DOI NUMBER: 1019255/JMPM029011

“FIT FOR PURPOSE BUILDING INFORMATION MODELLING AND SYSTEMS INTEGRATION (BIMSI) FOR BETTER CONSTRUCTION PROJECTS MANAGEMENT”

Rogier Wolfert, Sander van Nederveen, Ruud Binnekamp

FACULTY OF CIVIL ENGINEERING AND GEOSCIENCES
DELFT UNIVERSITY OF TECHNOLOGY, THE NETHERLANDS
r.wolfert@tudelft.nl
g.a.vannederveen@tudelft.nl
r.binnekamp@tudelft.nl
March 2022

Abstract: Building Information Models (BIM) should reflect all aspects and phases of the construction projects life cycle. However, in current contractor practices, a proliferation of different information systems has arisen, each of which in turn illuminates a different information model dimension (nD) for usually only one construction project management purpose. To solve this problem it seems obvious to build a unique overarching system based on a single prescribed data modelling structure. We argue that this attempt is unrealistic, will not serve industrial practitioners and has failed already several times. We propose to link BIM to the concept of Systems Integration (SI), to develop tailormade and integrative information systems for its intended multidimensional (nD) modelling and construction projects management purpose: i.e. a targeted BIMSI fit for nD purpose enhancing better construction projects management.

In this paper this nD BIMSI concept is introduced and demonstrated by a number of grassroot projects, which have been developed and validated in close cooperation with the AEC industrial practice and construction management and (civil) engineering master student projects at TU Delft. An overview of these grass root development projects is provided. These projects show how the BIMSI concept improves construction project management in areas such as generative design, safety during construction, and AI applications for effective budgeting. The focus of these projects is not on extending or evaluating BIM knowledge and theory, but rather on transforming BIM concepts into integrative information systems to solve real life problems. Finally, a state of the art education concept developed at the TU Delft is presented to demonstrate its unique position in master education on information systems for the construction industry. This so-called Open Design Learning (ODL) education integrates the nD BIMSI concept to better prepare students for both industrial and R&D construction project management practices.

1. INTRODUCTION

Information systems which reflect building information models (BIM) supporting construction projects management have evolved since the early 1980s from basic 2D CAD systems and non-graphic tools to a range of applications including 3D BIM (e.g. Revit), construction scheduling simulation (e.g. Primavera), resources planning (e.g. SAP), systems engineering management (e.g. Relatics) etc. For a typical construction project where a contractor[1] is responsible to design, (re)build, maintain and/or to dispose certain engineering assets, this can result in a comprehensive information systems landscape as depicted in Fig 1. It demonstrates a proliferation of different information systems, each of which in turn illuminates a different information model dimension[2] (nD), usually only for a single construction project management purpose.

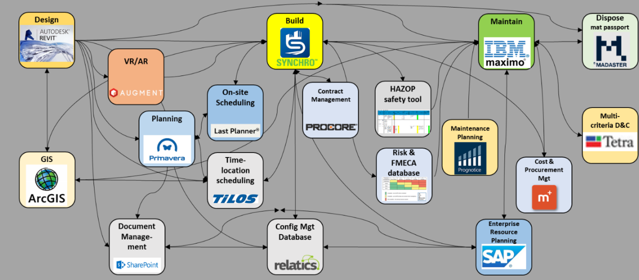

FIG 1. INFORMATION SYSTEMS LANDSCAPE OF A TYPICAL DESIGN BUILD MAINTAIN DISPOSAL (DBMD) CONTRACTOR

It was the original vision of many BIM researchers[3] to converge into one central BIM system covering all construction projects dimensions and/or project life cycle phases. The early research activities on BIM were all based on the idea that a building information model should

1 For ‘grey-field’ (re)construction projects (i.e., constructing a new artefact starting from an existing system that partly has to be operatable), a typical contractor’s CWBS (contract work breakdown structure) is composed of design-, build-, maintain (during construction)- and/or disposal activities.

2 Many of these system applications can be positioned using the concept of nD modelling, as proposed by Auoad et al. (2005). Note: each single nD dimension, a specific modelling viewpoint, is a sum of one or more sub dimensions: i.e., nD can maximally integrate the sum of the lower [1..n-1]D modelling dimensions. So for example, [1,3,4]D could be integrated for a 8D modelling viewpoint and [1,2,3]D could be the integration for 4D modelling.

3 Actually, BIM started as a reaction on geometry-oriented CAD. In the 1970ies researchers proposed a “building description system” that described more than just geometry (see Eastman et al. 1974). In the 1980ies product modelling research, development and standardization became an important development. The term Building Information Modelling was first used in 1992 by Van Nederveen (one of the authors of this paper) and Tolman (1992). However, the term only became widespread about ten years later after commercial vendors such as Autodesk started to market BIM software on a large scale.

encompass much more than only 3D design and engineering information. It should involve "all" building information: all objects, their properties and multi-dimensional behaviour, during the entire project life-cycle stages[4]. Moreover, many contemporary researchers do follow this paradigm of centralizing all other system applications around the 3D model and harmonizing the data structure with the aim of creating a single comprehensive BIM system. From a first theoretical viewpoint it seems plausible and straightforward to build such a single and overarching system based on a unique data exchange and modelling structure. However, already many attempts (see e.g. the COINS[5] project) have proven to be disappointing as these did not help industrial practitioners to improve their construction projects management.

We propose an opposite approach: to link BIM with the concept of Systems Integration (SI), to develop tailormade and integrative information systems for its intended modelling and construction projects management purpose: i.e. a targeted BIMSI fit for nD purpose enhancing for better construction projects management. This holistic and different paradigm on nD BIMSI has inspired the construction management and engineering group at the TU Delft group to: (i) carry out a number of 'grassroot' R&D projects[6] and (ii) develop a state of the art education concept on learning and developing nD BIMSI together with reflective practitioners from the construction projects domain.

Firstly, we will use the concept of nD BIMSI modelling in this paper to position and introduce a number of these grassroot R&D projects that have been developed in cooperation between a Dutch AEC industrial partner and the CME group at TU Delft (and or with experts from the Computer Science faculty at TU Delft). All of these R&D projects aim to explore to what extend the use of nD BIMSI can help to improve the performance of construction projects management and validate the potential of the specific system development for further company implementation. The demonstrators for this paper, which is a limited set of all our grassroot projects of the last seven years, are structured as follows:

- 3D: generative structural design;
- 4D: construction planning and phasing;
- 5D: AI cost estimation;
- 6D: maintenance planning;
- 7D: sustainable design & construction;
- 8D: safety during construction;
- xD: construction projects information retrieval.

Per nD BIMSI grassroot R&D project, a short summary of the development gap, the main results and or further developments per nD project are presented. The full overview of each projects can be found on the repository of the TU Delft (see for names/titles per nD project the References and http://repository.tudelft.nl).

Secondly, the implementation of the nD BIMSI concept is presented for the course of Information Systems within the master of construction management and engineering at the TU Delft. This course has also been structured along the aforementioned nD modelling dimensions. The students have to develop a so-called Open Design Learning (ODL) response in which they demonstrate a mini-development project per nD information modelling dimension using a self-chosen construction project of interest (PoI). Apart from the BIMSI concept, this course is uniquely positioned amongst similar courses of con-colleagues of similar NL/EU universities since it follows the constructivistic ODL concept (see https://www.open-design.school). This concept unlocks the student's potential reflected in their self-created ODL response encompassing a set of nD computer models and improvement proposals for a real-life construction project. The concept is geared towards persistent learning & development rather than only short term knowledge gathering.

4 This is also reflected in the commonly used definition of BIM, formulated by the US National BIM Standard in 2014: "Building Information Modelling (BIM) is a digital representation of physical and functional characteristics of a facility. A BIM is a shared knowledge resource for information about a facility forming a reliable basis for decisions during its life-cycle; defined as existing from earliest conception to demolition", see NBIMS, 2014.

5 COINS (Construction Objects and Integration of Processes and Systems) is a Dutch development project aiming at integration of construction information towards an information model and exchange format by means of a container for BIM related data It is carried out in collaboration with TNO, large infrastructure providers and construction companies, see www.coinsweb.nl. Early developments on interdisciplinary communication within BIM systems were the basis for this COINS project (see e.g. van Nederveen, 2001 or van Berlo et al., 2012). Quote d.d. Feb. 2022 "Forum Standardization concludes no longer obliging or recommending COINS to the government.", in Dutch https://www.forumstandaardisatie.nl/nieuws/oidc-profiel-verplicht-aanbeveling-peppol-bis-coins-van-de-lijst-af-geef-uw-mening.

6 Grassroot R&D projects are early stage and real life development projects to validate functional improvements for better construction projects information modelling systems. These projects are carried out in cooperation between the Dutch AEC industry and master students from the CME group at TU Delft. The average lead time of these projects are 7-9 months. The projects have been managed by a multidisciplinary team from the CME group, experts from the Computer Science faculty at TU Delft and a project manager from the industrial partner. The functional requirements specification and the product validation are being done within the company or within real-life construction projects. These R&D projects can support the initiation phase for full product implementations within the industrial partner organisation of interest.

The paper is structured as follows. In section 2, a number of research and development activities is discussed along the aforementioned modelling dimensions (here from 3D to 8D and beyond). In section 3 we discuss how these developments are used in university education. The paper concludes with a short discussion and reflection on the overall results.

2. GRASSROOT BIMSI PROJECTS - FROM 3D TO 8D AND BEYOND

This section discusses a number[7] of grassroot nD BIMSI projects, in which fit for purpose and integrative information systems are developed with the aim to improve construction project management. Each development project focuses on one of the dimensions from 3D to 8D and beyond. For the chosen projects in this paper, a brief management summary is presented hereafter, indicating (1) the development gap ('what could not be done'), (2) the results ('what is achieved and will be possible to do') and (3) the validation and follow-up opportunities ('what should be developed further'). All of these projects are being conducted together with (industrial) construction projects partners, coordinated by the TU Delft CME group and in collaboration with different Engineering Structures and/or Computer Sciences groups of the TU Delft.

2.1 3D: generative structural design

Although most of the projects presented in this paper are related to a "higher" dimension, still a lot of interesting work is related to 3D geometry and spatial design. One area that is gaining a lot of attention is the area of parametric and generative design. These concepts have already been researched for many years, but tools such as Rhino, Grasshopper and Revit Dynamo have led to an increase in development initiatives.

An example of a project in the area of generative design is done by Skakun (2021). This project started from the observation that preliminary design of concrete (prestressed) viaducts (1) requires a time-consuming and human driven effort and (2) is sub-optimal because only few alternatives can be considered. The result of the project was a generative design tool that was able to generate a large number of realistic alternatives in a way shorter amount of time, whereas the characteristics of concrete structures were taken into account. The tool, as shown in Fig 2, was developed in the Revit Dynamo environment with Python code added for more flexibility and efficiency. The resulting prototype was tested and validated at the company Witteveen+Bos. It showed the potential of the chosen approach that automates the generation of structural design alternatives with the possibility to also generate design parameters to be used both for evaluation of alternatives and design optimizations. Since the structural design scope within this project was rather limited (e.g. only concrete bridges, only four types of bridge decks, calculations limited to rough cost estimation and environmental impact scores), there are many opportunities for extension of this generative design system. It was recommended to work on further systems integration with existing models such as pavement models. Practitioners expressed their interest for this generative design system as a solution space 'negotiation' medium in the preliminary design stage.

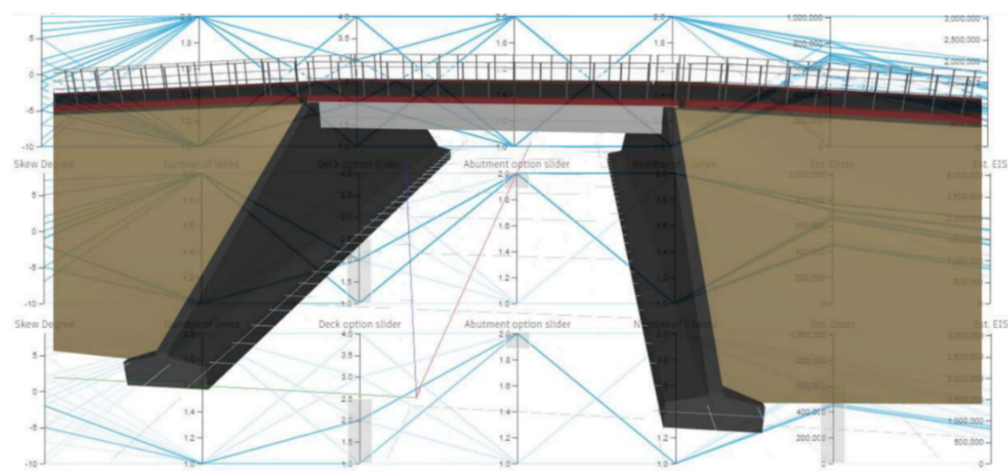

FIG 2. A PROTOTYPE GENERATIVE DESIGN SYSTEM FOR AUTOMATED CONCRETE VIADUCTS DESIGNING (SKAKUN 2021)

7 For most of the nD information modelling dimensions we did execute several of these grassroot projects over the last seven years. Only the most promising projects are presented here.

2.2 4D: construction planning and phasing

Construction planning and phasing taking into account spatial limitations over time can be challenging. Construction simulations using 4D tools can help, but these are (1) often difficult to develop the 4D model in an interactive way (2) mostly focussing on the end-result rather than integrating temporary works during construction (3) mainly used for communication purposes afterwards, after the actual construction planning has been completed.

Several challenges for typical construction project phase remain unsupported. First of all there is a need for truly interactive support of the construction planning process by 4D models. However, also for support of combining construction planning (as managed with e.g. Primavera ERP scheduling software) with spatial constraints (as managed with e.g. time-distance diagramming TILOS software). Combined knowledge about planning and spatial constraints is especially needed when construction works have to be carried out in a short and limited amount of time, such as rail construction projects require specific short-term possessions[8].

This issue has been explored for railway projects by Schouten (2015). In this project GIS technology was used for the spatial planning, since 3D BIM models of the railway elements were (1) not of the primary interest of the operational possession planning manager as in practice the complexity of 3D BIM models was not really needed for this possession planning purpose (2) not readily available (as a finished 3D product) at the time of a possessions request. The result of the project was a planning visualisation tool that was tested and validated at the construction company BAM Rail for the project OV SAAL. The project demonstrated that the combination of visualisation and construction planning is very useful, if not essential in construction projects with severe possession time constraints. For follow-up many practical suggestions were given, such as enhancing the tool for better visualisation. Next to that it was suggested to turn the planning visualisation tool into a planning optimization tool, that not only is able to visualize planning decisions, but also will be able to support best fit for project planning decisions, especially for possession based construction projects with spatial constraints.

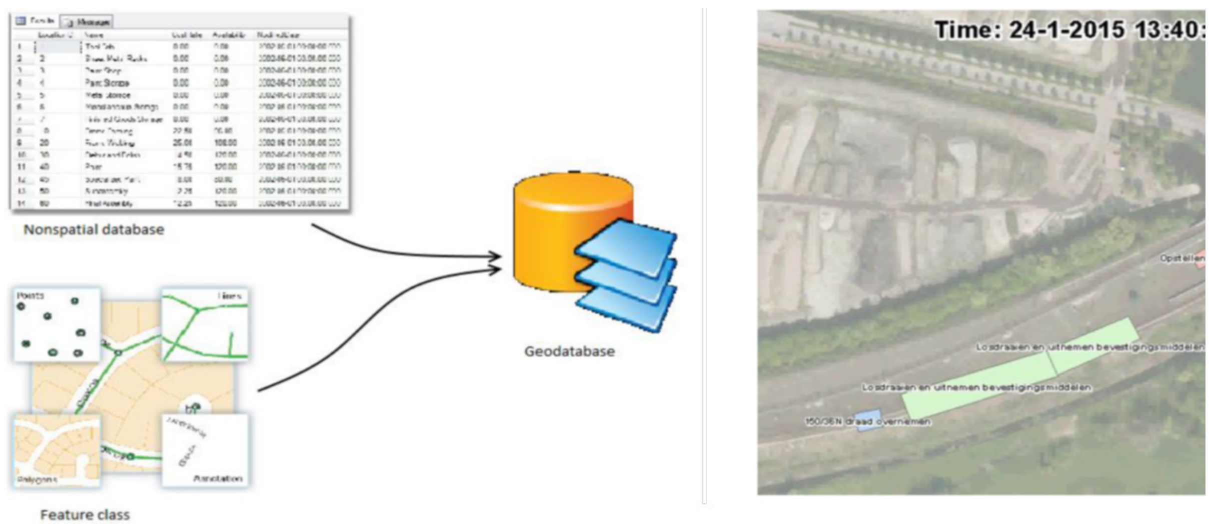

FIG 3. PLANNING VISUALISATION FOR RAIL POSSESSIONS (SCHOUTEN 2015)

In general, the 4D BIM and construction planning development should also be extended with lean construction approaches such as the Last Planner approach, see Sacks et al. (2018). Moreover, there are a number of R&D challenges left in topics such as linking 4D BIM with construction robotics, cyber-physical systems and/or with the dynamic Mitigation Controller (MitC) software for optimizing construction projects planning on the run (see Kammouh, 2021-a). Currently we are further exploring these topics in joint collaboration with PrimaNed/Primavera.

8 Possession based rail construction project planning is a kind of ‘military operational’ planning since the construction works do exactly have to fit the given timeslots by the rail infra manager. These planning should support the possession request at a time way before the detailed design execution is ready.

2.3 5D: AI cost estimation

Cost estimation is another area where information technology can contribute to better construction project management. A simple example is 5D BIM: add cost data to BIM objects and calculate the total. This approach has limited value, because the models are in essence based on bills of quantities and do not include costs that are not related to objects such as connections, processes etc.

A more advanced development is a data-driven and machine learning cost estimation approach: i.e., the development of so-called ‘virtual costing assistant’ (VCA). A good example is the project by Zhou (2018), who developed a machine learning approach for conceptual cost estimation. She observed that proper cost estimation is highly dependent on experienced estimators, especially in the conceptual design stage. In an attempt to reduce this dependency and to objectify the construction budget input data, a machine learning tool was developed using the so-called adaptive neuro-fuzzy interference system (ANFIS) approach. This VCA approach was applied to cost estimation of pavement alternatives, see Fig 4. For this purpose historical construction costs were collected and used to train the system. This data-driven approach indeed worked technically well. However, the business application turned out to be limited by the lack of reliable data at the moment of this grassroot project. Actually the lack of proper data storage is a contemporary problem in the construction industry, since most construction companies do have an engineering and craftmanship culture rather than an information management culture.

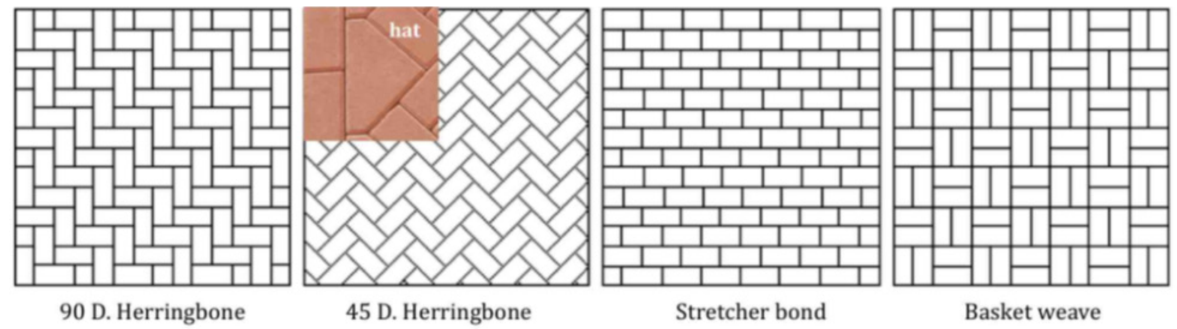

FIG 4. PAVEMENT PATTERNS USED FOR A MACHINE LEARNING SYSTEM FOR COST ESTIMATION (ZHOU 2020)

Another similar example of a VCA project on data-driven cost estimation was carried out by Masah (2021). This project focused on maintenance costs and started from the observation that maintenance cost estimation is also highly dependent on experienced cost estimators. In this case a data-driven “virtual assistant” for estimating maintenance costs was developed, see Fig 5. For this purpose the machine learning technique Decision Tree Classification (DTC) proved to be very effective. The developed prototype showed the viability of the approach. However, also here, it became apparent that both lack of reliable historical data and lack of standardization are bottlenecks for further implementation of the approach. So, overall one can conclude that the VCA 5D approach are promising from a technical viewpoint, but that for their full potential the construction companies will have to improve their data management process over their entire construction projects and/or maintenance contracts portfolios.

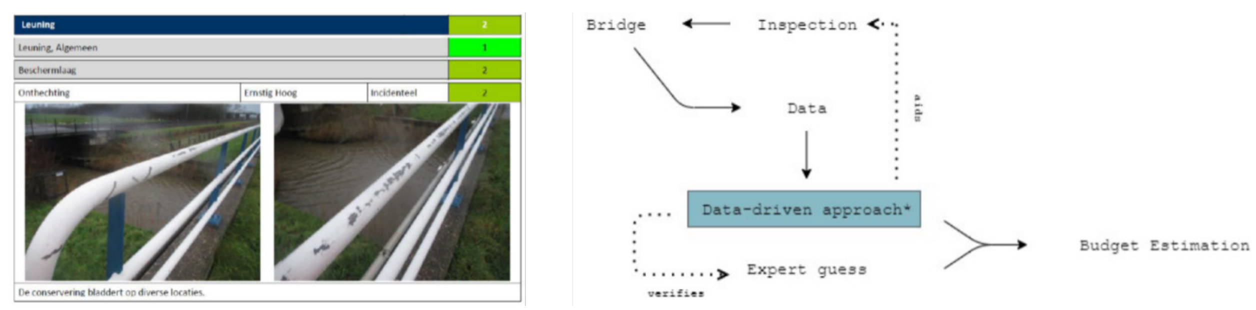

FIG 5 EXAMPLE OF CONDITION ELEMENT IN AN INSPECTION REPORT (LEFT) AND VISUALISATION OF THE DATA DRIVEN VCA APPROACH (RIGHT) (MASAH 2021)

2.4 6D: maintenance planning

Maintenance of infrastructure is gaining ever more attention as our infrastructure shows more and more traces of ageing. Moreover, in construction projects where the contractor is responsible for design, (re)build, maintain and or dispose activities for both new and existing engineering assets, it becomes even more important to have 6D information modelling systems. A great challenge in maintenance is to predict when (condition based) maintenance is needed, thus enabling predictive maintenance planning tools is key.

Also for this 6D modelling domain of interest, smart use of the right data and systems integration can be very effective. This leads to methods such as data-driven predictive maintenance. Nedelcheva (2019) explored different prognostic methods for this purpose, leading to the conclusion that proportional hazards modelling (PHM) worked best, see Fig 6. This approach was successfully applied in a test case for tunnel engineering systems maintenance for Rijkswaterstaat. Rijkswaterstaat has expressed that they see great potential in applying the results and findings for their future maintenance management. Later, Nedelcheva successfully followed up on the 6D BIMSI development at the contractor Croon Wolter&Dros and together with the COB.nl

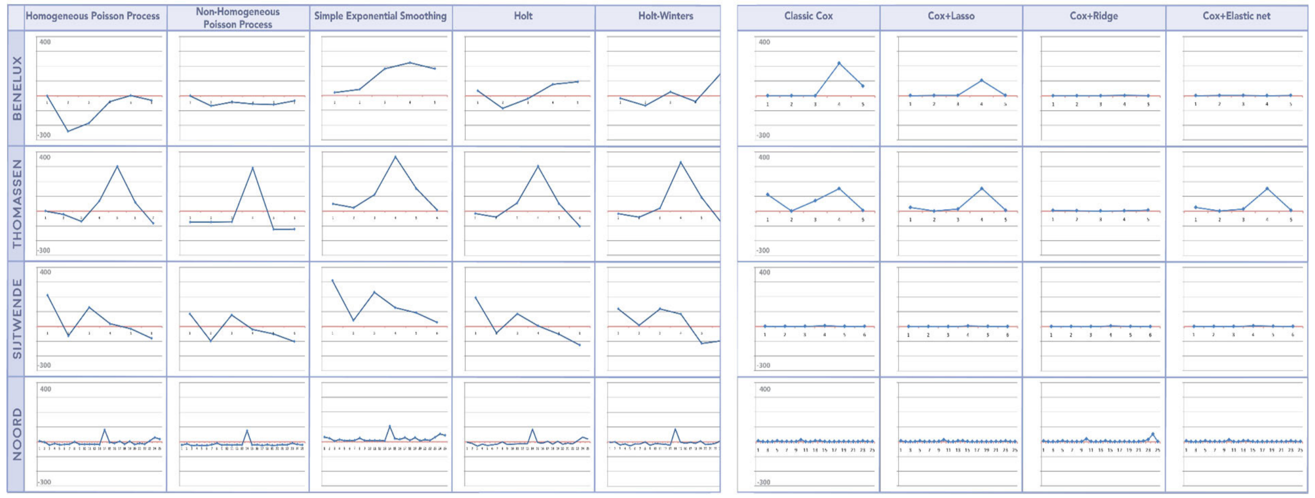

FIG 6. ANALYSIS OF EIGHT PROGNOSTIC METHODS FOR PREDICTIVE MAINTENANCE OF TUNNELS. THE Y-AXIS REPRESENTS THE DIFFERENCE BETWEEN THE REAL VALUE AND THE PREDICTION. THE PHM METHODS OF COLUMNS 6 TO 9 PERFORM BEST (NEDELCHEVA 2019).

Last but not least, recently the CME group at TU Delft has developed a novel 3C planning concept, which is an integrative multi-system and multi-stakeholder optimization approach for managing engineering asset interventions such as heavy maintenance and or renovation construction works (see Kammouh et. al., 2021-b). The introduction of the 3C concept within construction projects will lead to systems integration of 3C planning method based tooling with different 4D and 6D BIM systems.

2.5 7D: sustainable design & construction

Sustainability is another broad theme with many possibilities to integrate building information systems for better project performance. First of all, 7D BIM models can be used to generate a materials database of a building or engineering structure that can be used for renovation and circular building purposes when the structure is to be disposed and or demolished. This idea has already been elaborated and implemented by the Dutch company Madaster (www.madaster.com). However, the scope of Madaster is rather limited. The information at element level does exist within this information system, but integrated information on connectivity and or disassembly information that is essential to assess the potential for circular use is missing. 7D BIM models can be extended to assess the socio-eco impact of construction works: i.e., the ecological footprint and CO2 emissions of construction of buildings and structures, economical impact of transporting materials and equipment, and the social and or regulatory impact of the (re)build operations. For this, preference function measurement & modelling (PFM) theory should be integrated with the actual 7D BIM models (see Binnekamp, 2010).

Moreover, with the growing interest for sustainability as an important embedding system dimension, it is important to integrate 7D BIM in design & construction management decision support tools. Bhatia (2021) has addressed one these aspects in his project and has developed a nD BIMSI tool[9] that can justify investments in sustainable based design methods to stimulate the acceptance and integration of new sustainable products. Termed as the "Total Value for Society" (TVS) model, it uses a PFM based multi-criteria evaluation methodology to select a fitness for purpose design and construction project with the most "true life cycle value" out of multiple options of the same functional equivalence, see Fig 7. The tool was tested and validated at the construction company Heijmans. The validation of the tool showed its usefulness and its robustness for owners/investors, contractors and designers and leaves room for design optimisation improvement.

Last but not least, currently the CME group at TU Delft is focussing on two other 7D BIMSI projects: (1) within the current EU NRG-storage research project we are developing a multi-stakeholder design optimization methodology for better construction management: i.e., a shift from fitness for purpose evaluation towards best fit for common purpose optimization, (2) together with PrimaNed we are developing extended Mitigation Controller (MitC) software which enables for multi-objective optimizing construction projects planning on the run. In both projects we are integrating several nD BIM dimensions with PFM based construction project management decision making.

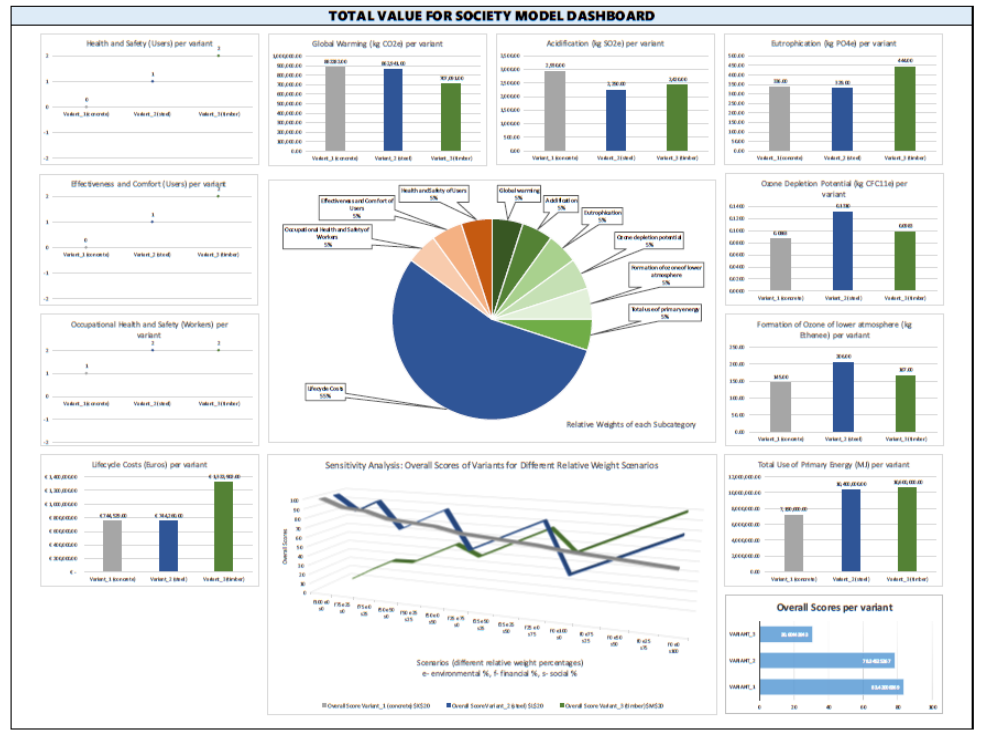

FIG 7. A PFM BASED MULTI-CRITERIA EVALUATION TOOL FOR FITNESS FOR PURPOSE DESIGN AND CONSTRUCTION (TVS MODEL BY BHATIA, 2021)

2.6 8D: safety during construction;

Within the broad theme of 8D BIM construction safety modelling, the topic of safety during construction is underexposed in contrast to structural safety. During construction the objects on the site are changing continuously and 'moving' towards the end result situation. For example, scaffolding is placed and removed, construction materials are temporary stored, cranes are installed and operated, temporary facilitating structures are constructed etc. This information is usually neither integrated in a common 3D BIM model, nor in a simple 4D BIM model that only shows the construction sequence of the engineering asset itself. Therefore, a construction project manager needs an 8D BIM tool that integrates both a 4D modelling aspects as described in section 2.2 and that makes the most predominant operational safety hazards (e.g., construction workers falling from height) visible during different phases of the construction process.

9 Integration of BIM3D, 7D and PFM Tetra tooling, see https://scientificmetrics.com/

This integration was made by Ramsey (2021), who developed a 8D BIMSI tool that can identify hazards in 3D/4D models on different moments in time during construction, see Fig 8.. The tool was tested successfully at the construction company BAM in both a real estate building and within an infrastructural asset construction projects context. The tests and the practitioner validation confirmed the added value of the tool, but also revealed a number of possible improvements such as further systems integration BIM models such as GIS, etc. More fundamental suggestions for further development were given on the integration with advanced technologies for construction safety (.e.g., the integrative use of VR/AR for virtual safety walks and/or the application of data or image pattern recognition for risk identification). Other development opportunities in the 8D BIM area is the development of digital twins for simulation of construction project execution including the automated identification of operational safety hazards by spatial modelling and simulation of temporary structures, such as scaffolding and moving cranes.

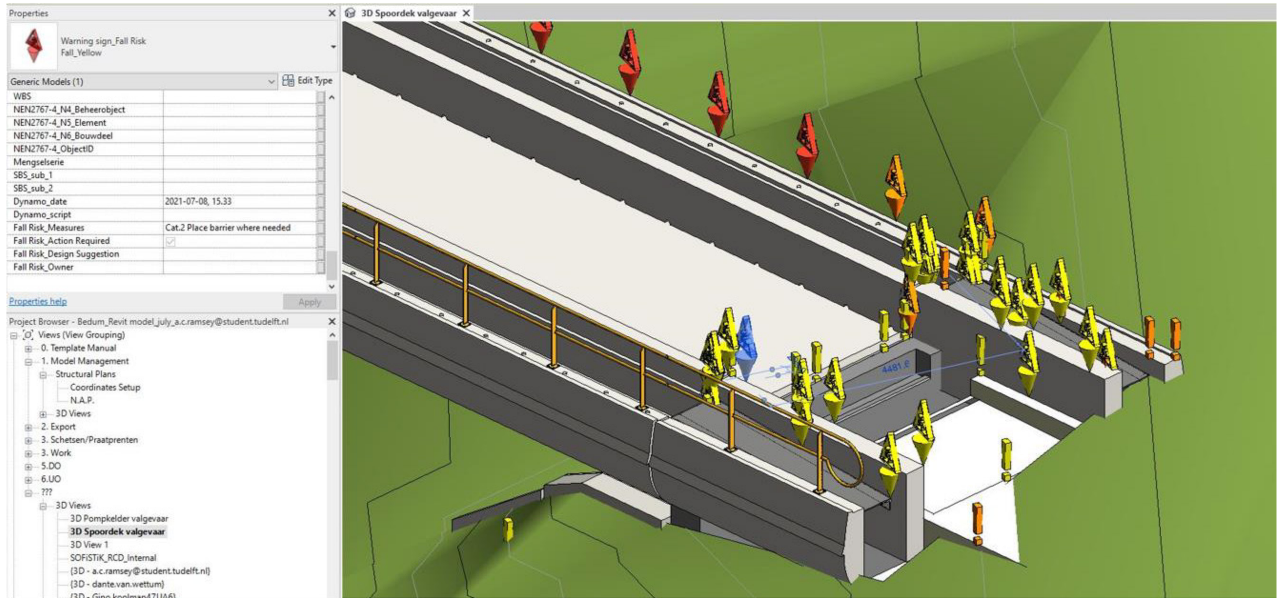

FIG 8. IMPROVING ON-SITE SAFETY WITH BIM TECHNOLOGY (RAMSEY 2021). THE GENERATED CONES INDICATE FALL FROM HEIGHT HAZARDS.

2.7 xD construction projects information retrieval

One topic that touches almost all dimensions is the general topic of information retrieval from different nD BIM systems. For a long time the common way of thinking was that all construction information systems could somehow be integrated by using one single information model enabling a ‘central way’ of information retrieval. However, in recent years, construction project practices have shown that this approach does not work and a shift has been made to a distributed/federated approach (see van Nederveen et al., 2015). Within these developments often new technologies play a role such as semantic web, ontologies and linked data (see Borrmann, 2018).

Within this federated context an interesting project was carried out already in 2015 by Wiggers (2015). This project was motivated by the common problems in practice with interoperability of construction information systems: inflexible standards and predefined formats, loss of information, difficulty to retrieve data in a heterogeneous systems environment. In order to cope with this problem, Wiggers developed an alternative approach for BIM’s traditional way of data linking and retrieval. The core of this approach is a vendor and technology-independent indexer that makes use of innovative open source technologies such as NoSQL databases and the JSON exchange format, see Fig 9. This indexer can explore (semi) unstructured data sources of many different kinds, including BIM-models, spreadsheets, planning documents and/or meeting minutes. The indexer does not require a specific format, as it “crawls” through the different types of information.

In order to test this approach, a prototype was built and tested for an integrative DBFMD contract reflecting the SAAone project of the construction company VolkerWessels. The test was successful and confirmed the potential of the alternative approach based on crawling through unstructured models and data using open source technologies such as JSON and NoSQL.

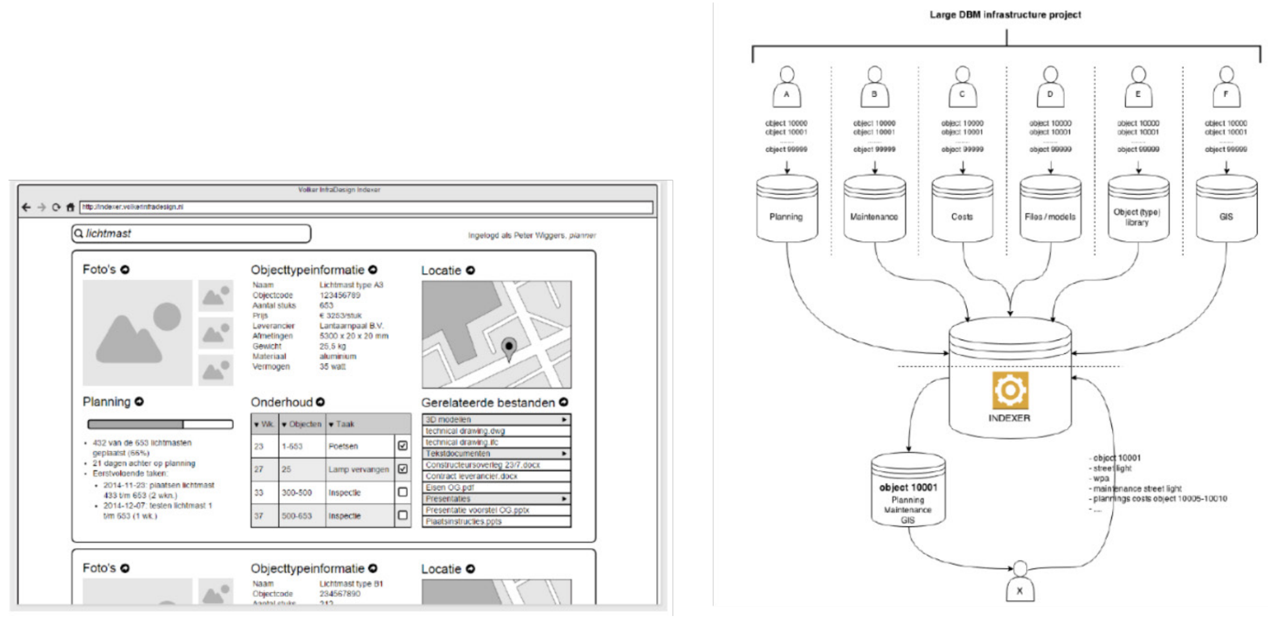

FIG 9. IMPRESSION OF A JSON BASED INFORMATION ND BIM WEBCRAWLER (WIGGERS 2015)

3. MSC EDUCATION FOR CME ON INFORMATION SYSTEMS AND THE ODL CONCEPT

In this section we show how a state of the art education concept, developed over the last years at the TU Delft, is applied in MSc education for CME on Information Systems. This education concept is based on a constructive learning & development approach, named the Open Design Learning (ODL) concept, which ensures persistent learning & development. Classical education concepts are self-sealing in the sense that students are required to demonstrate during a test at the end of a course that they can provide the answers that the teacher expects from them. This classical approach lacks student engagement resulting in a shallow understanding of course concepts, how concepts relate to one another and their real life connection. In contrast, the ODL concept is open-ended in the sense that students apply course concepts to a self-chosen ‘Project of Interest’ (PoI) resulting in a self-created unique course ODL response. The self-chosen PoI not only enhances student engagement, but also ensures a deeper understanding of course concepts, how they relate to real life and how they are inter connected. The creation of a unique response that captures all course concepts requires an integral line of reasoning where students show that they not only internalized course concepts but can also communicate these in a clear way. For a full description of this ODL concept see Binnekamp et al. (2020) and the open-design.school website.

3.1 MSc education at TU Delft

The MSc course[7] “Information Systems for the Construction Industry”, offered at TU Delft by the CME group, is based on and structured along the aforementioned nD BIMSI concepts. Students choose their own real-life project of interest (PoI) and apply and translate the different nD BIM course concepts to their self-chosen construction project. Every week a new concept is introduced, that students need to apply to their own PoI, resulting in a self-created information model per concept, read a unique mini-grassroot development per modelling viewpoint. This guarantees a continuous learning and development line between the course and their final grassroots projects.

Moreover, the course not only integrates nD BIMSI concepts but also provides an outlook of topics for further specialisation and development. More specifically, students are not only to analyse to which extent state of the art nD BIMSI developments apply, but are also challenged to use their new insights to develop real life improvements where applicable. Many of the grassroots projects discussed in Section 2 are in fact in-depth elaborations of the concepts introduced in the course.

Actually, the course allows that students work on making improvements on what they see in practice making use of the provided state of the art course concepts. These improvement proposals often serve as the starting point for their final graduation development project. Students then

7 In average 80-100 students from different backgrounds (MSc Construction Management and Engineering, Civil Engineering, Offshore Engineering) follow this course.

Aligned with the nD BIMSI approach students are taught how information systems on different modelling dimensions can be connected to maximize their fit for nD purpose. In this course the 3D BIM model and the supporting systems engineering breakdown structure serve as the basis to which the other dimensions are related. For instance, after creating their 3D model, students are asked to integrate a 7D BIM sustainability information tool to at least their 3D model and or other relevant information systems.

This ODL education setup combined with the nD BIMSI learning & development approach has resulted in a stimulating and challenging course that does not focus on in-depth technical BIM ICT issues but rather addresses the relationship between information technology concepts and their fit for purpose systems integration for the real world of construction projects. An example table of content (TOC) of an ODL response developed in this course is shown in Fig 10. More ODL response information can be found on the open-design.school/ website.

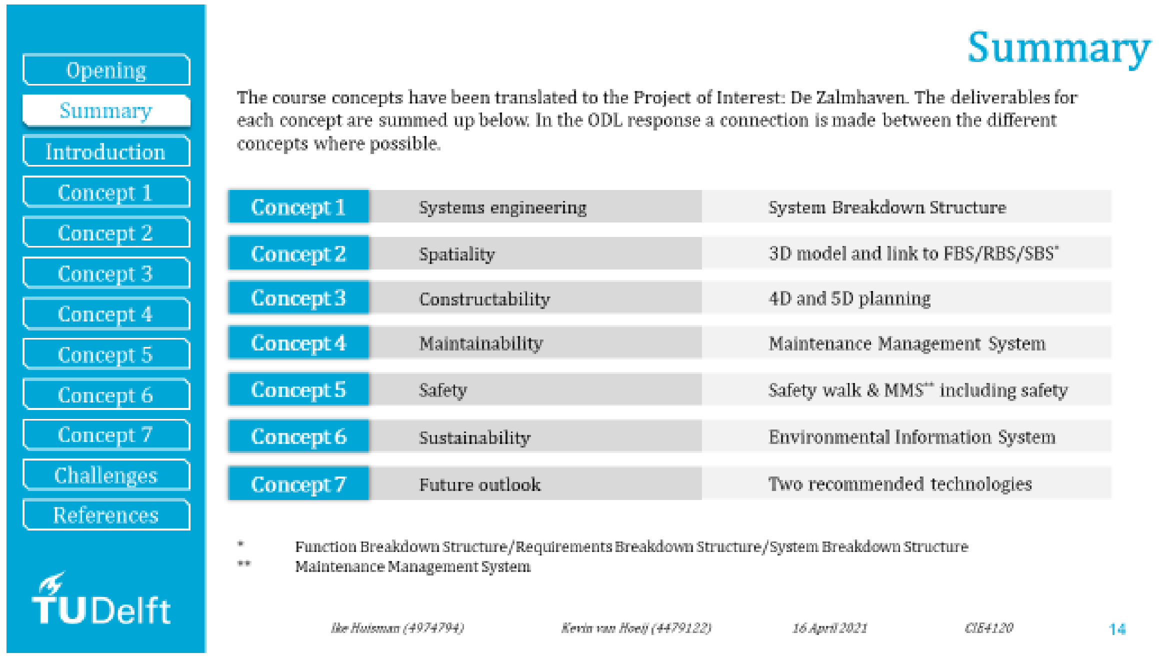

FIG 10. EXAMPLE TOC FOR A ODL RESPONSE USING THE ND BIMSI CONCEPT.

graduate on using the nD BIMSI approach for developing solutions to real life construction management problems.

3.2 Comparison with other technical universities

A scan of a number of other Dutch[8] and European technical/ engineering universities, shows that the TU Delft’s nD BIMSI approach on education, embedded within the ODL teaching concept, is distinct, as will be substantiated later in this section.

As a starting point in the scan it is seen that many other universities use the well-known research books on BIM by Sacks et al. (2018) and/or the book Borrmann et al. (2018). These books[9] of course have their value as a reference works, but often have a theoretical research focus instead of a learning & development oriented approach and are therefore less in line with the fast changing field of BIMSI in real-life construction projects. As a result, they often miss the direct connection with CME students who are trained for both R&D and project management within the AEC industry.

At TU Eindhoven a few high-level MSc courses on BIM topics are offered, but the focus is also mostly on design and engineering (fundamentals of BIM, parametric design and collaborative design) (see reference link TU Eindhoven). At University Twente a slightly different perspective is taken in the course “BIM and 5D planning”, with a focus on design and project management (see reference link University Twente). At ETH Zürich we only found some courses in which BIM was considered as supporting technology of something else, i.e. “Lean, Integrated and Digital Project Delivery” and “Design-Integrated Life Cycle Assessement” (see reference link ETH Zürich).

On the other hand at TU Munich we found a range of BIM Courses forming a Specialization Branch Building Information Modelling (led by Prof. Borrmann) (see reference link TU Munich). This specialisation branch provides an interesting opportunity for students to specialize in both BIM and supporting software skills. However, also in this program the focus is primarily on the traditional application domain of design and engineering.

Finally, figure 11 gives an overview of the different positioning and or the similarities of the MSc education approach at similar programs of different technical universities as discussed before.

8 Actually the MSc CME is a 4TU master which is offered at 3 other Engineering Universities in NL.

9 The authors have tried over the last 7 years many forms of education for this information systems course, including test based exams using Sacks and/or Borrmann as study books (instead as reference works). Because the concepts are mostly presented theoretical-ly, our group has switched over the past few years to the experiential learning concept in which multi-dimensional information models are created by the students on the basis of a real-life learning vehicle.

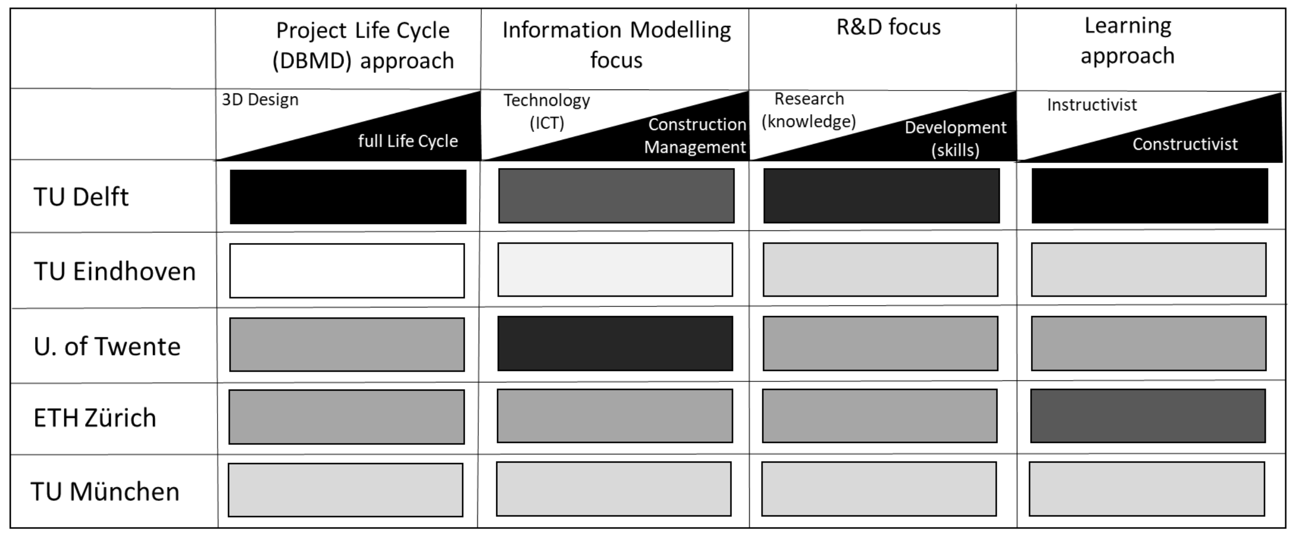

FIG 11. COMPARISON OF MSC EDUCATION FOCUS AND APPROACH OF A SELECTION OF INFORMATION SYSTEMS COURSES AT SIMILAR TECHNICAL UNIVERSITIES IN NL/EUROPE.

4. CONCLUSION AND REFLECTION

In this paper it is shown that in the fast changing field of construction information systems, only a targeted and or federated nD approach of building information modelling combined with systems integration (BIMSI) will lead to efficient and effective construction project information systems fit for purpose. It has been demonstrated that on the basis of this nD BIMSI approach, the collaboration between construction project practices and TU Delft has paid off. Many of the so-called grassroots development projects have resulted in spin-offs for further development and implementation within the industrial partners. Some of these projects, which were carried out by MSc students at their final graduation phase, even provided added value to the project in question during implementation.

It is also shown how the nD BIMSI approach is taught by means of an innovative educational concept called Open Design Learning (ODL). This concept aims to create persistent learners & developers and stimulates integrative systems thinking. Persistent learning is achieved by means of a self-chosen real life Project of Interest (PoI) to which students apply nD BIMSI course concepts. Integrative systems thinking is achieved by requiring students to self-construct their ODL response where they have to communicate how course concepts apply to their PoI and how these interconnect. The nD BIMSI approach is introduced by requiring students to use the 3D model as a basis to which other nD BIM systems are connected to achieve a set purpose.

REFERENCES

Aouad G, Lee A and Wu S (2005). From 3D to nD modelling. *ITcon,* Vol. 10, Special issue From 3D to nD modelling, pg. 15-16. http://www.itcon.org/paper/2005/2

Binnekamp, R., Wolfert, A. R. M., Kammouh, O., & Nogal, M. (2020, April). The Open Design education approach-an integrative teaching and learning concept for management and engineering. In 2020 *IEEE Global Engineering Education Conference* (*EDUCON*) (pp. 756-762). IEEE.

Binnekamp, R. (2010). *Preference-based design in architecture.* IOS Press.

Borrmann, A., König, M., Koch, C., Beetz, J. (eds) (2018). *Building Information Modeling – Technology Foundations and Industry Practice*. Springer.

Eastman C., Fisher, D, Lafue, G, Lividini, J, Stoker, D, and Yessios C. (1974). *An outline of the building description system*. Carnegie Mellon University.

ETH Zürich. Course descriptions *Lean, Integrated and Digital Project Delivery* by D Hall and *Design-Integrated Life Cycle Assessement* by G Habert. http://www.vvz.ethz.ch.

Kammouh, O, Nogal, M, Binnekamp, R & Wolfert, A.R.M. (2021-a). Mitigation Controller: Adaptive Simulation Approach for Planning Control Measures in Large Construction Projects. *Journal of Construction Engineering and Management,* vol. 147, no. 8, 04021093. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002126

Kammouh, O., Nogal, M., Binnekamp, R., & Wolfert, A.R.M (2021-b). Multi-system intervention optimization for interdependent infrastructure. *Automation in Construction*, 127, 1-11. [103698]. https://doi.org/10.1016/j.autcon.2021.103698

NBIMS (2014). *Frequently Asked Questions About the National BIM Standard-United States - National BIM Standard - United States*. http://nationalbimstandard.org.

Sacks, R., Eastman, C., Lee, G., Teicholz, P. (2018). *BIM Handbook: a Guide to Building Information Modeling for Owners, Designers, Engineers, Contractors, and Facility Managers* (third edition). John Wiley and Sons.

TU Eindhoven, course descriptions *Fundamentals of BIM* and *Parametric Design* by P Pauwels, and *Collaborative Design* by B de Vries. http://tu.osiris-student.nl.

TU Munich, *Specialization Branch: Building Information Modeling* by A. Borrmann. http://www.cms.bgu.tum.de.

Universiteit Twente, course description *Building Information Modelling and 5D Planning* by F Vahdatikhaki. http://osiris.utwente.nl.

van Nederveen, G.A. and Tolman, F.P. (1992). Modelling Multiple Views on Buildings. *Automation in Construction*, 1, 215-224. http://dx.doi.org/10.1016/0926-5805(92)90014-B

van Nederveen, G.A., & Tolman, FP. (2001). Neutral object tree support for interdiscipline communication in large-scale construction. *Electronic Journal of Information Technology in Construction* (online), 6, 37-46.

van Nederveen, G.A., Wolfert, A.R.M., & van De Ruitenbeek, M. (2015). From BIM to life cycle information management in infrastructure. In A. Mahdavi, B. Martens, & R. Scherer (Eds.), eWork and eBusiness in Architecture, Engineering and Construction - Proceedings of the 10th European Conference on Product and Process Modelling, *ECPPM* 2014 (pp. 115-119). CRC Press / Balkema - Taylor & Francis Group. https://doi.org/10.1201/b17396-22

van Berlo, L., Beetz, J., Bos, P., Hendriks, H., & Tongeren, R. v. (2012). Collaborative Engineering with IFC: new insights and technology. *Proceedings of the 9th European Conference on Product and Process Modelling ECCPM* (pp. 811-818). Reykjavik: New York: Routledge.

Wolfert, A.R.M. & van Nederveen, G.A. (2022), *Reader -CIE4120 Information Systems for the Construction Industry*, https://www.open-design.school/cie4120.

A listing of the grassroot projects discussed in this paper can be found in Appendix A.

Appendix A

Of article “Fit for purpose Building Information Modelling and Systems Integration (BIMSI) for Better Construction Projects Management” by R. Wolfert, S. van Nederveen and R.. Binnekamp

The nD BIMSI projects as summarized in this article can be found at TU Delft Repository, http://repository.tudelft.nl

- 3D : Skakun, N. (2021), “Integration of generative design of civil structures with criteria ranking calculations”.
- 4D : Schouten, L. (2015), “Planning visualization during rail possessions”.
- 5D : Masah, G. (2021), “Virtual Assistant for maintenance budget estimation: Using Machine Learning to improve the objectivity of maintenance budget estimates of civil engineering structures”.
- 5D : Zhou, L. (2020), “A Machine Learning Approach for Conceptual Cost Estimation”.
- 6D : Nedelcheva, Y. (2019) “Prognostics for systems in tunnels with event logs: An application with pump systems”
- 7D : Bhatia, S (2021), “Total value for society model”
- 8D : Ramsey, A. (2021), “Improving fall from height risk reduction: Creating a safer construction site with the use of BIM technology”.
- xD : Wiggers, P (2015), “Towards a Vendor and Technology Independent Enterprise Asset & Resource Management Indexer for Integrated Infrastructure Projects: An open-source alternative for BIM’s current way of data linking and retrieval”. 7D : Bhatia, S (2021), “Total value for society model”

ABOUT AUTHORS

Prof.dr.ir. A.R (Rogier). M. Wolfert

Dr. Wolfert (Rogier) is a professor of engineering asset management at the faculty of Civil Engineering& Geosciences of Delft University of Technology. His main research interest lies in mathematical modelling of managerial decision making within complex interconnected systems (such as project management systems or other socio-technical systems). He is the author of multiple publications and the co-developer of several scientific creative common products. He lectures different courses on systems engineering design and engineering project & asset management. He is the co-founder of the Open Design Learning concept (ODLc).

Rogier has built a proven track-record of operating different industrial management roles both within infrastructure service provider (T-Mobile) and within engineering projects & services contractors (Boskalis, VolkerWessels, TBI, Huawei). Currently, he is a project director within Boskalis Offshore Energy.

Rogier holds both a Doctor’s and Master’s degree from Delft University of Technology.
More info:
https://www.open-design.school/
https://odesys.nl/

Dr.ir. G.A. (Sander) van Nederveen

Sander van Nederveen (1961) is an experienced academic lecturer and researcher in the field of information systems for construction, systems engineering, integral design and related fields. Currently, Sander holds a position as senior lecturer at the faculty of Civil Engineering and Geosciences at Delft University of Technology. He has been teaching BSc en MSc courses and supervising graduate and undergraduate students in topics such as information systems, Building Information Modeling (BIM), integral design, project management, systems engineering, and systems dynamics..

Prior to joining TU Delft in 2005, Sander worked for many years as a researcher and project leader at the research institute TNO. He was part of a team who did pioneering research and development work in the area of BIM, many years before the BIM acronym became common. He worked in European R&D projects as well as national projects on information systems with participants from industry (mostly building and/or infrastructure).

During his time at TNO, Sander also worked for three years (1997-2000) as a systems engineer in construction practice for a consortium of NS Railinfrabeheer, DHV and Holland Railconsult (now ProRail, RHDHV and Movares, respectively). This period learned him a lot about the practical aspects of implementing approaches such as systems engineering.

Sander holds a Doctoral and a Master’s degree in Architecture from Delft University of Technology. He is 60 years old, married and has two children.