Monitoring. In 12th International Workshop on Structural Health Monitoring 2019. Stanford University.
- Zhang, C., Xu, W., Liu, J., Liu, Z., Zhou, Z., & Pham, D. T. (2019). A reconfigurable modeling approach for digital twin-based manufacturing system. Procedia CIRP, 83, 118-125.

16 TNO uses (a) physics-based models, (b) data-based models and (c) a combination of both (hybrid models). Traditionally, physics-based models have been developed and applied. These are increasingly combined with data-based models, resulting in hybrid models (Artificial Intelligence - From research to application | TNO).

17 This concerns the total number of concrete, steel and movable bridges.
See: Bleijenberg, A. (2020). Instandhouding civiele infrastructuur; Proeve van landelijk prognoserapport vervanging en renovatie. Bouwagenda (Conservation of civil infrastructure; Trial of national forecasting report on replacement and renovation. Construction agenda).

18 See, for example, the Horizon 2020 project Atelier (https://smartcity-atelier.eu) and the Horizon 2020 project Syn.ikia (https://www.synikia.eu).

19 See, for example, the Horizon 2020 project Sphere (https://sphere-project.eu/pilots/).

20 This is now being done, for example, via the NTA 8035. See: NEN (2020). Semantische gegevens-modellering in de gebouwde omgeving. Nederlandse technische afspraak, NTA 8035:2020 (Semantic data modelling in the built environment. Dutch technical appointment, NTA 8035:2020). Royal Dutch Standardization Institute Foundation.

21 See, for example, the activities of digiGO on the realisation of a Digital System of the Built Environment (www.digigo.nu).

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