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Trusted elements in the digital model of the tunnel

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ABSTRACT: The application of Building Information Modelling (BIM) in Tunnelling involves the generation, co-evolution, and maintenance of digital models. This often requires the collaboration of multiple stakeholders on the same digital model over multiple project phases, which, in turn, necessitates the sharing of responsibility for the same model element among those stakeholders. For example, a niche in the tunnel inner lining may be designed simultaneously by a structural engineer, by a fire safety expert who needs to install a fire hydrant in it, and by a HVAC engineer who needs a ventilation control panel in it. Shared responsibility requires trust. Lack of trust often leads to the duplication of models so that each stakeholder can work on a separate model, free from the influence of the work of others. The consequence is a break-down of model continuity and unsustainable usage of personnel and resources. In this work, we present a method for introducing trusted elements into the digital model of the tunnel. This can be accomplished by anchoring those elements to contractually relevant documents, such as the Employer Information Requirement (EIR) according to the ISO 19650 series. Trusted elements can guarantee formally that a certain contractual or technical requirement has been fulfilled, e.g., that the measurement of carbon monoxide for the emergency ventilation system is designed in accordance with ISO 23431. In addition, formal requirements within a trusted element can be tested automatically by the common data environment (CDE) of the project. In case that one stakeholder changes the trusted element so that a requirement is no longer fulfilled, an automatic alert can be issued. We present a standardized workflow for the creation and maintenance of such trusted elements in a digital model on the use case of the design of a ventilation system in a road tunnel.

Keywords: Tunnelling, BIM, Digital model, Trust, Technical guidelines

1 INTRODUCTION

Over the past decades, the Architecture, Engineering, and Construction (AEC) industry, including the tunnelling sector, has been adapting the digital methods originating in automation (Barbosa et al., 2017). These include handling of both geometry and non-geometric, typically highly domain-specific, information (Hegemann et al., 2019). One of the most widely used such methods is Building Information Modeling (BIM) (Laakso and Kiviniemi, 2012; Borrmann et al., 2015). In spite of all these efforts, data integration remains a challenge not only when experts from multiple domains are involved (Haymaker et al., 2000; Lai and Deng, 2018; Rasmussen et al., 2019; Steel et al., 2012), but even within the same domain (Scheider and Kuhn, 2015; Millán et al., 2016).

One of the main goals of BIM is the generation and maintenance of a digital twin (Kaewunruen et al., 2018), a digital counterpart of a built structure that both supplies and receives information from it, thereby regulating its function and reacting to changes in the state of its systems (Lai and Deng, 2018), respectively. Ideally, this digital twin should be a digital model with meaningful interconnections between model elements that carry unambiguous domain-specific semantics (ITA Working Group 22, 2022).

Often however, the digital twin corresponds to the ISO 11354-1 1 definition of a federated model (ITA Working Group 22, 2022). The federated model is simply a set of separate (partial) digital models with possible mappings between them (Leng et al., 2021), i.e., a landscape of heterogeneous syntax and semantics that cannot be easily managed or navigated. For example, querying the relevant information for a particular task, or tracking the direct and indirect effects of a model element update throughout the entire digital twin both necessitate the implementation of specialized views and workflows (Eastman et al., 2011; Hegemann et al., 2019), often embedded in a Common Data Environment (CDE).

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1.1 *Motivating example*

This complexity and lack of transparency affects the level of BIM acceptance in the AEC industry in general and in tunnelling in specific (Lehoczky et al., 2022). For example, if during the operational phase of a road tunnel project we need to assess the air quality, different experts may use different technical guidelines, e.g., the ISO 23431:2021 “Measurement of road tunnel air quality”, or ISO 4224:2000 “Ambient air — Determination of carbon monoxide — non-dispersive infrared spectrometry method”. Those guidelines offer slightly different methods for the evaluation of carbon monoxide presence in air.

On the one hand, ISO 23431:2021, Section 5.5.2 describes the following method for the calculation of gas concentration over a measurement path in *ppm*:

$$c = \frac{c_r L_c}{L} + \frac{c_b(L - L_c)}{L} \tag{ISO23431.3}$$

where c_r is the reference test atmosphere concentration in *ppm volume fraction*, c_b is the background pollutant concentration in *ppm*, L_c is the calibration cell length in *m* and L is the measurement path length in *m*. The conversion to *mg/m³* is described in Section 5.7:

$$C_m = \frac{C_v m}{V_m} \tag{ISO23431.7}$$

where c_m is the gas concentration in *mg/m³* under the conditions of *standard temperature* and *standard gas pressure* of 101.3 kPa, c_v is the gas concentration in *ppm* volume fraction, *m* is the molecular weight of the gas, and V_m is the molar volume at 0 °C and at *standard gas pressure* of 101.3 *kPa*.

On the other hand, ISO 4224:2020, Section 11 defines the conversion from *ppm* to *mg/m³* for gases in the following equation:

$$\rho_1 = \frac{\rho_2 m_r\ 298\ p}{24.45\ T\ 101.3} \tag{ISO4224.11}$$

where ρ_1 is the gas concentration in *mg/m³*, ρ_2 is the measured gas concentration in *ppm volume fraction*, $\mathrm{m_r}$ is the molar mass of the gas (e.g., 28 *g/mol* for CO), 298 is the standard absolute temperature in *K*, ρ is the measured gas pressure in *kPa*, 24.45 is the molecular volume of 1 mole in l, *T* is the measured absolute gas temperature in *K*, and 101.3 - the standard gas pressure in *kPa*.

The question is, how is an expert to know which guideline has been used and whether it has been applied consistently for all assessments in the federated model? In fact, instead of creating confusion and uncertainty, both of these technical guidelines can be used to create *trusted elements* in a digital model, regardless of its complexity. Our task is to utilise the equations and their parameters as *semantic anchoring points* for the relevant elements of the *digital twin.*

2 APPROACH

Our approach involves the formalisation of guidelines written in a natural language into a graph representation and the subsequent annotation of digital data models with elements of this graph.

2.1 *Semantic anchoring*

Let us have a look at one possible formalisation of both technical guidelines. Figure 1 shows on the right-hand side the graph representation of equation

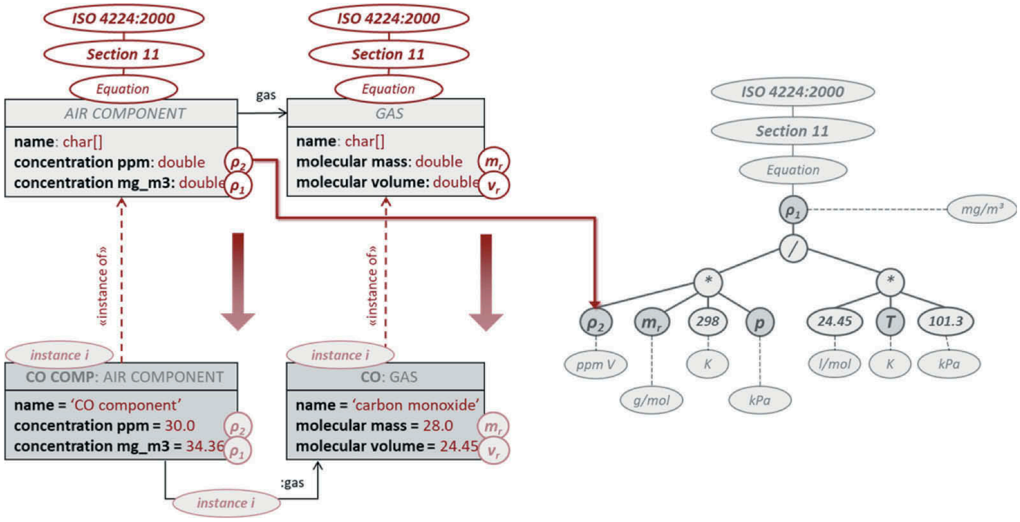


Figure 1. Mapping of a domain model to the ISO 4224:2000 guideline.

ISO4224.11 with both parameters and mathematical operations as nodes. The root of the graph indicates the identity of the guideline, followed by the section and equation (which in this case has no number). Since ρ_1 is a result of division, the only child node of ρ_1 is the corresponding operation, which has two children, both multiplication operations that produce the dividend and divisor, respectively. Each node that contains a parameter or a value has the corresponding unit attached to it, e.g., for ρ_1 it is mg/m^3 These units are by no means just informative. They can be used to describe the *type* of the node they are attached to.

On the left-hand side of Figure 1 is an excerpt of a domain-specific digital model that uses this guideline as a *semantic anchoring point*. In the top row we see the type definitions, for example *AIR COMPONENT* and *GAS*. They tell us that the digital model can save air component objects described by attributes "name", "concentration ppm" and "concentration mg_m3" and referencing objects of type GAS, i.e., gases, which in turn are described by attributes "name", "molecular mass" and "molecular volume". This is by no means a prescription of how such information should be structured, it is just an arbitrary example to illustrate the point that *any* object-oriented data model can be used in the exact same way.

In the bottom row on the left-hand side of Figure 1 we see the instances produced by the type definitions. **CO COMP** is an instance of *AIR COMPONENT* and, consequently, has slots that correspond to the type definition's attributes. For example, attribute "concentration ppm" produces a slot by the same name that carries a specific value (the double 30.0). In the same way **CO** is an instance of type definition *GAS*. The relationship between the type definitions and their instances is represented by the red dashed arrows annotated with *instance of*.

Another type of relationship, between type definitions, is the one between *AIR COMPONENT* and *GAS*, named "gas". It indicates that each air component references a specific gas, i.e., that the air component makes sense only if its definition includes a specific gas, such as carbon monoxide. This relationship can be instantiated as well, as can be observed in Figure 1. There, the instance **CO COMP** references the instance **CO** via the instance of "gas".

Now that we have a digital model capable of holding the information we need in order to comply with ISO 4224, Section 11, we can proceed with making the model elements we just described *trusted*.

The graph representation of the guideline has several features that enable *semantic anchoring* to any of its elements. First, its graph structure makes it easily serializable, e.g., in a common digital format, such as XML. This makes distribution of the formalised guideline or its hosting on a CDE platform quite trivial. Second, the graph structure is efficiently traversable, which presents an advantage in querying both the guideline and any digital model elements attached to it. Third, this structure is well suited for anchoring, since each graph node can play the role of an anchor. This is demonstrated in Figure 1, where both the type definitions and their attributes have been annotated with elements of the graph (see the red labels on the left corresponding to graph nodes on the right). For example, attribute "concentration ppm" of *AIR COMPONENT* has been annotated as "ρ_2" and effectively anchored to the corresponding equation parameter, as indicated by the continuous red arrow pointing to the graph node.

We can observe that the structure of the *domain model on the left does not have to correspond in any way to the structure of the guideline or the equation on the right*, since annotations make the anchoring independent of structure.

Additionally, the anchoring in the type definitions is automatically transferred to their respective instances by the *class – object* relationship characteristic of most object-oriented programming languages.

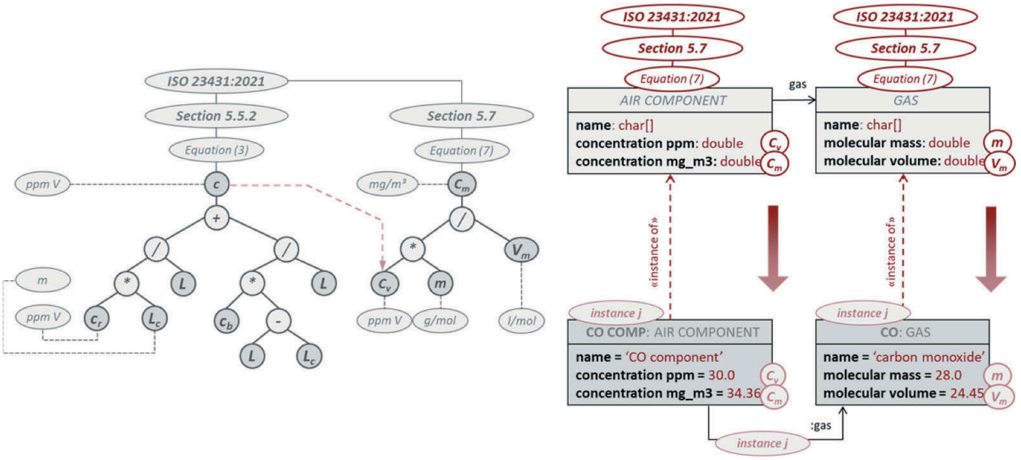


Figure 2. Mapping of the same domain model as in Figure 1 to the ISO 23431:2021 guideline.

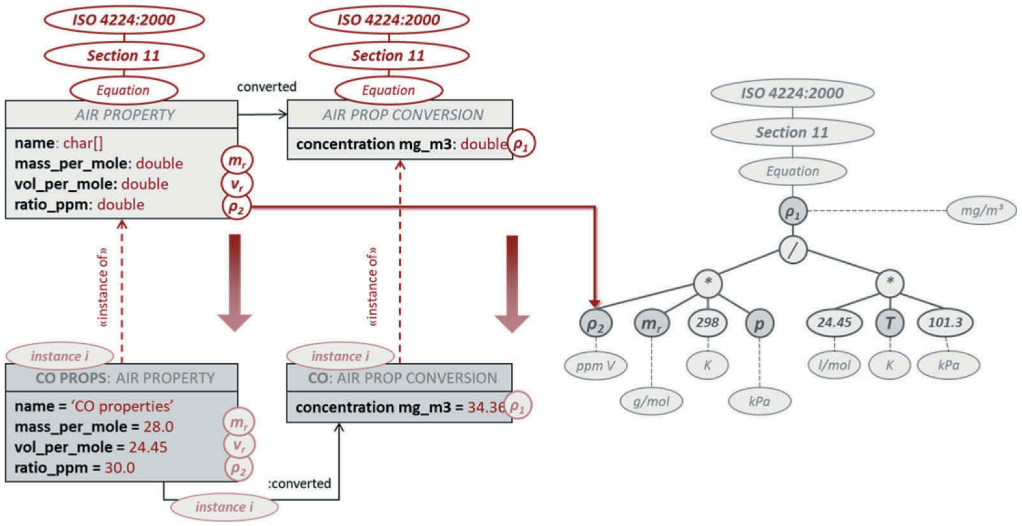


Figure 3. Mapping of a second domain model to ISO 4224:2000 (compare to Figure 1).

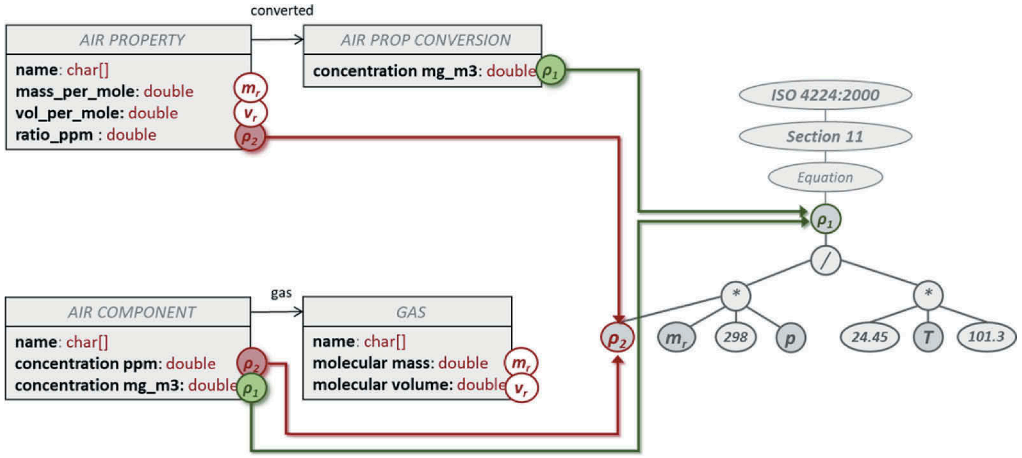


Figure 4. Data integration between two different domain models based on their anchoring to the same guideline equation.

Thus, annotations in the type definitions are sufficient for the annotation of all of their instances, regardless if there are ten or ten thousand of them. Furthermore, grouping of instances that build the same semantic unit are possible via instantiable relationships, such as the one between *AIR COMPONENT* and *GAS* (see the "instance i" labels in Figure 1).

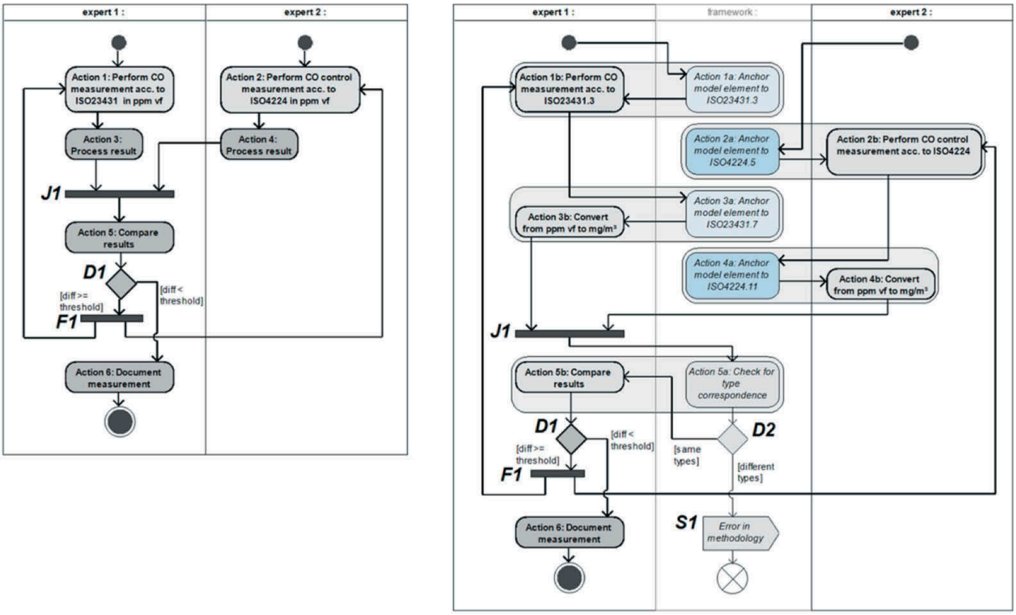
A further example of the semantic anchoring of the same domain model, but this time to the ISO 23431:2021 guideline is shown in Figure 2. Here, we have two formalised equations, equation (ISO23431.3) on the left and equation (ISO23431.7) on the right. This gives us the opportunity to indicate that the result c of equation (ISO23431.3) is input Cv to equation (ISO23431.7). Otherwise, the domain model now has different annotations that indicate its anchoring to ISO 23431:2021.

It is of note, that these annotations are not mutually exclusive. On the contrary, they exist in parallel. In other words, *the same domain model can be anchored to multiple guidelines* to indicate its compliance to all of them, if necessary.

2.2 *Data integration based on semantic anchoring*

Apart from demonstrating compliance with technical guidelines and providing an automated path towards compliance checking (Jiang and Wang, 2021), this type of annotation allows for automated data integration.

Figure 3 shows a second domain model anchored to the same equation of the ISO 4224:2000 guideline as in Figure 1. Its type definitions differ not only in name, but also in structure from the one we discussed in



(a) (b)

Figure 5. Practical application of semantic anchoring: (a) standard workflow, (b) adapted workflow including anchoring and automated compliance checking.

detail in the previous subsection. However, since the anchoring to the guideline depends only on the guideline's own structure, and not at all on the domain model's structure, the result are the same annotations, but attached to different elements of this second domain model. This is exactly what allows us to find a reliable mapping between the domain models in Figure 1 and Figure 3.

This mapping is shown in Figure 4. Since both the type definitions and their attributes have different names, a mapping based on those cannot be relied upon. A mapping based on their respective *semantic anchor points* on the other hand is both reliable, i.e., *trustworthy*, and can be performed automatically.

Let us look at anchor point ρ_1 first (shown in green in Figure 4), which corresponds to the gas concentration measured in mg/m^3. This is the result node of the equation in Section 11 of ISO 4224:2000. In the domain model at the top of Figure 4, this anchor point is placed on attribute "concentration mg_m3" of type definition *AIR PROP CONVERSION*. In the domain model on the bottom, the same anchor point is placed on the attribute of the same name in type definition *AIR COMPONENT*.

Analogously, anchor point ρ_2 (shown in red in Figure 4), which corresponds to the gas concentration measured in *ppm volume fraction*, is placed on attribute "ratio_ppm" of type definition *AIR PROPERTY* in the top domain model and on attribute "concentration ppm" of type definition *AIR COMPONENT* in the bottom domain model. We can see that neither name differences, nor attribute grouping within type definitions are of any relevance here. We can transfer or consolidate information along the green or red lines regardless.

2.3 *Guideline-based type safety*

So far, we were concerned with the semantics of the data models. Correct semantics, however, include correct units and unit conversion. In our case, we regard the unit associated with a graph node, e.g. mg/m^3 for node ρ_1 in Figure 3, as that node's *type*. We use the fact that SI units can be subjected to automatic conversion, e.g., mg/m^3 multiplied with m^3 results in *mg*, to provide us with *type safety*. This is based on the formal mathematical methods for calculation with types, or *type reduction*, which proves type correspondence (Bertot and Castéran, 2004). This means that we cannot perform a mapping between, e.g., attributes of type g/m^3 and of type mg/m^3 since g/m^3 cannot be reduced to mg/m^3. However, mapping between *Pa* and $kg/(m*s^2)$ is possible. This gives us an additional layer of *trustworthiness*.

2.4 *The workflow*

The methods we outlined in the previous sections can be applied in the following general workflow:

- **Guideline formalisation**: a standardisation body performs a partial or complete formalisation of a guideline;
- **Semantic anchoring**: the domain experts perform a *one-time* annotation of the domain model they utilise for a specific task, which anchors this model to the formalised digital form of the guideline;
- **Creation of trusted model elements**: the domain experts using the above-mentioned domain model instantiate it in the course of their regular work. This causes the anchors attached to the domain model's type definitions to be transferred to each and every instance automatically. All such instances can be regarded as *trusted*.
- **Automatic compliance checking**: Every trusted instance can be subjected to automatic compliance checking against the formalised guideline. This can be particularly useful in a scenario where multiple experts work on the same model and share responsibility for the same model elements. Trusted model elements can be checked for compliance after each significant update, which maintains their role as a *source of trust* in the digital twin.

This workflow can be applied both to a federated as well as to a monolithic digital model. It can run on a single machine or as a part of a CDE.

3 USE CASE MEASUREMENT OF CO CONCENTRATION

Here we give a brief (and simplified) example of the practical application of our approach on the use case of obtaining and recording measurements of CO concentration in a tunnel.

Figure 5(a) shows the standard workflow as a UML activity diagram. It involves two experts who perform measurements independently, according to ISO23431 and ISO4224, respectively. In *Action 1* expert 1 takes one measurement, while in *Action 2* expert 2 takes a control measurement. Following that, each processes the obtained results in *Action 3* and *Action 4*, respectively. The *Join Node **J1*** synchronises the information flows and transitions into *Action 5: Compare results*. The result of the comparison is fed to *Decision Node **D1***. If the difference between the measurements is less than a predefined threshold, then the result can be regarded as valid and is recorded in *Action 6: Document measurement*, after which the workflow terminates. If, on the other hand, the difference exceeds that threshold, we transition to *Fork Node **F1***, which transitions back to *Action 1* and *Action 2*, effectively forcing a repeat of both measurements and, subsequently, of the entire workflow we described this far.

If the difference in the two measurements results not from equipment calibration, or environmental conditions, but from an incorrect application of any of the referenced guidelines, there is a real possibility of this workflow causing an infinite loop, if run in an automated fashion in a CDE. Alternatively, there will be a need for an in-depth manual check for the error to be detected. This problem should be mitigated by the adapted workflow we propose in Figure 5(b).

Here we introduce an additional actor, a framework that applies our *semantic anchoring* approach (see the swim lane between expert 1 and expert 2 in Figure 5(b)). One immediate consequence of this is the splitting of *Action 1* to *Action 5* from the standard workflow we discussed above into two new actions each. For example, before expert 1 can even take a measurement in *Action 1b*, the correct model element for the task is instantiated and anchored to the appropriate equation in ISO23431 by the framework in *Action 1a*. The same applies to *Action 2* from the standard workflow, which is split into *Action 2a* and *Action 2b* in the adapted workflow.

Action 3 and *Action 4* are also split. This time the processing of the results becomes an explicit conversion from *ppm volume fraction* into *mg/m³* (see *Action 3b* and *Action 4b*). But before the experts can perform the conversion, the appropriate model elements are again instantiated and anchored to the relevant equations by the framework in *Action 3a* and *Action 4a*, respectively. This allows us to pass through the *Join Node **J1*** with *trusted elements* in our model, which lend themselves to formal checks, e.g., type checking. This is exactly what happens in *Action 5a*. Here, the framework performs a type check. Since anchoring to nodes in an equation allows us to obtain a specific unit, which, as we discussed in Section 2.3, can assume the role of the *type* for the anchored model element, in *Action 5a* we check if the type of the measurement by expert 1 is reducible to the type of the measurement by expert 2. For example, if something went wrong during conversion for one of the experts, we might be comparing *ppm volume fraction* with *mg/m³*. This will immediately produce an error message (see node ***S1*** in Figure 5(b)) and will terminate the workflow, giving the experts involved the opportunity to address the issue without delay. Another possibility is the mishandling of units during calculation, which should also become apparent here, e.g., if we were comparing g/m³ with mg/m³.

All of the above makes the comparison in *Action 5b* more reliable. Due to the utilization of *trusted model elements*, we can claim with some confidence, that if the results differ too much, the likeliest reason is not a data modelling error, but rather a problem with the actual measurement. In addition, the adapted workflow doesn't require the experts themselves to adapt (compare the expert swim lanes in Figure 5(a) and 5(b)). *The only adaptation that takes place is in the technology itself.* This makes the framework we present a good candidate to foster user acceptance and trust in the digital technology in tunnelling (Lehoczky et al., 2022).

4 RELATED WORK

The approach to increasing trust in the digital model of the tunnel we presented in the previous two sections builds on several well-researched concepts.

While there have been many proposals for the utilization of the blockchain technology in communication in the AEC industry (Elghaish et al., 2023; Raslan et al., 2020; Wonjiga et al., 2019), its application in interoperability has been limited to recognising the *presence*, but not the *semantics* of model updates (Xue and Lu, 2020).

On the other hand, graph representations of semantic concepts and the linking between such representations, even when stemming from different domains, shows promise (Witherell et al., 2013; Borrmann et al., 2014; Wang et al., 2023).

In the area of Automated Compliance Checking (ACC) there has been great emphasis on building codes and corporate guidelines as a trust-generating basis for digital models (Häußler et al., 2020; Jiang et al., 2022; Lehoczky et al., 2022).

These are all *a posteriori* approaches, i.e., based on checks of already existing models. However, the most robust approaches, those that provide an *a priori* guarantee of correctness, come from computer science. For example, a formal mathematical proof can guarantee the correctness of a digital model before even one element of it has been instantiated (Bidmeshki and Makris, 2015). This is also where the idea of type safety as a means of providing trust originates (Bertot and Castéran, 2004). It is of note that these approaches come at a very high performance (Bajczi et al., 2022) and maintenance (Sanchez-Stern et al., 2023) cost and are rarely applicable in the large digital models typical of the AEC industry and tunnelling. Nevertheless, in small but critical parts of the model, they can play a significant role.

5 CONCLUSION AND FUTURE WORK

In this paper we discussed a method for ensuring that no matter how complex the *digital twin* of a tunnel may become, it is always possible to ensure that those parts of it that are of critical importance for a certain domain can be designed as *trusted elements*. This trust is based on formalised technical guidelines from the domain itself that provide both *semantic anchoring* and *type safety*. The advantages of this approach include the ability to structure the domain model as required by the expert while at the same time maintaining compliance to a guideline with possibly entirely different structure. In addition, data integration of different domain models can be robust and reliable when built around *trusted elements*. The same method can be utilized to ensure compliance with an Employers Information Requirement (EIR), making parts of the digital twin an *implementation of a formalised contract*. All of this should contribute to increased acceptance of the BIM method in the AEC industry and in the tunnelling sector.

Finally, the approach we presented here handles anchoring to information; in our future work we intend to extend this idea to the geometry of the tunnel, in order to produce *trusted geometry*.

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