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Review

Using Linked Building Data for managing temporary construction items

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ABSTRACT

For decades, the construction industry has experienced poor productivity due to challenges such as increasing project complexity and a fragmented project environment. Even though some technological innovations around Building Information Modeling (BIM) might have the potential to overcome these challenges, data integration across disciplines, companies and software solutions is yet to be solved entirely. Trending advancements try to enrich existing BIM data using Linked Data technologies to semantically describe the building information and facilitate data integration. By that, project data from different data sources is made available in an accessible format, so project participants can use it for their planning efforts.

In this paper we explore the use of Linked Building Data (LBD) on a specific use case to answer the question of how the planning of Temporary Construction Items (TCIs) can be improved by integrating data and automating the demand calculation. A literature review concludes that TCIs only experience little attention in the current planning of construction projects but have a critical impact on the outcome of a project. Thus, the objective of this paper is to develop standard ontologies to provide a semantically rich terminology of the data and to propose a framework for TCI consideration within a BIM based project delivery system. A prototype solution is developed, taking formwork as a TCI representative. The result is a process for automatically creating a TCI utilization plan that quantifies the precise time- and location-based on-site TCI demand by integrating data from BIM, Location-Based Scheduling (LBS) and TCI information. Based on the results of prototyping and findings from expert interviews, this research integrates the solution into the process of construction and finally proposes two implementation scenarios for the solution – one being based on the current industry situation and one exploring the future vision of a more integrated and decentralized project delivery in the construction industry.

1. Introduction

The construction industry falls behind the technological development of other industries and suffers from decades of neglecting investments in this area [1]. Barbosa et al. [1] state that this is the reason why poor productivity at a construction site is an omnipresent problem in almost all construction projects around the globe. According to Changali and v. Nieuwland [2], 98% of big construction projects are facing cost overruns, resulting in an average cost increase of 80%, and average time delays of 20 months. In comparison to the manufacturing industry, where productivity has been increased tremendously over the recent decades, the productivity rate in construction has hardly changed [3].

Recently, new technologies and methods are challenging the old traditions of building, trying to disrupt the industry. By developing a digital representation of the building, BIM greatly enhances the production planning as it allows to virtually build the building before the construction actually begins and constantly compare the dynamic model to the physical asset during construction. This is not only boosting the planning quality and transparency but also highly improves early decision making in order to establish more efficient construction processes [4]. In combination with Lean Construction methods such as the Location-Based Management System (LBMS), all resources on a construction site can be properly planned in order to increase construction performance [5–7]. Compared to conventional planning methods, LBMS can increase construction productivity on average by 37% due to higher transparency and production control with its spatiotemporal consideration of resources [8].

However, most technologies focus on the planning of Permanent Construction Items (PCIs), viz. all items that will become part of the building, as they immediately impact the project in regards to time, cost and quality. TCIs are often left out in this consideration [9]. Although

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improper use of these items can highly impact project performance, including productivity and safety, there is a lack of attention regarding proper planning and management of TCIs [10]. Handling TCIs consists of many, sometimes complex components and activities and in order to integrate TCIs into construction planning, a meta data layer (or ontology) is required to formally put the information into context and define relations, properties as well as classes. With Linked Data, an emerging technology is found that is capable of integrating different data from the construction process by adding an ontology layer and providing an innovative technology stack for information management and knowledge creation. Linked Data has already gained much attention in other industries and might be able to boost digitalization and information management in construction [11].

Motivated by the fact that technologies exist to improve construction productivity, this paper aims at finding and developing a potential solution to consider TCIs in the construction management process in a simple way. Facilitating this solution, we propose a TCI ontology that describes the management of TCIs and allows data integration for TCI information within a BIM-based project delivery using Linked Data technologies. The following recommendations are derived from this motivation:

(1) Semantically describe TCIs in terms of construction and site management in a TCI ontology
(2) Integrate TCI data into the context of BIM and Lean Construction using the LBS-methodology
(3) Use of a Linked Data environment, making data available for information sharing

Furthermore, the paper presents a framework for the application and adoption of the solution in the industry. The development of a prototype and its application on a case project subsequently proves the functionality of the framework. Lastly, two different scenarios of how the framework can be implemented in the process of construction, are explored.

2. Literature review

In this section, an analysis first demonstrates how TCIs are currently planned and managed. The analysis is built on statements in current literature and findings from expert interviews with professionals from the industry. Then, Linked Data technologies are introduced in order to reveal their potential for combining the four recommendations with the consideration of TCIs.

2.1. Handling TCIs on construction projects

"Temporary structures in construction are those structures that are erected and used to aid in the construction of permanent projects" [12,p. 292], such as formwork, scaffolding and supporting structures. Facilitating the construction process is the main purpose of TCIs, assigning them a primary impact on the outcome of construction projects while they receive only secondary attention in the project planning and management. Traditionally, these items highly impact construction in terms of time, cost, quality, safety, and efficiency due to their quantity, their labour intensive handling and the fact that they are reused many times during a construction project [10]. Nevertheless, TCI planning is still based on a preliminary and primitive estimation and the manual assessment of the construction manager on a daily basis, which is leading to several problems on site. To name a few, inefficient construction workflow, wasteful procuring as well as site and logistics management of TCIs [13].

Although commercial solutions like PERI CAD and DOKA Tipos try to integrate TCIs into BIM-based planning, there are some limitations to a full integration.

- Most commercial tools are product specific, creating a dependency towards one producer.
- Commercial tools for TCI planning use CAD-modeling which is labour and time intensive and is often considered too resourceful for these secondary and cheap elements [9].
- Commercial solutions are external tools with limited data integration. Design changes lead to the manual reconsideration of the whole TCI plan and little automation is possible. This hinders the further consideration as in time scheduling or site logistics management [14].

As the further process of developing a solution requires to select a representative of TCIs, formwork is chosen due to its appropriateness. Specifically for buildings with a high percentage of in-situ-concrete, formwork highly impacts the productivity as those elements are high in number, frequently moved around, used hundreds of times and directly affect value-adding activities on site [15,16]. According to Robert T. Ratay [17], 60% of time in formwork operations can be saved with a better planning, standardization and monitoring. Formwork is furthermore identified as the largest cost component of a building's structural frame [16,18]. Thus, an improvement of the formwork operation is highly correlated with a successful project outcome regarding cost and time.

In order to improve formwork operation and simultaneously boost productivity on site, TCIs first have to be integrated into current planning processes. Here, Teizer [19] informs that a construction project can only succeed with adequate planning and monitoring of all resources, also TCIs. However, as TCIs are barely integrated in BIM-based planning and modeling TCIs is labour and time intensive [9,20], a new solution is required that allows to plan TCIs in a simple way by integrating information about TCIs with existing BIM-data, comprising of the building model and the location-based schedule [21]. As commercial tools are not capable of solving the challenges in their entire context, a few academic efforts resulted in proposing alternative solutions. Kim and Teizer [22] and Hara et al. [23] focused on developing an automated process for designing scaffolding systems. [15] proposes a framework for the automatic generation of formwork consumption and Lee et al. [14] analyses the use of an existing formwork automation design software. Although all research is highly relevant to the apparent problem, they all focus on the design part of TCIs, based on a BIM model. This paper extends this consideration by focusing on the data integration part to ensure a flexible integration of different products across all relevant project stakeholders in the same process and tries to wrap it into an applicable framework for the construction industry.

First, the TCI information must be specified. In case of formwork, this can either be extracted from a specific product catalogue or defined in a default set of formwork elements. When all raw information is available, there is a need for data integration of both the geometry of the building and LBS information from BIM planning applications with data about TCIs. Then, a logic needs to be developed which automatically analyses the given geometric conditions of the building and allows to adequately derive the demand of TCIs with their spatiotemporal properties according to the geometry and the project schedule [24]. Lastly, this logic must be converted in a machine-readable and rule-based algorithm in order to automatically integrate the data of the BIM planning process [22].

A technology that supports the required data integration is found in Linked Data. Unlike current data generation within specialized and closed software environments, *"Linked Data technologies can provide an open and common environment for sharing, integrating and linking data from different domains and data sources"* [25,p. 1]. Thus, the following section introduces the concept of Linked Data and its potential for this research.

2.2. Linked data technologies in construction

The World Wide Web Consortium defines Linked Data as a *"collection* *of interrelated datasets on the Web"* [26]. Behind Linked Data lies the concept of creating a web of data, called semantic web, which, unlike the common web, is not only a network of documents but contains interconnected data, accessible through the web. Hereby, any kind of data can be structured with Linked Data technologies and published in the semantic web. By utilizing the Resource Description Framework (RDF) as a standard model for data interchange on the Web and RDF Schema (RDFS) as well as the Web Ontology Language (OWL), providing terminology and description logics, Linked Data technologies are able to describe data semantically meaningful and create object and property relations to link data. Linked Data can be stored in a data graph that consists of triples. Triples always comprise a subject, a predicate and an object. This constellation has the power to create classes and relations within a data model in order to create a interconnected data graph. The semantic query language SPARQL allows to retrieve and process the data of the data graph. Through relationships, different data can be connected and processed with Semantic Web tools, thus, creating a large-scale integration of data, usable for any kind of application [26]. According to Pauwels et al. [11], "*across industries, Linked Data is recognized as an important set of fundamental methods and technologies to address interoperability and information exchange challenges"* [11, p. 195]. It is further explained, that especially Linked Data features like the use of Uniform Resource Identifiers (URIs) for data identification and a standardized data format founded on standardized ontologies with a universal query and rule languages are crucial aspects for enhancing interoperability in an industry. The benefits of this approach in several industries have also motivated researchers in the construction industry to engage in Linked Data, resolving interoperability issues of common authoring systems in BIM-based construction [27]. Quinn et al. [28], for example, proposed a framework for Building Automation System (BAS) with Linked Data approach to connect Internet of Things (IoT) data with BIM, while Beach et al. [29] investigated the adoption of automated regulatory compliance checking in the built environment with focus on Linked Data technologies and Werbrouck et al. [30] applied Linked Data technologies on a "scan-to-BIM" process of existing buildings to semantically enrich the information and overcome current process challenges e.g. element classification. However, to properly use Linked Data technologies, a standard way of describing building data must be established across the construction industry. Hence, domain-specific, standardized and open ontologies have to be developed to improve collaboration across projects and disciplines [31].

The W3C - LBD community group and other researchers developed ontologies to describe building information in the context of Linked Data, such as the Building Topology Ontology (BOT) which describes basic elements in the scope of buildings and their relation to each other [32]. As these ontologies only give a general concept of describing a building, stakeholders in the industry are encouraged to extend or develop new ontologies, aiming to eventually describe all aspects concerning construction as standardized Linked Building Data. According to the LBD community group, the use of Linked Data in the construction industry shall lead to a decentralized and integrated information infrastructure. Zhang and Beetz [25] additionally highlight the importance of using an open data environment as Linked Data for sharing and linking construction data from different sources and domains. Integrating data in the construction industry is increasingly gaining attention and relevance and therefore, Linked Data technologies are proposed from several research projects to face this need [25,33,34]. Data, in this concept, is supposed to be created and owned by different stakeholders. For the purpose of collaboration within a project, data can be made accessible for authorized parties. In this way, integration of different disciplines is achieved by linking and providing specific data, rather than entire building models. Depending on the task in a construction project, the available datasets can be queried by applying a ruleset or a calculating algorithm in order to retrieve the required output data. By providing all required data from different stakeholders through the semantic web, engineering or construction management related tasks can be solved by simply querying and processing the project data across disciplines [35].

Hence, the use of Linked Building Data fits the previously identified requirements for considering TCIs in construction planning for several reasons. Firstly, it allows to integrate data from all kinds of domains and data-sources as long as an underlying ontology in RDF is used to describe the data. Secondly, RDF allows to enrich rich a data model with semantic relations between objects and properties and thus, retrieve implicit knowledge. Thirdly, it creates a common data environment and thereby, allows to link data from different construction disciplines. Then, the enriched building data can be processed with an algorithm that queries the required information to derive the TCI demand and additionally, as the data is stored in a standard and machine-readable format, the output data is suitable to be converted and further used for the purpose of data visualization. Lastly, Linked Data constitute an open data environment and therefore allows to be extended with new data from several sources, such as IoT-sensor or product catalogues.

Linked Building Data provides the required technologies to integrate TCI data into the existing BIM-based construction process, as proposed in the previous chapter. Thus, this paper aims at unlocking the value of LBD for the improvement of TCI planning and management in order to improve productivity on construction projects.

3. Proposed framework to consider TCIs in construction planning

Resulting from the recommendations in Section 1 and the correspondingliterature review, the following requirements are derived to guide the solution development and determine its purpose:

(a) Automatically evaluate the building model geometry and semantically enrich the data
(b) Identify required TCIs to each building element of the building model by applying the rule-based algorithm
(c) Link the building objects with their respective TCI demand to the building locations and schedule
(d) Develop a TCI utilization plan based on the building elements, their locations and schedule information
(e) Passive tci monitoring with progress data from the construction site
(f) Visualize data automatically and interactively for all relevant stakeholders

By reflecting on the determined purpose, the following framework (Fig. 1) for the innovative planning and management of TCIs is proposed. Here, it provides an overview of the whole data flow for the process of planning and managing formwork in construction. The scope of the solution includes the integration of the required raw data from BIM and LBS, provided by the VDC-Manager as well as the TCI data which may be based on a default dataset or on a specific product. Progress monitoring data from the construction site is also obtained, keeping the schedule data always up to date. All raw data is then combined in a Linked Data environment for data management purposes, where it can be processed to automatically create a TCI utilization plan by running a rule-based algorithm. This plan enables integrated TCI planning and includes information about when and where which type and quantity of temporary elements are needed on the construction site, as it combines the three data domains BIM, LBS and TCI data. Visualizing the TCI utilization plan in accordance to the stakeholder needs is eventually achieving the last purpose of the solution.

In the next sections, the developed solution is presented in detail. First, the ontologies, describing the different domain data, are introduced. Then, the previous findings are utilized to develop a functioning system architecture of the data environment for the proposed solution framework. Here, the various aspects of the solution are highlighted individually to gain a comprehensive understanding. The considerations and developed prototype is open source and can be found in the GitHub repository LBD-for-TCI.[1]

3.1. Ontologies for describing the context of planning and managing TCIs

Linked Data requires the data to be structured as in RDF format [26], and therefore, standardized existing or new ontologies have to be used to describe different domains [31]. In this case, ontologies must describe the context of a building and its comprising elements, the context of a location-based schedule as well as the context of formwork utilization for a construction project. Following the principles of Linked Data technologies, it is tried to reuse existing ontologies, already describing the regarded domain and create new classes and properties to extend existing ontologies beyond their contextual limitations.

3.1.1. The building topology ontology

BOT[2] was developed by Rasmussen et al. [36] in order to create a simple ontology for expressing the semantics of a building. BOT can be used for various domains as an underlying frame and extended with domain-specific information. Here, BOT is used to describe the basic building classes from a BIM model, e.g. walls are exported as *bot:Elements*, levels as *bot:Storeys*. BOT is then extended by the PROPS[3] and PRODUCT[4] ontologies of the W3C LBD Community Group to describe specific properties [34]. A wall, for instance, is defined as a subclass of a building element with the triple *product:Wall rdfs:subClassOf bot:Element*. A wall instance can then have specific property relations as *props:ElementID* or *props:length*. Bonduel et al. [37] demonstrates the benefits, BOT and the other ontologies provide for extracting and enriching building data. The following data excerpt shows how the information of a wall instance is expressed in RDF format, using the existing ontologies.

```
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#> .
@prefix bot: <https://w3id.org/bot#> .
@prefix inst: <http://test/resources/> .
@prefix props: <http://lbd.arch.rwth-aachen.de/props#> .
@prefix product: <http://lbd.arch.rwth-aachen.de/product#> .
@prefix lbs: <http://test/lbs/> .

inst:Wall_A
       a product:Wall, bot:Element ;
       bot:adjacentElement inst:Wall_B , inst:Wall_C ;
       props:elementID "641019" ;
       props:revitGUID "40cab1d1-1d6f-47a3-9afb-bd8c6300ff7e-0009c7fb" ;
       props:area 24.0 ;
       props:height 3.0 ;
       props:length 8.4 ;
       props:level "Level2" .
```

Listing 1 Data graph excerpt of BIM data.

3.1.2. LBS ontology

In contrast to the semantics of a building, there is no ontology available, that describes the scope of a location-based schedule. Thus, a new ontology that covers the required LBS-information to the extend of time, progress and location was developed with the exemplary namespace *http://test/lbs/*. An example of the resulting data graph is shown the following snippet.

```
inst:1000.0.146034 a bot:Element ;
       lbs:hasCompLoid "1000.0.146034" ;
       lbs:hasLocation "Lev2_locb(e)" ;
       lbs:haslocLoid "1000.0.354874" ;
       lbs:hasschedLoid "1000.0.321768" ;
       lbs:hastaskLoid "1000.0.358596" ;
       lbs:taskActualEndDate ""^^xsd:dateTime ;
       lbs:taskActualStartDate "2019-04-15"^^xsd:dateTime ;
       lbs:taskPlannedEndDate "2019-04-22"^^xsd:dateTime ;
       lbs:taskPlannedStartDate "2019-04-15"^^xsd:dateTime ;
       lbs:taskProgressCompletion "0.55"^^xsd:nonNegativeInteger ;
       lbs:taskProgressDate "2019-04-17"^^xsd:dateTime ;
       props:elementID "641019" ;
```

Listing 2: Data graph excerpt of LBS data.

3.1.3. TCI ontology

This ontology comprises the main knowledge for the developed solution as it represents the TCI information. As there is also no existing ontology, describing TCIs, a new ontology with namespace *https://w3id.org/lbs/tci#* is developed, expressing the context of TCIs. Although, the ontology was mainly developed to the extend of formwork, it is designed to cover the whole range of TCIs, and is therefore easily extendable with other items as scaffolding or supporting structures. This required the development of new classes, properties and their relational organization (see Fig. 2).

As shown in Fig. 2, the TCI ontology follows a hierarchical order and is able to distinguish between the two types of TCIs, *tci:ConfirmedProduct* and *tci:DefaultProduct*. A default product is a generic TCI set that is derived from existing products and is used to calculate the TCI utilization plan before the specific products are known, to get a first estimation of the TCI demand and the corresponding requirements for space and logistics. The default formwork set, used for the developed solution is a common steel frame/ wooden panel vertical formwork with several

[1] https://github.com/Alex-Schlachter27/LBD-for-TCI
[2] https://w3id.org/bot#
[3] http://lbd.arch.rwth-aachen.de/props#
[4] http://lbd.arch.rwth-aachen.de/product#

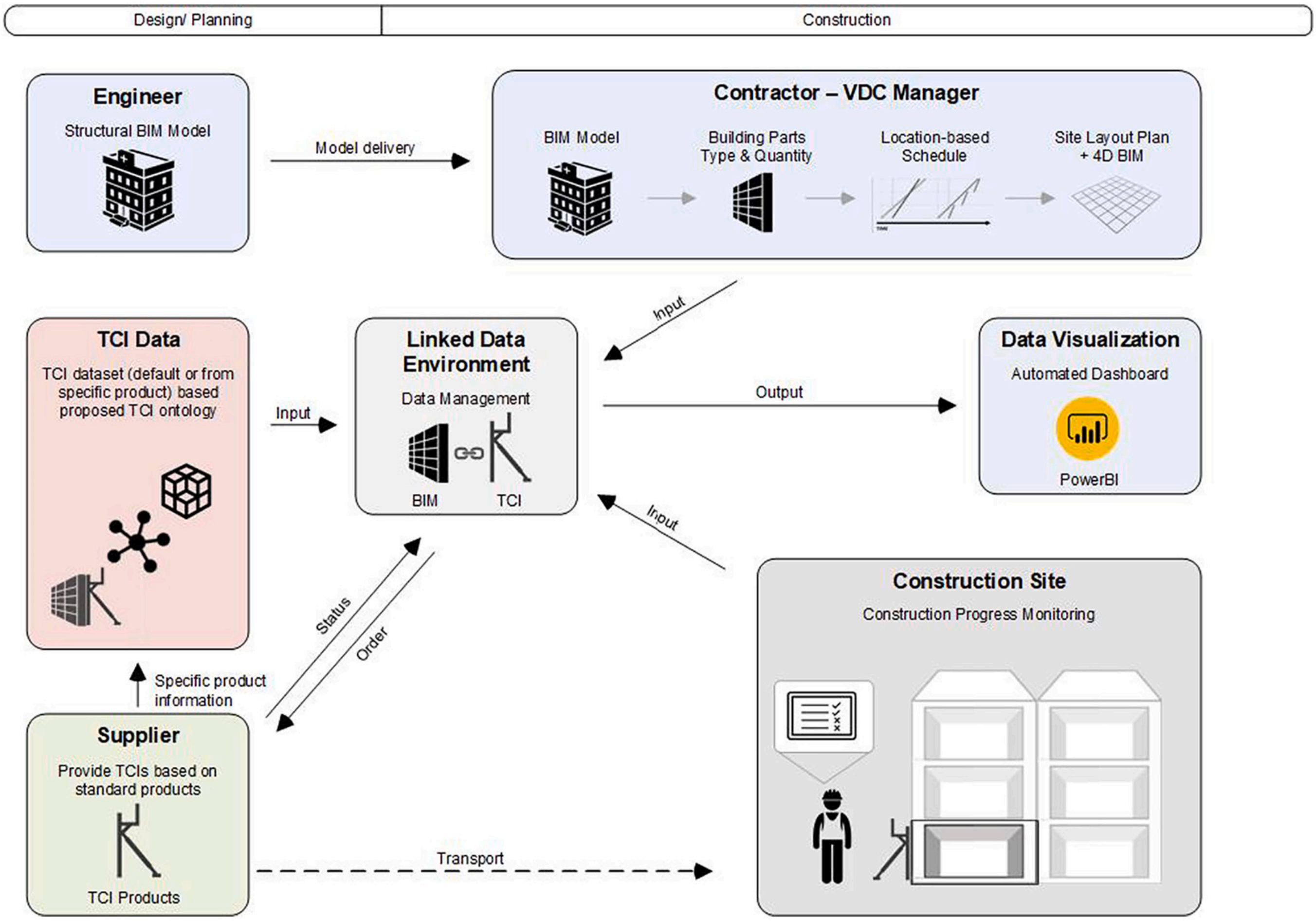


Fig. 1. Proposed Framework for the innovative TCI management.

auxiliary components, as shown in Fig. 3. As soon as a specific product is chosen, data of the confirmed product can be used, directly translated from a product catalogue into RDF format. Here, the formwork solution “MAXIMO MX15”[5] of the company PERI was chosen as an example.

3.2. System architecture

Having introduced the different ontologies that are used to express the context of the different data sources, this section is now exploring the developed solution on the basis of the system architecture (Fig. 4).

As revealed here, the solution consists of four sequential steps, covering the entire process of a data value chain from data generation to data visualization. These steps are derived from the big data value chain, which offers a structured approach for the data management in this solution, ensuring a holistic perspective on the complex process [38]. The following sections will examine those steps in detail.

3.2.1. Data sources and extraction

For the development of the proposed solution, four main datasets are needed to deliver the raw data. The raw data is then extracted with different methods and converted into individual RDF graphs. The model data from a Revit model is extracted with the visual-scripting environment Dynamo[6] and provides information about the building elements. The LBS data with information about the planned construction tasks is extracted from a location-based schedule, created in VICO Office,[7] a 4D and 5D planning software. It is extracted and converted into RDF triplets, using a Python program. The LBS data can be further extended with updated progress information. Here, the progress monitoring feature of the application Exicute[8] is used to update the schedule according to the construction progress. Depending on the project advancement, the data sources are either complemented with a default set of formwork or a specific product, as described earlier. The developed default set can be simply integrated as a RDF graph into the system architecture, while a new product, first has to be converted into RDF format by using the TCI ontology.

3.2.2. Data management

The individual datagraphs now contain sufficient information to quantify the TCI demand for the given building model data of the project. However, in order to harness the information, the data first has to be stored in the Linked Data environment, where it can be accessed and processed by a calculation program, using the semantic ontologies, the data is structured with. Generally, Linked Data is stored in a database called triple store which is accessible through a simple HTTP request. In this case, the triple store Jena Fuseki was utilized. Data in a triple store can either be queried directly through the interface, using the SPARQL query language or for more advanced data processing, the data can be accessed through a SPARQL query over HTTP request on the SPARQL

[5] https://www.peri.com/brochures/jcr:af4fc9a6-1bca-40ef-ba82-849c803bd562/MAXIMO-Panel-Formwork.pdf
[6] https://dynamobim.org/
[7] https://www.construsoft.com/bim-software/vico-office
[8] https://exicute.dk/tidsstyring/exicute-app/

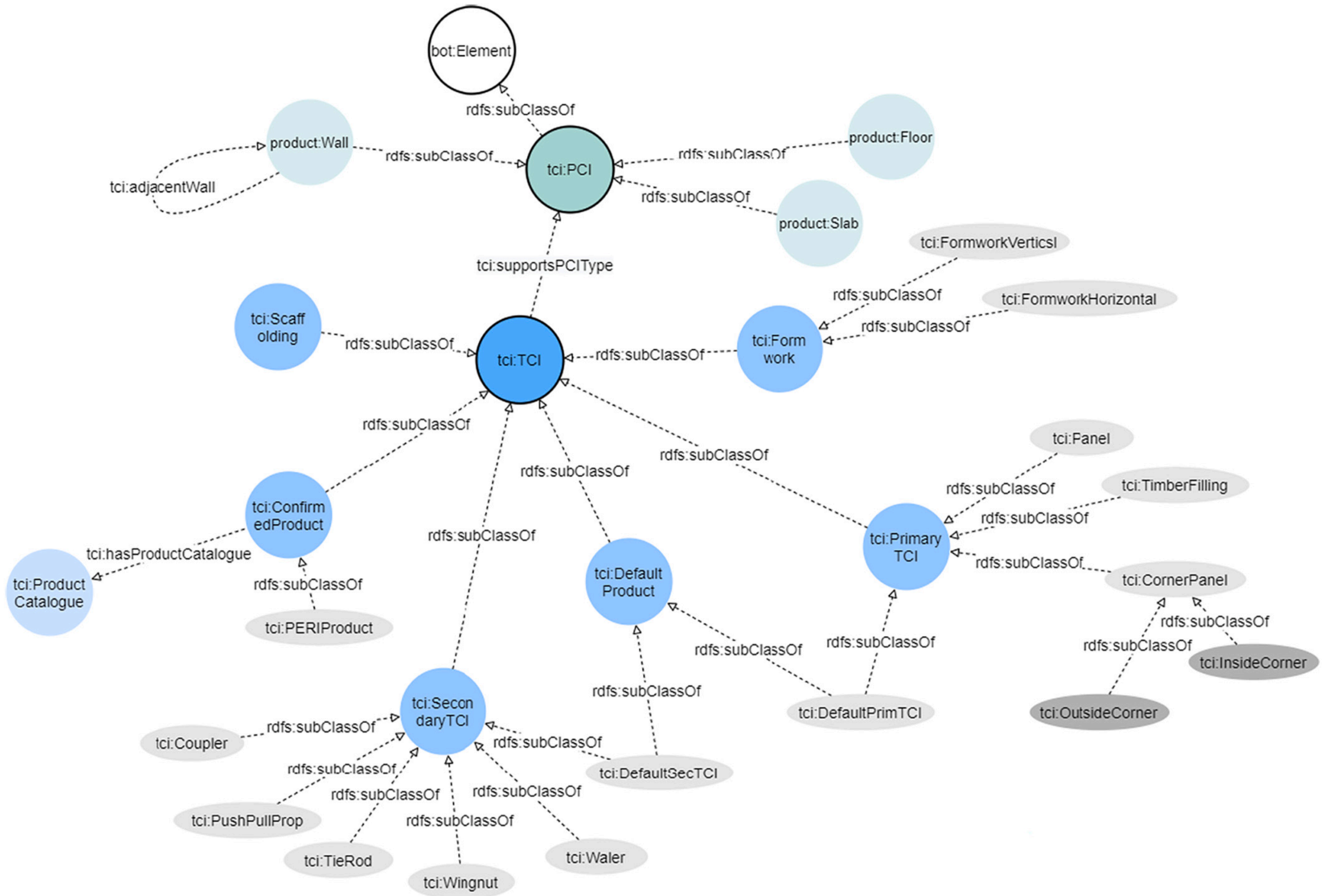


Fig. 2. Class hierarchy of the TCI ontology.

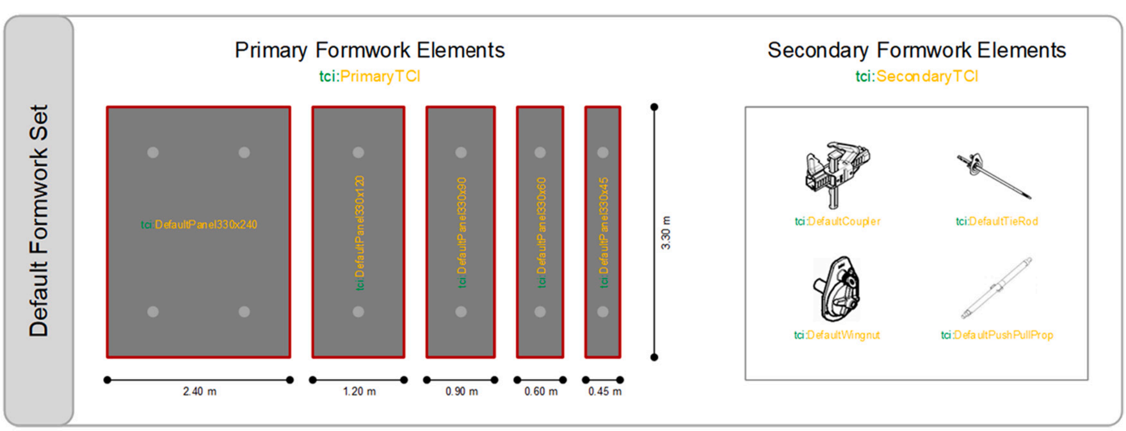


Fig. 3. Default Set of Formwork.

endpoint URL, which allows to receive queried data, process it in a program and write it back to the triple store [39]. The latter working principle is utilized in the third step of the solution and is explored in the next section. The following two queries were utilized to retrieve the input data for the algorithm regarding BIM and TCI data.

```
SELECT * WHERE {
   ?s a product:Wall ;
      props:elementID ?ID ;
      props:length ?length ; props:angle ?angle .
   OPTIONAL { ?s bot:adjacentElement ?adjacentElements } }
```

```
SELECT * WHERE {
   ?TCI a ?tciSet, tci:Panel ;
      props:length ?length ; props:height ?height ;
      props:area ?area ; props:width ?width ;
      props:weight ?weight . }
```

3.2.3. Data processing and querying

In order to generate a TCI utilization plan, the TCI demand of each wall instance has to be first calculated by applying a rule-based calculation tool, linking the model and TCI data. Then the schedule information must be added to integrate the time and location dimension. As SPARQL queries are quite limited in their functionality, a simple formwork calculation algorithm was developed in Javascript for advanced data processing. For every in-situ wall instance, the tool calculates the quantities of the formwork elements, following the consecutive steps of Fig. 5.

This simple calculation logic is validated by a formwork provider and aligned to the standard process of quantifying formwork elements for simple wall structures. Apart of this logic, the algorithm considers wall adjacency and their angle to each other to formulate a logic that also calculates corner elements. The developed calculation tool serves as a proof of concept for an automatic TCI planning solution and does not aim at creating an advanced formwork calculation program. More complex applications, e.g. for horizontal formwork would require more sophisticated algorithms that solve a two dimensional formwork allocation, for instance by considering the bin packing problem [40]. This solution rather provides a methodology and demonstrates the ability to describe and combine different data domains in BIM-based planning to automate and integrate the process of planning TCIs. Thus, the rule-based algorithm is kept as simple as possible and only covers the calculation of vertical formwork elements on simple wall structures with L-corners. To cover complex wall structures, a more sophisticated algorithm or manual analysis must supplement this process.

The combined data graph now contains all information to generate a time- and location-based TCI utilization plan that is continuously updated with progress information from the construction site, so the construction manager always knows when and where which type and quantity of formwork elements are needed. After writing the result of the program back to the triple store, the individual datasets are combined into one rich data graph, forming the basis for the TCI utilization plan. The model and LBS data are combined through their common ID code “ElementID”, identifying each wall instance. Considering only the presentation of the raw data, a SPARQL query can be used to query the combined data graph and display the basic information of the TCI utilization. The resulting table is shown in Fig. 6, containing all information and the respective data source.

3.2.4. Data visualization

More advanced data visualization is used to distribute the right information to the specific target group in the most convenient and accessible way. Hereby, aspects of Ratajczak et al. [41] are taken into consideration, as the paper proposes an interactive and automatic

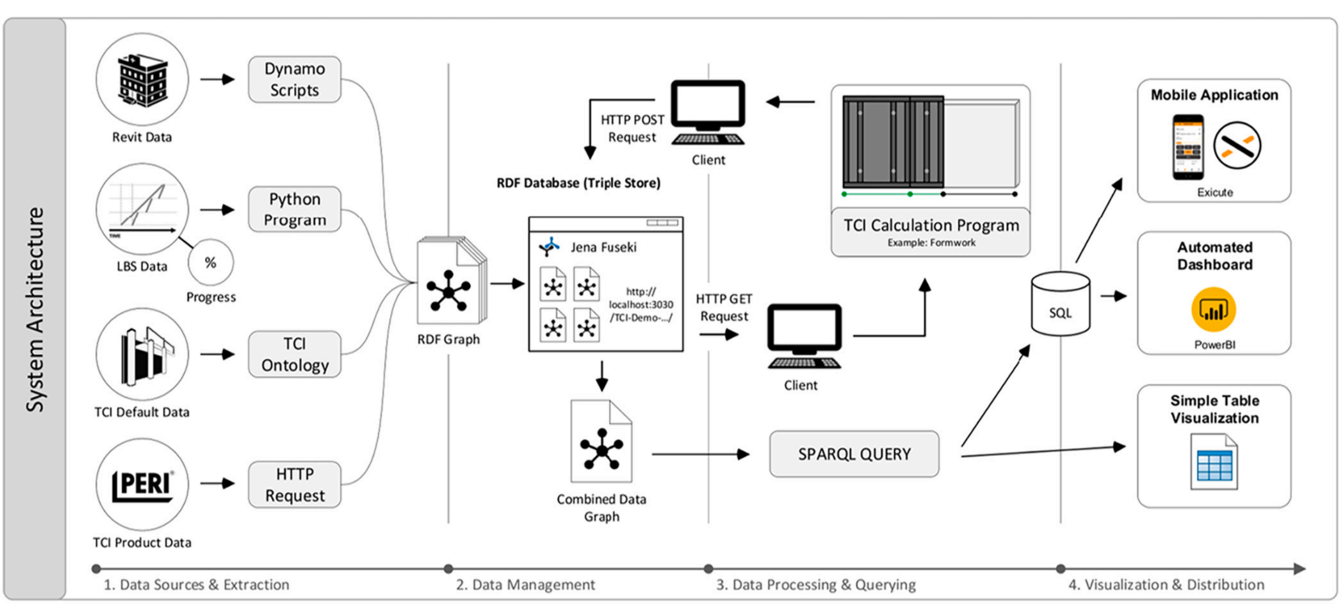


Fig. 4. System architecture of the proposed solution.

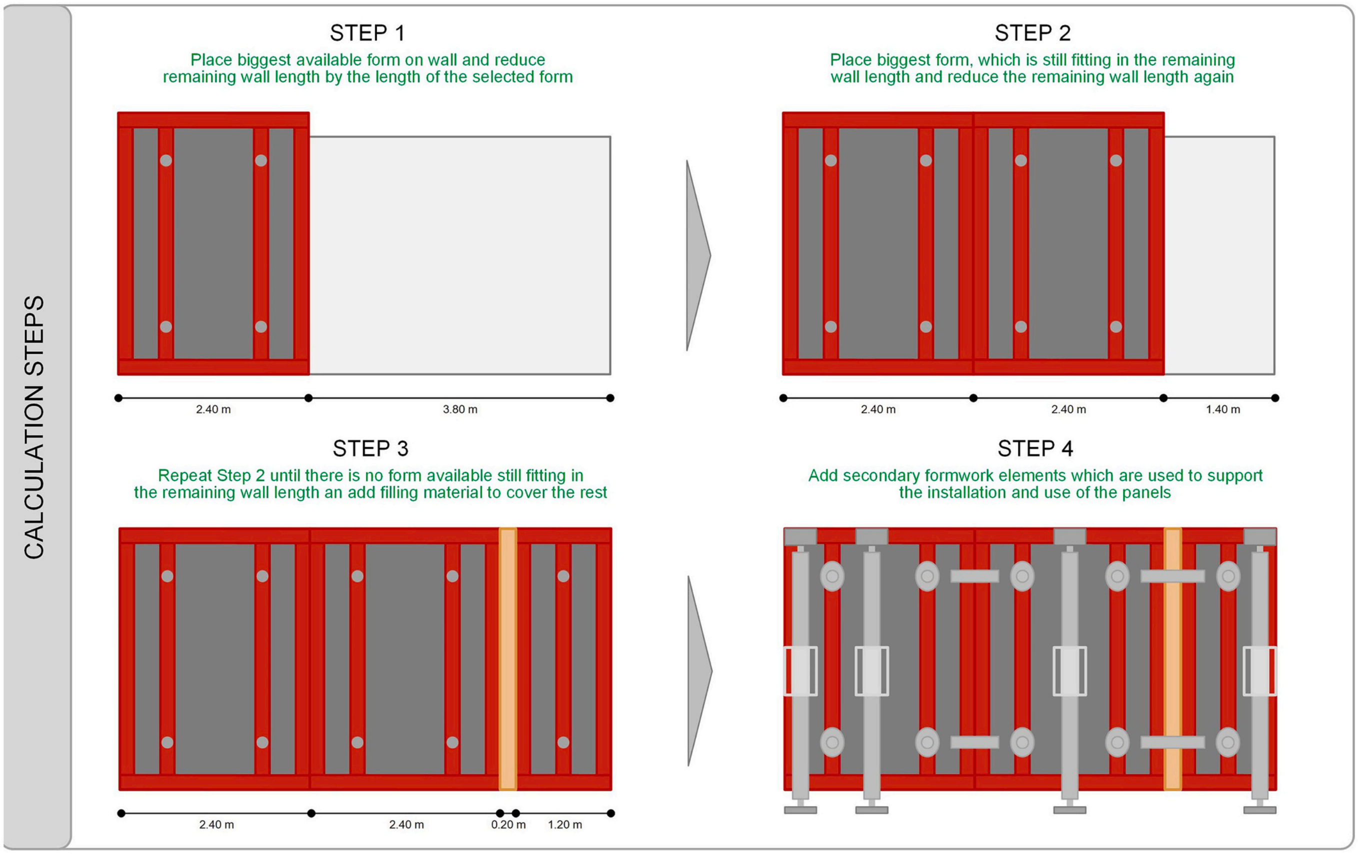


Fig. 5. Consecutive steps of the formwork calculation.

dashboard application that fits well to the purpose of the proposed solution. Since the output data in the proposed solution is stored as RDF-triples in an accessible triple store, there are several options on how to visualize the data. For the proposed solution, two tools are explored that cover data visualization and distribution to all relevant stakeholders. The first tool is a PowerBI dashboard that is directly linked to the data. As a second visualization tool, a new tab in the Exicute application is intended to display the TCI demand for each specific construction task. The former aims at visualizing the data for the management perspective, giving a general overview of the TCI utilization as well as cost information and important Key Performance Indicators (KPIs), the latter at providing the contractor on site with updated TCI information for each upcoming construction task.

In order to use the data in both visualization tools, a data conversion

Revit		TCI					VICO		Exicute			
ElementID	props: length	Primary Formwork	Count	props: length	Secondary Formwork	Count	taskPlanned StartDate	taskPlanned EndDate	taskProgress Date	taskProgress Completion	taskActual StartDate	taskActual EndDate
string	*m*	*string*	*integer*	*m*	*string*	*integer*	*DateTime*	*DateTime*	*DateTime*	*%*	*DateTime*	*DateTime*
585914	6.20	Default Panel 330x240	4	2.40	Default Wingnut	12	2019-04-04 11:00	2019-04-08 07:28	2019-04-06 11:00	70.0	2019-04-04 11:00	NULL
		Default Panel 330x120	2	1.20	Default Tie Rod	12						
		Wooden filling material	2	0.20	Default Coupler	16						
					Default PushPull Prop	6						
					Default Waler	0						
644734	6.20	Default Panel 330x240	4	2.40	Default Wingnut	12	2019-04-08 07:28	2019-04-09 11:57	2019-04-08 16:00	100.0	2019-04-08 11:00	2019-04-08 16:00
		Default Panel 330x120	2	1.20	Default Tie Rod	12						
		Wooden filling material	2	0.20	Default Coupler	16						
					Default PushPull Prop	6						
					Default Waler	0						

Fig. 6. Raw TCI utilization plan in table format.

to Structured Query Language (SQL) is required. This is being done with a Javascript program that accesses the triple store, receives the required data with a SPARQL query, converts the data into a SQL query and writes it directly to an existing SQL database. In this process, several SQL tables are created which represent the output data of the TCI utilization plan (see Fig. 6) and are used to apply the data to the selected visualization tools. This additional step is necessary as the triple store Jena Fuseki does not support the ODBC protocol, to directly link a triple store to PowerBI. Other triple stores as Virtuoso, however, support that direct link in order to visualize SPARQL queries in PowerBI [42]. The resulting visualization tools are presented in the next section, where the functionality of the proposed solution is tested on a real case project.

4. Proof of concept - application on case project

After creating the system architecture, the next step of prototyping a solution is the application with real data. Therefore, a case project was chosen to proof the concept of the solution and its functionality for a big scale construction project. Findings of this process will later help to reflect on its current level of development.

The case project is a public construction project of a new healthcare science faculty, in which in-situ concrete walls are applied as structural elements for the lower levels. Here, the developed solution is applied to automatically plan the formwork demand of the project and develop a time and location-based TCI utilization plan to efficiently manage the

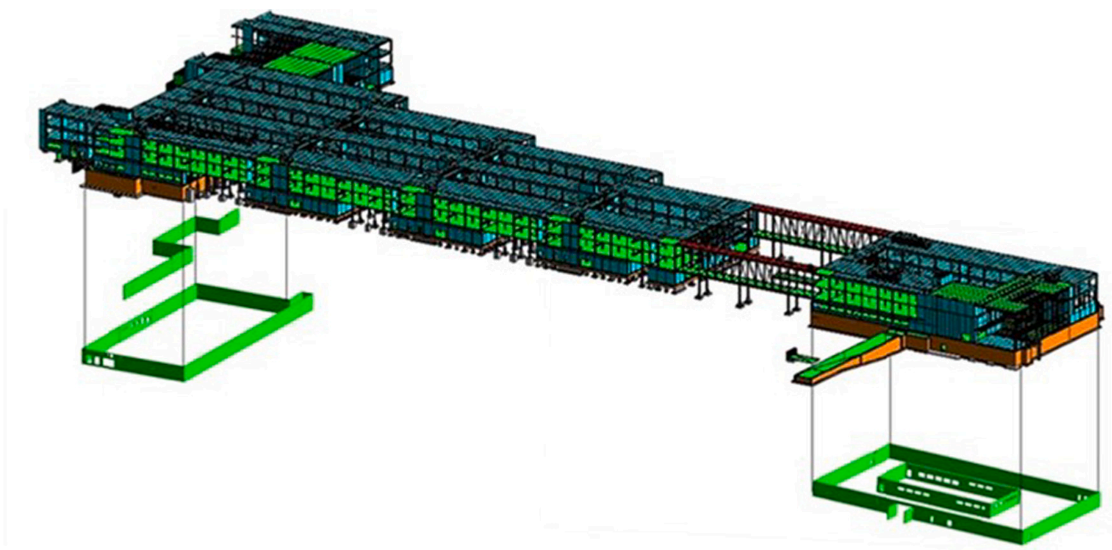
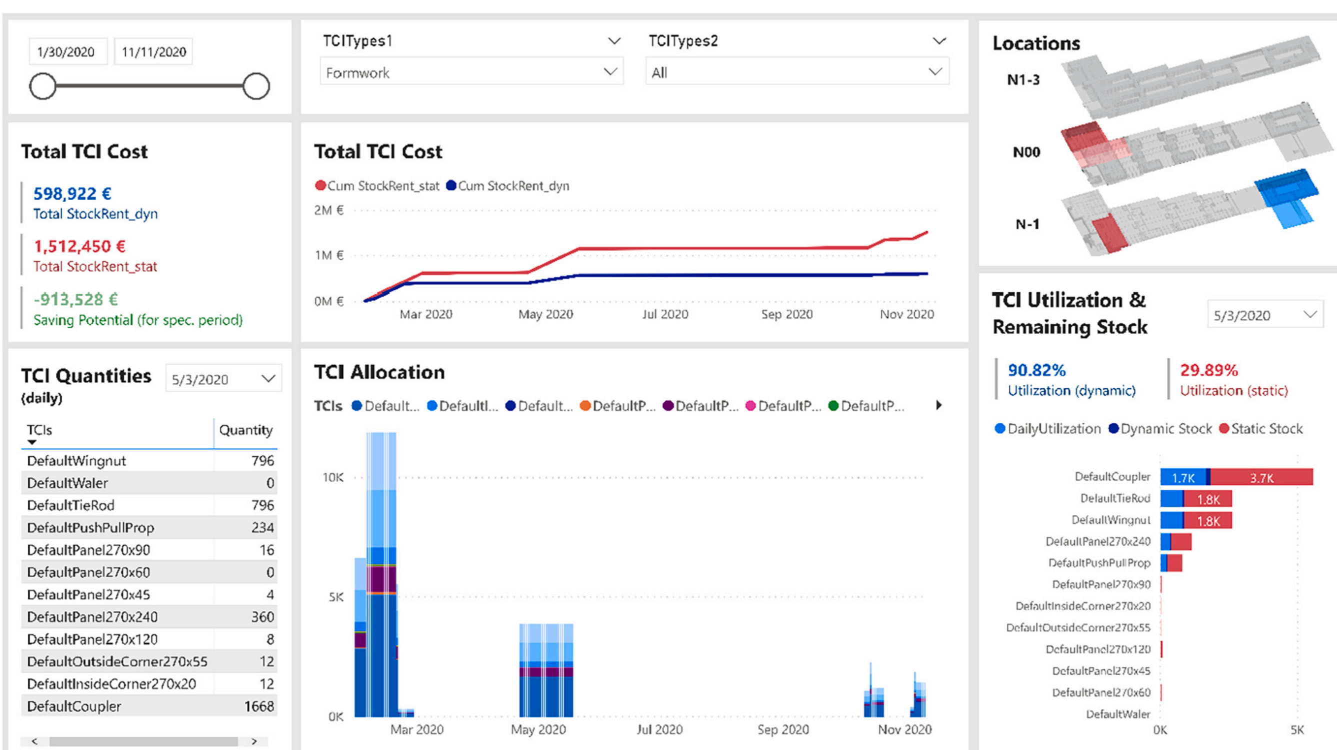


Fig. 7. Revit model of the case project with the regarded in-situ walls.



TCIs	Quantity
DefaultWingnut	796
DefaultWaler	0
DefaultTieRod	796
DefaultPushPullProp	234
DefaultPanel270x90	16
DefaultPanel270x60	0
DefaultPanel270x45	4
DefaultPanel270x240	360
DefaultPanel270x120	8
DefaultOutsideCorner270x55	12
DefaultInsideCorner270x20	12
DefaultCoupler	1668

Fig. 8. Dashboard with the projects the TCI utilization.

items on site. The required data came from the structural model in Revit (see Fig. 7), a location-based schedule from VICO Office and the default set of formwork elements for providing the TCI data.

Except for some minor adjustments, the developed system architecture of Section 3.2 worked well with the provided data and going through the different steps of the solution, the TCI utilization plan for the case project was created automatically. Based on the regarded insitu walls, the TCI utilization plan contains the required TCI quantities that are needed to construct the walls. For better insights, this knowledge is then visualized in an interactive dashboard. The resulting dashboard structures the project data into four pages - *Project Overview, TCIs/PCIs, TCI Utilization and TCI Tasks*. The following list provides all the features, the new dashboard incorporates to visualize the TCI utilization plan while Fig. 8 illustrates the main page (*TCI Utilization*) of the dashboard. The full dashboard can be found in the GitHub repository, mentioned earlier.

- Project overview and dashboard content
- Exploded building view of building model divided by its location management system allowing to select specific locations
- Time slicer to specify the regarded period or specific date
- Selection tool to specify the TCI type to be reviewed in the dashboard
- TCI allocation graph showing the TCI utilization on a time axis
- Comparison between static stock and dynamic stock (Static stock is calculated with the peak amount of TCI demand in the project and dynamic stock is representing the actual TCI demand with a buffer of 10%, that is enabled with the proposed solution)
- Graph showing an accumulated cost comparison of TCIs on the construction site, based on the comparison between the static stock and dynamic stock
- List of all TCIs used in the project
- List of all PCIs which are modelled in the project and supported by the TCIs during the construction activities
- Gantt-Diagram, showing each task and its linked TCI information as well as the status of task completion (if received from the construction site)

In the central position, the dashboard provides an overview of the TCI utilization over time for the whole construction period. It takes into account each day, the tasks that are scheduled that day, the building elements that this task contains as well as the calculated TCI demand of each building element. Thus, it gives a clear overview of what TCIs are needed on each project day on the construction site. As the solution is also built on a location-based schedule, a location filter on the upper right side of the dashboard allows two either select a location to receive the tasks and TCI quantities for this specific location or the user can select one specific day in order to visualize the TCI quantities of this day as well as where the tasks of this day are located on site. On the lower left side, a simple table also reveals the TCI quantities of each day, if the user simply wants to check what items are needed on a specific day.

A further consideration that reveals a measurable benefit of the proposed solution is the comparison between a static and dynamic stock of formwork elements. The static stock represents the current practice in the construction industry, where the site manager is ordering formwork elements for the whole period of construction based on his estimation and with the intention to cover the estimated peak amount of formwork demand plus a contingency buffer. This approach leads to high quantities of formwork elements on site, requiring avoidable rent and transportation as well as using up valuable space on the construction site. In contrast, the proposed solution enables a dynamic stock with a just-in-time delivery approach, where the communication with the TCI provider is enhanced and formwork elements are ordered and delivered as they are needed on site. This results in a much lower number of formwork elements on site, saving money, space and time. This comparison is shown in three different parts of the dashboard. On the lower right side, the dashboard contains the proportionate TCI utilization rate of a specific date, considering both the static (red) and dynamic (dark blue) stock approach. Secondly, a cost comparison over time, in the upper center of the dashboard, shows the different cost development of both stock approaches, clearly identifying lower total costs of renting formwork elements with the dynamic approach. Just left to this, another visual presents the total costs of both approaches for the whole project as well as the potential savings in rent, a construction site could generate by implementing such a dynamic stock for formwork elements.

In conclusion, the developed dashboard is a powerful tool for visualizing the TCI utilization plan. It clearly targets the management perspective of a contractor who is receiving an easily understandable and visually appealing presentation of location and time-based TCI information in order to better plan and manage the construction site. In addition, a new tab in the mobile application Exicute was outlined to address the needs of the construction workers, who require task-based TCI information on site. In the app, a construction worker can select a specific task by time or/and location and display valuable information about the formwork utilization as the quantities of formwork elements for the reviewed task, serving as a checklist for the workers, suitable for the use on site. Such a checklist can also serve as a monitoring tool and feedback from the construction site about the progress and whether all formwork components are installed as planned. This would further

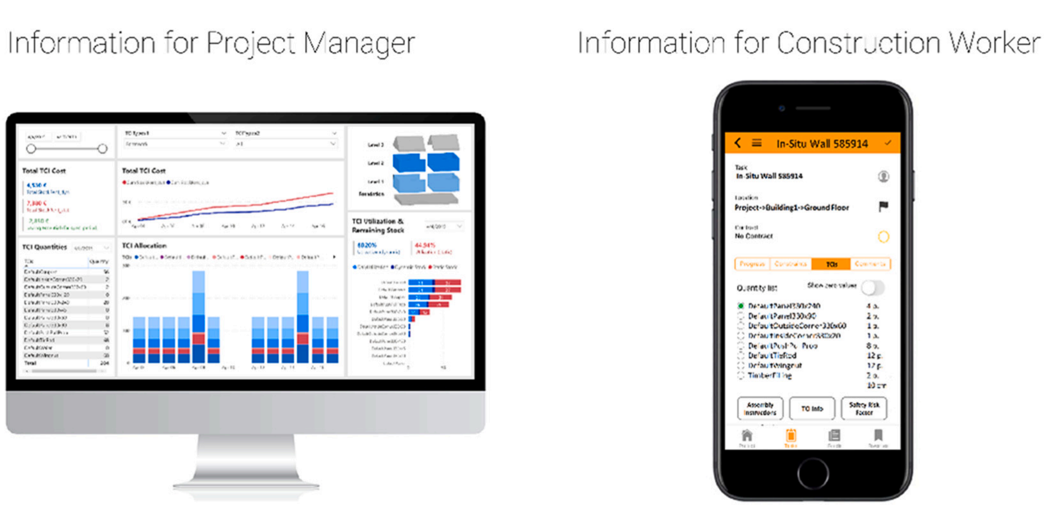


Fig. 9. Tools for data visualization and distribution to relevant stakeholders.

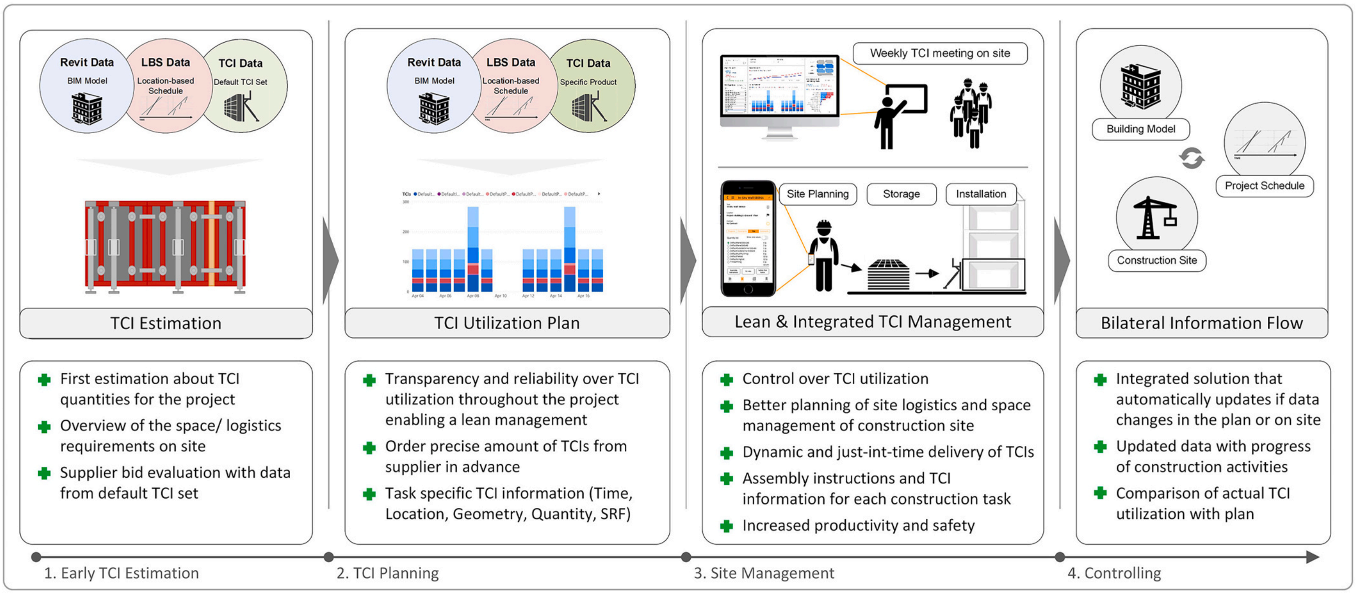


Fig. 10. Process integration of the proposed solution and added value.

validate the dynamic stock as the feedback data can be compared to the planned stock number. Fig. 9 presents both tools for visualizing and distributing the generated data to add value to the construction project.

In order to evaluate the value of the proposed solution for the construction industry, expert interviews with 12 construction professionals from different disciplines as contractors, engineering consultants, clients and manufacturers were conducted. The findings of the interviews were also used to conceptualize implementation scenarios for the solution and contribute to conclusion and recommendations for further research (Anonymous participants, personal interview, 21.04. - 01.08.2020). Generally, all interviewees agreed that the solution provides an innovative and valuable approach on tackling an existing problem in practice. Standardizing the construction data semantics with ontologies that can be used across the industry was considered a very important advantage of this approach as it ensure data integrity and usability in practice when integrating information from different stakeholders. Most of the interviewees also highlighted that data integration from existing BIM data with TCI data from product catalogues is targeting a niche in construction which is not yet fully optimized. Furthermore, the automatic creation of a dashboard from the calculated TCI utilization plan was considered a very useful tool to provide the project with important information regarding TCIs, also in early design phases for construction management. However, it was also stated by several interviewees that the solution has to be tested more thoroughly on a construction project to grasp the whole complexity of TCI planning. Then, the calculation algorithm has to be optimized - potentially by manufacturers as they already have the know-how and manufacturers have to be encouraged to contribute to such a solution by providing their product information using the TCI ontology.

5. Implementation scenarios

Based on the current state of the developed prototype solution, this section revisits and tries to fulfill the research motivation by deriving a process integration of the proposed solution. The first part is concentrating on how the solution can be implemented in the current project delivery practice of construction projects in order to determine whether the solution is able to improve productivity issues on site. Then, a further consideration highlights a future scenario in which the full potential of the solution can be unlocked.

5.1. Lean and integrated process of planning and managing TCIs

The research motivation aimed at utilizing existing technologies to properly integrate TCIs into construction planning and management, which shall lead to a lean management process of temporary construction items with an automated and data-driven information flow between planning and construction to improve productivity on site. By taking into account both the initially defined purpose and the final result of the proposed solution, the following process captures the solution's different areas of utilization in a construction project as well as the generated value (green plus signs). The given process assumes that the calculated TCI quantities are correct.

The proposed process integration in Fig. 10 is divided into four different steps, representing different tasks in a construction project, where the developed solution can be applied to create value. The first step takes place in the early project development, where a contractor could, based on a default TCI set, already calculate a first estimation of the TCI quantities for the project. Although, this step does not refer to real product information, calculating the TCI demand with a standardized set of default elements provides an important overview of space and logistics requirements early in a project, enabling to better plan the construction site layout and workflow. Furthermore, already having a reference to the TCI demand allows to later evaluate incoming offers from TCI providers by comparing it to the quantities of the default TCI estimation. As soon as a specific TCI provider is selected in a project, the default TCI set can be replaced by specific product information in order to automatically create a TCI utilization plan that mirrors exactly the utilization of the items on the construction site. This is done in the second step of the process integration, called TCI planning, in which task-specific TCI information about time, location, geometry, quantity and safety risk is generated to add value to construction. The main benefit in this step is the transparency and reliability it provides regarding the TCI utilization throughout the project. Moreover, the TCI utilization plan enables the contractor to order the precise number of TCIs from the supplier in advance, ensuring an efficient production flow.

While the first two steps mainly concern the planning part, the third step, *Site Management*, reveals the potential of using the solution directly on site. By providing two options for the visualization, the solution addresses all needs of the stakeholder who require information from the TCI utilization plan. The management level of the site contractor can review the dashboard to get an overview and gain control over the TCI utilization on site over time and by location. Hence, the management level could arrange a weekly TCI meeting with the foremen, where they get instructed regarding the TCI utilization. Consequently, when executing the planned tasks, the construction workers can retrieve the task-specific TCI information with the mobile application. Besides a checklist, which quantities of TCIs have to be installed for the specific construction activity, the mobile application can further display assembly instruction from the supplier, how to safely and accurately install, use and dismantle the items.

Applying the developed solution on site adds value to construction as it provides transparency and control over the TCI utilization. This, further leads to a better planning of the site logistics and space management, increasing the efficiency of the construction workflows. By enhancing the collaboration with the TCI provider and sharing the precise number of TCI demand on site, a dynamic stock consideration with just-in-time delivery of TCIs is enabled. This will not only reduce the amount of rent, as fewer items are stored on site but first and foremost reduce the waste of valuable storage area on site and enables lean management of TCIs. By also addressing the safety aspect with adding assembly instructions as well as the safety risk factor for each construction task and generally providing transparency of which items are when where, the solution is able to also increase the safety on a construction site. Finally, the fourth step of the proposed process integration, *Controlling*, is generating benefits from the interlinked system architecture of the proposed solution. The solution enables bilateral information flow between planning and construction. On the one hand, changes in the building model or the location-based schedule are directly affecting and updating the TCI utilization plan. On the other hand, changes on site as delays or other not foreseen circumstances can directly be integrated into the data model by including in the information into the progress monitoring. Hence, the provided data of the solution is always up to date according to changes in design as well as the progress of the construction activities. Providing knowledge of all TCIs that are planned for the task, the site manager can perform a comparison of the actual TCI utilization with the plan as the construction workers would document the use of TCIs for each activity.

Having established and explained the process integration for the developed prototype in the current project delivery system, this paper has fulfilled the initial motivation by developing a functioning solution for the use case of formwork that takes into account both the recommendations from Section 1 as well as the determined purpose of the solution from Section 3 and contributes with an increase of productivity on the construction site. The theoretical benefits of the solution has also been verified by several construction professionals that participated in expert interviews regarding the proposed solution. Since this solution automatically evaluates the elements and geometry of the building model and enriches the data model semantically with implicit knowledge, any algorithm could be applied to calculate TCI quantities that are based on the geometry data. By classifying the explicit building data with RDF, geometrical operations can be applied to specific element types. An example provides Zgang [43], demonstrating geometry operations in the context of requirement checking. Thus, in the context of TCI, even more complex TCIs as scaffolding can be considered with this framework by applying an algorithm as proposed by Kim and Teizer [22]. The BIM data as well as the TCI quantities are then enriched in a data model and can be further used for site management, as demonstrated in Section 4.

However, this process integration is based on the current state of the construction industry, where the full potential of Linked Data technologies cannot be unlocked due to the technological underdevelopment of the construction industry. This refers primarily to the fact, that most construction stakeholder are not able to simply share their data as Linked Data to a data model, from which it can be further processed. Therefore, the current solution, as proposed with the system architecture in Fig. 4, requires an entity that collects the required data, converts it to Linked Data and stores in the project's data model, where the algorithm can then generate the TCI utilization plan. Thus, the proposed process integration is regarded as the ideal current scenario. An alternative way, how Linked Data can add even more value to the whole construction industry, is outlined in the following section. This second scenario for implementing the proposed solution aims at exploring a future vision of how the developed solution can disrupt the construction industry by introducing the Linked Data approach to develop a new project delivery system.

5.2. Ideal future scenario with a new project delivery system (linked data vision)

The state of art report characterized the current industry as highly fragmented [44] and although the projects and construction sites become more and more complex [1], the conservative industry is lacking disruptive developments for decades, leaving behind a highly underdeveloped and underperforming construction industry [3]. In this context, this paper envisions a new project delivery system with an open project environment, aiming at becoming the needed disruptive change for the industry. This system would be based on a data-driven approach, where data is generated decentralized by the different stakeholders in order to develop a rich and central data model, which is used to derive and calculate new data and further develop the construction project. According to Zhang and Beetz [25], Linked Data provides the technological capabilities to put such a vision into practice, leveraging the whole industry to become a more integrated and well-functioning ecosystem. Rasmussen [35] labeled this vision *"the vision of a decentralized, distributed AEC information infrastructure using Linked Building Data technologies"* [35, p.1]. Here, the vision aims to create a *"semantically-rich integrated"* [35, p.1] model to which data from different disciplines can be integrated, allowing, for example, to perform engineering tasks for the project by simply applying standard equations on the data model to produce an output. With that, design and engineering work is first approached in a decentralized manner and then combined centrally to create value for the project.

So far, which is also exemplified by the prior example, Linked Building Data has mainly found implementation for the design phase of construction. As described by Pauwels et al. [11], linking decentralized data from different disciplines to a central model by using Linked Data allows to maintain the discipline-oriented characteristic of design work and simultaneously enables to overcome interoperability issues and foster an integrated design development. However, Pauwels et al. [11] further acknowledge that having a wide stakeholder range, generating specialized information in a construction project occurs not only in design but also in *"[...] planning, construction and maintenance of the built environment"* [11, p.181]. Thus, this situation is affecting the whole life cycle of a building and requires close collaboration between the stakeholders and standardized data integration from the heterogeneous domains and formats. Therefore, this chapter aims at developing a new framework for the proposed solution that is aligned to the Linked Data vision in order to unlock the full potential of Linked Data in construction, both for the TCI integration and for other processes in construction industry.

The framework comprises a decentralized project delivery where all stakeholders generate and own their data, but provide specific data as a consultancy service in the linked project environment where the individual datasets are integrated into a central data model. From there, the enriched data model allows to distribute specific data to authorized stakeholders in order to further develop the project and derive new data. The envisioned framework can be utilized to outsource the calculation engine of the TCI quantification towards the specialized supplier who will provide more advanced and product-specific algorithms to calculate the TCI demand and link it to the BIM data. Since this solution only integrates the results to the data model, it incorporates a potential beyond the application of TCI planning and management. Thus, all discipline-oriented tasks in a project can be managed decentralized and

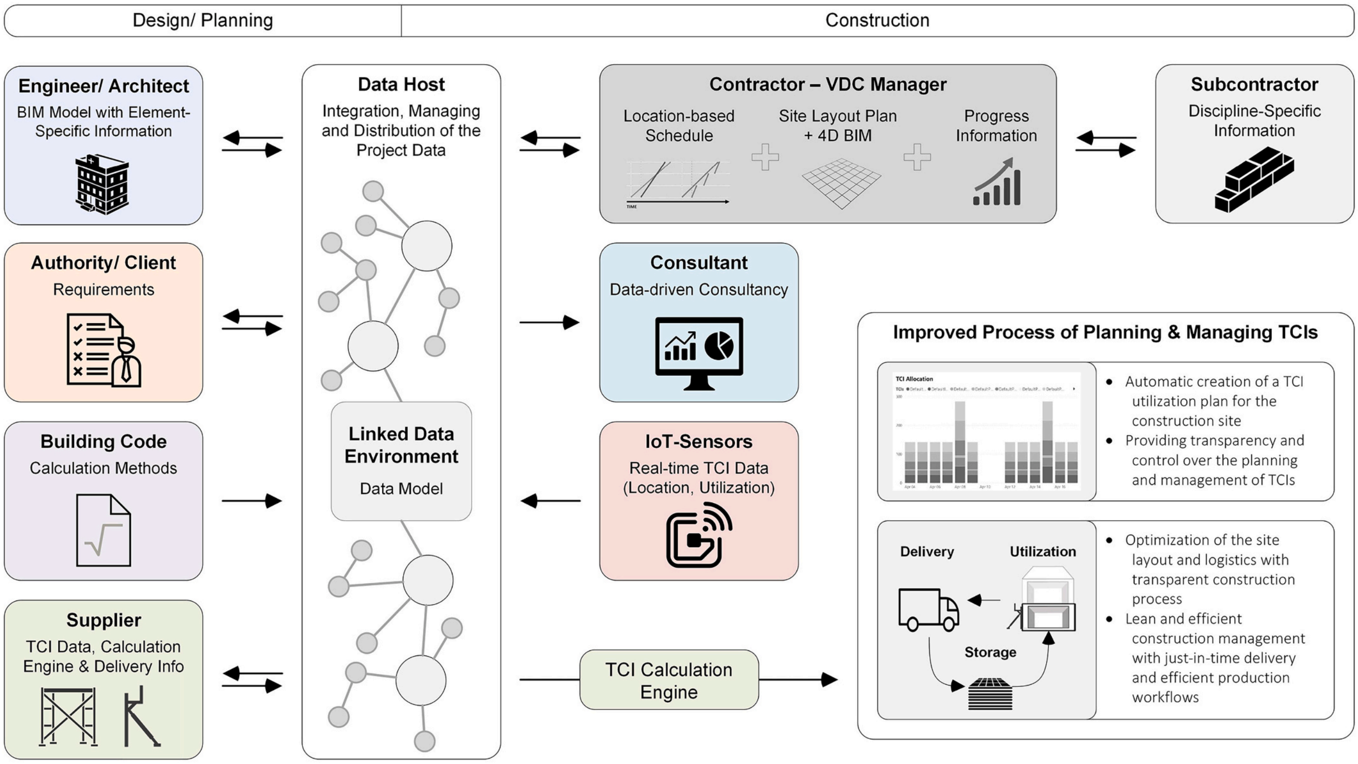


Fig. 11. New solution framework in the ideal future scenario.

the results are later integrated into the data model.

A research organization in the Netherlands already proposed such a decentralized system where intelligent online systems (BIM Bots) integrate stakeholder expertise into the project delivery and perform various tasks like calculations, simulations or analyses for the project, resulting in fewer design and construction errors. BIM Bots are smart tools, retrieving data directly from the BIM environment, automating the communication and information transfer between the involved stakeholders as well as early integrating their expertise to generate “time gains, cost savings and greater efficiency” [45]. The decentralized project delivery system with Linked Data, proposed in this paper, can be referenced back to the idea, proposed by TNO, as it perfectly describes and conceptualizes a decentralized delivery system and thus, acts as the basic foundation.

While the following framework in Fig. 11 outlines the decentralized project delivery system for the application of TCI planning and management, utilizing a TCI calculation engine that is provided by the TCI provider, it is identified that the vision of a Linked Data-enabled and distributed information infrastructure for the construction industry can be applied to various tasks in the life-cycle of the built environment [11,35]. In contrast to the framework of the previous chapter, this framework describes a future vision of the solution and thus, contributes to the knowledge base as a recommendation for future research, proposing a scenario to overcome current challenges in the industry.

In conclusion, the new framework reveals the potential of using Linked Data for construction planning as well as forging the link to the proposed solution. By that, a new project delivery system is proposed. Among others, four values are mentioned in Fig. 11, which are added to the construction site by utilizing the proposed framework for planning and managing TCIs. Wrapping up, the developed frameworks from Section 3 and Section 5.2 propose a process map for improving construction with a data-driven and integrated project delivery. The first scenario covers the project delivery in the current industry, whereas the second scenario envisions a new system of a more integrated and decentralized project delivery using Linked Data. In both solutions, the developed prototype can be applied to improve the management of TCIs on a construction site.

6. Conclusions and future work

In this paper, it is demonstrated how Linked Data technologies can be utilized to semantically describe different domains in construction, link datasets together and apply an algorithm to automate the planning effort of temporary construction items. It is furthermore explained how the generated and visualized TCI utilization plan can increase transparency and productivity on construction sites. The proposed solution was then tested in a case project, to proof its functionality with real data from a construction project. By finally proposing two different frameworks to which the developed solution can be applied, the authors distinguish between an ideal current scenario and an ideal future scenario. In the ideal current scenario, an innovation, like the developed prototype, requires the data to be extracted from the different BIM authoring tools or stakeholders and to be converted into RDF triples. The ideal future scenario, in contrast, foresees a decentral project delivery where the different stakeholders act as service providers and integrate their specialized data into a central model, from which other stakeholders can retrieve, process, and add new data to further develop the project. Nevertheless, the main contribution in both scenarios lies in the use of domain specific data models that are linked and enriched by semantic relations and on which any algorithm can be applied to further add knowledge. Previous research and technological advancements were usually focused on providing solutions to properly design TCIs, based on a BIM model. However, the approach of this paper extended the design concentration with a focus on data integration and presented a solution where data from different stakeholders can be obtained, structured in a standardized way and integrated into an existing process of automatically planning TCIs. By utilizing a data-driven approach with a generic perspective on a narrow problem, the solution has great potential to be further developed and applied to various areas in construction, thus, increasing its added value to the industry.

As the developed prototype only focuses on the narrow case of formwork utilization and includes several simplifications, it is considered primarily a proof of concept. Thus, an exhaustive list of future research opportunities can be implied to further develop the prototype. First, the prototype must be extended and include more algorithms to also consider other TCIs than formwork, e.g. scaffolding [22]. Moreover, a quality assurance method must verify the calculated TCI quantities of the used algorithm. This can either be done by the TCI provider as a service or through review sessions of the TCI quantities. Then, the prototype must eventually be implemented in a pilot project to validate its functionality and quantify its real and practical benefit for the different stakeholders. Here, it is recommended to further utilize the created transparency and control of the TCI utilization and integrate the data into a construction site optimization tool like the *Smart Construction Planner* [46] to improve site logistics and increase the efficiency of the construction workflows. A further consideration to bring the TCI utilization plan to the construction site can be achieved by integrating the data into the mobile application Exicute, as outlined in Section 4. Research must also consider the question, why a decentralized project delivery hasn't been introduced earlier to the construction industry, by investigating the business models of different construction stakeholders and where their revenue is generated. Lastly, the authors urge other researchers to contribute to the efforts of the Linked Building Data community group to further develop standardized ontologies for various applications in construction, eventually disrupting the industry to become more integrated and efficient by realizing the Linked Data vision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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