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Preface

The following book summarises the research and development results of the Construction & Robotics Masters students of the summer term 2022. As part of the Research Driven Project, the international Masters students from the fields of architecture, civil engineering, mechanical engineering and computer science have researched topics related to digital management in the areas of construction costs, construction operations and supervision, automation of concrete and timber construction processes and the reuse of building components.

A special opportunity this term was the excursion to digitalBAU in Cologne. The students had the opportunity to get in touch with leading representatives of digitalisation in the construction sector and to gain experience with current digital solutions. Afterwards, they were able to delve deeper into specific topics over the course of the semester and develop ideas for future possibilities of digitalisation and automation.

We are pleased to publish the students' results to inspire students, researchers and other stakeholders in the construction industry about future opportunities and approaches to building. This book is the third in the series of Research Driven Project publications. The open access publications of the previous semesters are published at the following links.

- **Research Driven Project, Volume 1, SS 2021**
  https://doi.org/10.18154/RWTH-2022-02992

- **Research Driven Project, Volume 2, WS 2021**
  https://doi.org/10.18154/RWTH-2022-06617

We would like to thank all the students who contributed to the Research Driven Project at RWTH Aachen University during the summer term 2022

Aachen, 07. September 2023

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BIM-Integrated Cost Management Practices in Construction

ABSTRACT

The construction industry represents an important part of the global GDP, thus putting cost management in a key role in nowadays building projects. By understanding important concepts such as quantity take-off, cost estimation and cost control throughout various construction phases, this paper intends to analyze the state of the art in cost management and potential improvement points in the field. Especially, using cost management in coordination with Building Information Modelling (BIM) holds the potential to provide significant improvements in the avoidance of major delays and budget overspendings. The research is based on a literature review of research on similar topics, a survey applied to industry players, and a software analysis of the current solutions in the market. Even though there are many solutions regarding pre-construction cost management processes, only a few studies are focusing on cost control. Therefore, the study aims to discuss possible solutions that can be implemented in the industry and respond to the challenges discovered through a flexible and user-friendly interface. Two different approaches are presented, one with open-source tools and one with private tools. Different from the previous studies the integrated open-source solution focuses on the visualization of the cost status of building elements through colourization. In future studies, the approaches will be further developed with the data of existing construction projects.

Keywords: Cost Management, Earned Value Analysis, Cost Control, Construction Management.

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1. Introduction

The construction industry has a share of 13% of the global Gross Domestic Product (GDP) and accommodates 7% of the working population [1]. Considering its impact on the world economy, the construction industry must adopt meticulous cost management approaches. By analysing the state of the art in cost management, this study aims to discuss possible solutions in various construction phases through BIM (Building Information Modelling) applications. Especially improvements in cost control can potentially be helpful for managers to analyze a project's performance and to be more proactive in making prompt decisions and timely adjustments. This could consequently result in the avoidance of major delays and budget overspendings.

When major delays and budget overspendings are the issues, it is possible to find many examples from the past. Some of the budget overrun examples are listed below, showing the scale of the problem:

- Pune Metro in 2009, estimating project cost to be 1.2B $. Revised to 1.7B $ [2].
- 332 facility projects funded by the US Air Force: 72% were not completed within time [3].
- Whole complex construction projects in the UK are likely to be finished more than six months late [4].
- Road construction in Norway: Mean cost overrun as 7.88% [5].
- Government and private building projects in Hong Kong: Time overrun of 9% and 17% [6].
- Nigeria: Average time overrun of building projects could range from 59.23% to 92.64% depending on the value of the project [7].
- A survey of 359 completed projects in Malaysia found that 55% experienced cost overruns [8].

Looking at these examples it is possible to assert that cost management is a significant tool that can aid the shareholders in the construction industry ranging from architects, planners, and engineers to clients. For this reason, this paper focuses on the possible use of BIM-integrated systems in cost management processes.

Quantity take-off, cost estimation and cost control are the main phases of a cost management system. Quantity Take-off, cost estimation (cost analysis, budgeting, cost breakdown structure) and cost control (Earned Value Analysis) will be introduced and discussed in depth in the following sections. State-of-art in this field and the current solutions will be discussed. Then, the results of the survey conducted with construction company representatives regarding cost management will be presented. As result, this research promotes driving all findings toward a solution that can be flexible and user-friendly to be implemented in real projects covering most of the difficulties discovered in the last section.

2. Research Methods

2.1 Literature Review (Concepts)

As the aim of the research is to implement cost management practices in automated and digitalized ways, the first thing we need to do is to understand and explain cost management and concepts related to it. Cost management is one of the core processes of project management combined with scope and time management [9]. According to the Project Management Institute (PMI), cost management can be divided into four domains namely, planning cost management, estimating costs, budget determination and cost controlling [10]. Planning cost management is a phase of cost management that it is described how to estimate costs, determine budgets, monitor, and control the costs of the project. Estimation of the costs is the phase where the project's monetary resources to complete work are approximated. The third phase is where the estimated costs are structured in a way to be tracked. It is important because structures of planned values and actual costs should match each other to be aggregated and compared. This is called budgeting of the project. And in the cost control phase, the budgeted costs are controlled and the status of the project in terms of costs is determined.

Cost Estimation

Cost estimation is the process of quantifying and costing the resources needed to complete a work or project [11]. For cost estimation there are various tools and techniques, also there are different classes of estimation for different goals. Cost estimation can be classified into 5 classes concerning their estimation detail and ranges [11]. For control purposes, class 1 and class 2 estimates are being used where there are detailed unit costs and take-offs.

Cost estimation has three main processes which are quantity take-off, costing of the works and budgeting. For more effective and detailed cost control, the costs should be estimated bottom-up. To make a bottom-up estimation, a detailed work breakdown structure (WBS) should be created from the scope of work, to determine the resource requirements of each specific activity to complete the total work. These works include the direct works and indirect works to complete the total scope. To determine those requirements, unit price analysis is done for each work item in the WBS. The resources can be divided into groups according to their types. These types are labour, material, equipment, and subcontractor and sometimes it can be currency.

Quantity Take-off

Quantity take-off is the process of quantifying and measuring the work to be performed. It is the starting point of cost estimation as it provides the quantity information of a project. The set of quantities produced by quantity take-off is called the 'Bill of Quantities'. Bill of quantities is an important part of a construction contract as it is used for tendering, cost estimation, progress payments etc. Because of this, quantity take-off should be done according to agreed terms and rules by the contracting parties. There are many measuring rules published by different organizations around the world which can be used as guides and standards for quantity take-off. Quantity take-off is an activity which is used throughout the lifecycle of a construction project (see Figure 1).

Cost Analysis of Work Items

The quantities measured in the quantity take-off process are installed by some work items called activity or task. In other words, the Bill of Quantities of items are elaborated with activities to install that specific item. These activities and tasks also have their own quantities to be measured or calculated according to the BOQ item. For each activity unit price analysis is done and required resource amounts are estimated. For a BOQ item, the activities listed below that BOQ item is used for estimating the unit price of that item. When each cost information is aggregated, the total cost of the project can be estimated in detail.

Budgeting

Budgeting is the next step to convert cost estimate into a controllable and manageable breakdown. This is because the structure which is used for tracking costs mostly differs from the structure of the cost estimate [12]. With budgeting, the budgets can be created where the costs of the project can be controlled and accounted for. Cost elements (resources) listed under WBS are cost-coded according to different attributes. These attributes can be owning a department, resource type, work section etc. Total resource requirements can be summarized in the desired level by cost codes and summarized in that coding structure for the budgets.

Cost Codes and Cost Breakdown Structure

Cost codes can be given at any level of WBS, including the activities and resources listed below them. Coding is for classifying the cost elements in a structured way to make it easy for actual cost tracking and cost performance measurements. It is ideal to have a CBS like WBS to make it easier to track costs and assign the costs to a schedule [12]. As it has been told CBS can be at any level, so it is better to have a CBS and cost codes in the resource level to track resources and see budget variances.

Cost Control

The concepts in cost management are interrelated. It means any activity being performed for cost estimation and budgeting directly affects the cost control system. According to PMI controlling cost is the process of monitoring the cost status of the project and change management of the cost baseline produced in the budgeting phase [10]. To do this, the costs of the project should

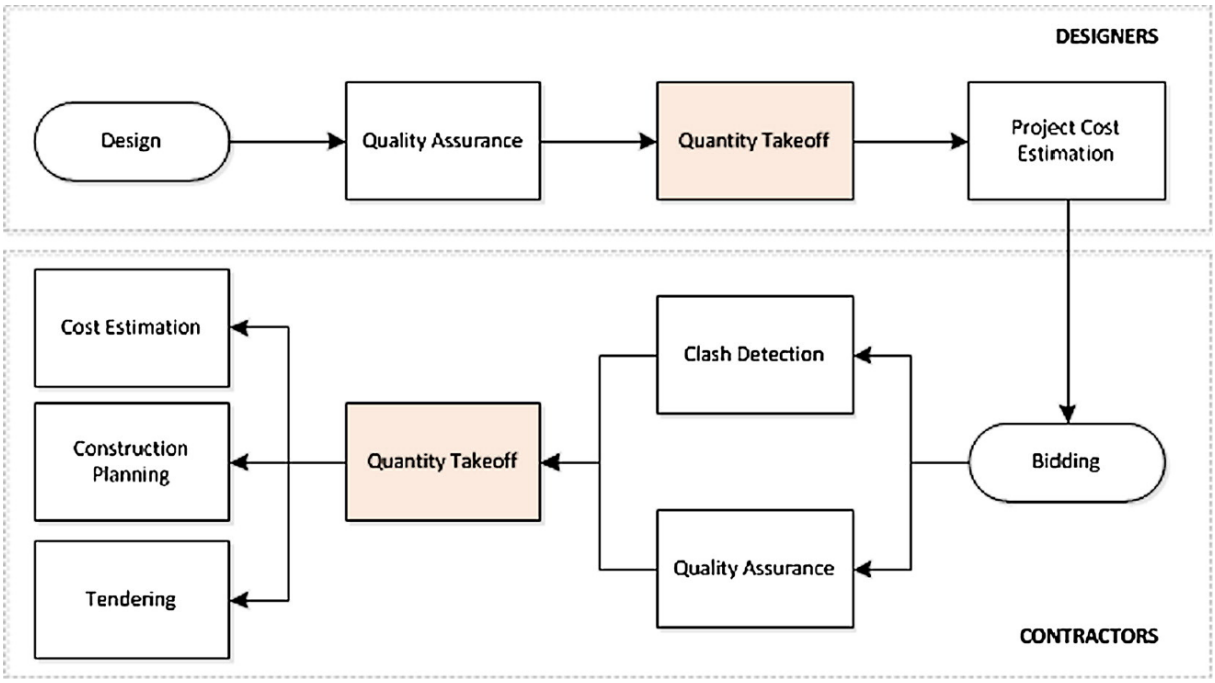

Fig. 1. Quantity take-off in the project life cycle [13].

be summarized in a cost breakdown structure and actual costs can be easily allocated to the elements of the cost breakdown structure via cost codes. There are many tools and techniques for cost control, however, one of the most efficient and successful techniques is Earned Value Management. In this report earned value management will be discussed. Another aspect of cost control is related to changes in the project.

Earned Value Management

Earned Value Management is a cost and schedule control technique to measure the schedule and cost performance of the project. It compares actual costs or values with the earned values of the budget or schedule and gives performance insight for the project with respect to progress. Earned values of a budget can be determined in various ways. For example, by integrating budget values into tasks via CPM (critical path method) scheduling tools, earned values of each budget can be determined with a cut-off date. Or installed quantities of works can be tracked to measure progress and calculate earned values. The percentage of the variance between planned values and actual values gives the performance indexes of budget and schedule. Applying earned value management in a project can give early warning for budget variances and lets the project management team take early decisions for these variances. Therefore, earned value management is an important part of cost control. According to AACEI [11] for a complete earned value system the followings are required:

- Organization of the program
- Work Breakdown Structure (WBS)
- Organizational Breakdown Structure (CBS)
- Responsibility Assignment Matrix (RAM)
- Work Authorization
- Planning, Scheduling, and Budgeting
- Performance Measurement Baseline (PMB)
- Control Accounts (CA)
- Risk Management
- Work Packages (WP)
- Planning Package (PP)
- Management Reserve (MR) and Contingency
- Earned Value Definitions
- Variance Reporting
- Change Management
- Performance Review

Change Control

Changes in a construction project have time and cost impacts on the project. Therefore, it is important to reflect those impacts on the budget to properly measure cost performance. These changes are tracked separately and integrated into the budget with forecast revisions.

Setting up an effective project cost management system is vital for avoiding cost overrun which remains a key risk of construction. Hence, the use of digital tools and technologies has fostered new solutions and potential improvements in terms of efficiency, quality, and precision during cost management processes. This research method is based on a systematic review which is carried out to find relevant papers and reports concerning the latest trends in cost management. The strategy follows this sequence: (1) finding all relevant publications, (2) classifying papers for in-depth study, and (3) synthesizing the literature. This flow serves to build up for the proposed approach, by thoroughly conducting market research, highlighting important concepts, and reaching upon the benefits and limitations of the latest trends. Academic databases such as Google Scholar were used for conducting the search by typing-in relevant keywords. The findings are classified based on applications and are summarized in the proceeding sections.

3. The State of the Art

3.1 Cost Management Using BIM

One of the most prominent technologies in AEC is the use of Building Information Modelling, BIM, which contains not only geometric data but can accommodate a great amount of engineering data over the lifecycle of a building [14]. There exists a growing interest in the use of BIM for coordinated, consistent, and computable building information/knowledge management from design and construction to maintenance and the operation stages of a building's life cycle [15]. It was reported that 87% of expert users are experiencing a positive return on investment with BIM; while 93% believe that even more return can be achieved for the potential value of BIM [16]. Nowadays exist numerous tools and technologies in the rapidly emerging BIM domain which may promote massive opportunities for project cost management professionals to dramatically improve the quality, speed, accuracy, value, and complexity of their cost management services and consequently ensure the future as key players in the BIM world. Nonetheless, the current paradigm is slow to embrace and evolve with the full potential that these technologies can provide.

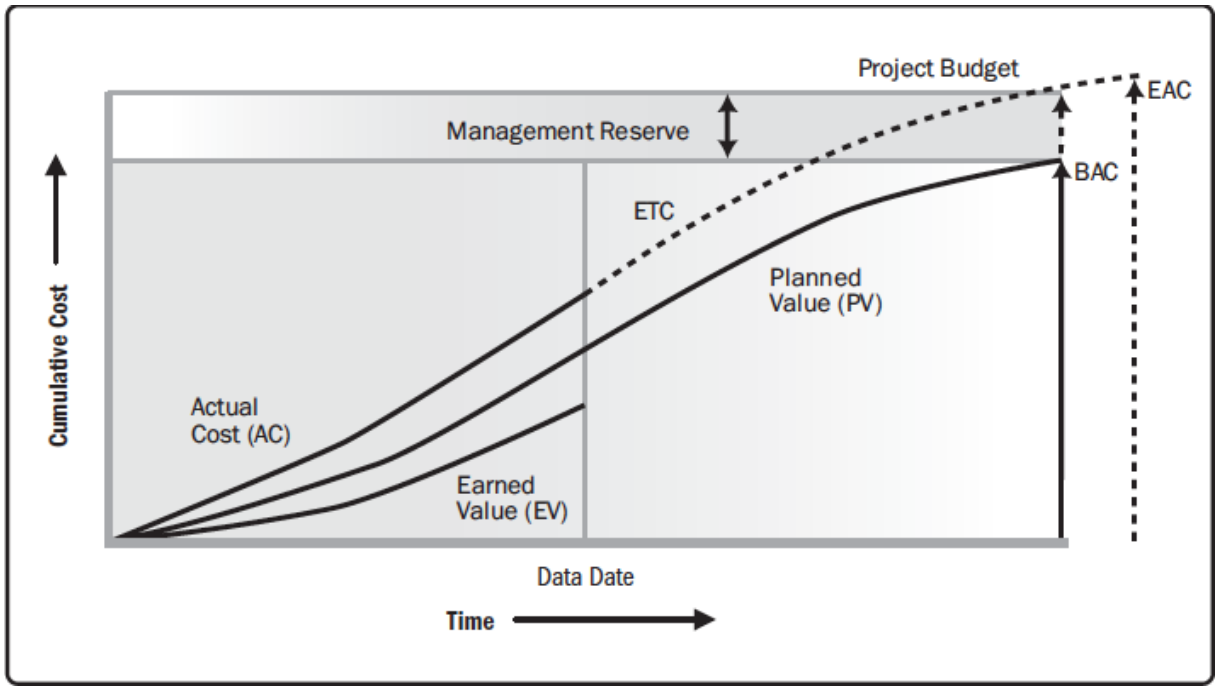

Fig. 2. Planned, Actual, Earned Values (PMI, 2017).

Quantity Take-off and Cost Estimation

Quantity take-off and cost estimation represent a basis for cost management. The efforts and results of cost estimation practices are interconnected with controlling the costs. Therefore, they cannot be considered separately for cost control.

Quantity take-off and cost estimation can be partly automated with various commercial tools on the market. These processes are done by in-house algorithms and individual results in terms of quantity take-off. Hence the outputs can be used to a certain extent and require tailoring to be used in the cost management of a project. Also, cost estimation practices can be varied according to many factors. For example, measuring and surveying rules and estimation structure can change according to countries and even organizations. Therefore, research about quantity take-off is mostly focusing on these interoperability issues and standards-programs compliance. Forgues et.al. [17] studied a potential approach using various tools including REVIT and databases like Timberline to automate cost estimation workflows. It is discussed that connecting the software and their data is a tricky process which is an obstacle to automating cost estimation workflow. Parameters of one software are usually different from other software. As a result, a huge amount of effort should be given to establishing an automated workflow. Another issue is the differences between data schemas of BIM and industrial standards. Industry Foundation Classes (IFC) is a data schema for data exchange between BIM applications. The objects in a 3D model are represented by entities in the schema. However, the mapping between entities and the breakdown of industry standards are not readily available. This issue has been covered by Lee et.al [18] by using ontological inference of work items according to BIM data. There are also other studies for matching IFC objects with standards. Zhiliang et.al. [19] investigated the possibility of using IFC standards for tendering in China complied with Chinese practices. They concluded that IFC entities can be mapped and used for tendering in China, however it doesn't cover everything needed for tendering and should be extended and studied more. This situation is most possibly the same for all other countries.

Integrated BIM & Lean Construction for cost management

Lean construction is an alternative contemporary construction management method influenced by lean production techniques applied by Toyota Company. The main philosophy of lean construction is the reduction of waste and improvement of productivity [20]. In this manner, BIM functionalities can be used along with Lean Construction with synergy. Visualization, automation of document and design generation, the collaboration between design and construction, planning evaluations, object-oriented data communication and information for computer-aided fabrication are these functionalities which can be used for lean construction management [20]. Exploiting BIM functionalities with lean construction has many benefits in terms of cost management. Predictive performance analysis, simulation of construction, decreasing changes, reduction of risk, collaboration, and structured data flow are some of the benefits of BIM lean construction synergy [21].

BIM 5D Visualization

It is believed that one of the main features of BIM is visualization, by adding another dimension to monitor and control deviations which can be detected and solved early by acquiring proper decisions. Elbeltagi [22] developed a mathematical model for evaluating construction performance with respect to cost by deriving a set of equations based on EVA. Furthermore, a BIM-based visualization system was introduced to facilitate tracking and monitoring of construction progress by enabling 5D visualization of the construction progress along with the geographical conditions by adopting colour coding which helped in pinpointing the areas that need immediate corrective actions. However, the model lacked a view to concurrently see the resources cost variances for activity along with the overall cost variance which would have added more functionality that comes along with BIM visualization capabilities.

Another BIM visualization application was the synergy of EVA and BIM by Mushamalirwa [23], which enables the user to clearly visualize the cost and time

The authors are responsible for the content of the papers.

performance of each element based on an Optimistic/Pessimistic assessment with the aid of a colour code system. This was made possible by the interoperability between Excel and Revit, and Dynamo for linking data. However, this Optimistic/Pessimistic approach might be naive since in the reality there exist more uncertainties in construction and the reality is more complex.

3.2 Cost Control

Cost control solutions with BIM focusing on the structuring of a system, are scarce. The use of BIM tools and automation for quantity take-off and estimations is researched commonly and has various applications in the industry. However, cost control still depends on spreadsheets, customized tools, and human effort mostly since it is a. dynamic process. As cost control needs a big amount of data flow from different parties, and the strategy for cost control can differ even for different projects, establishing a successful cost control system is not an easy task. The issues regarding cost-controlling practices themselves are also a factor which makes the processes harder. Interoperability of the software and quality of data and information are counted as some of the issues of BIM implementation [24]. Also lacking standards and software compatibility, and accuracy problems are other important issues [25]. Different practices, lack of standard compatibility and issues in implementing BIM require flexible solutions for different user requirements in digital cost management. Therefore, solutions such as spreadsheets, macros, plugins, and add-ins are mostly proposed for cost control in construction projects.

There are several studies on cost control and BIM integrations. Bejanaro [26] integrated earned value management into BIM connecting the Revit model with Excel via Dynamo plug-in. The author concluded the study by showing the benefits of BIM integration and visualization. Similarly, Chen et.al [27] described BIM practices for cost management throughout the life of a project starting from the preconstruction stage and conducted a case analysis for budget control with earned value analysis. Elbeltagi et.al [22] proposed a comprehensive solution for cost estimation and monitoring using the synergy of various software including Excel, Ms Project, Access, and Revit, discussing BIM and visualization provides useful information and benefits for cost control. Marzouk and Hisham [28] used bridge information modelling for earned value analysis specific for bridge construction, using BrIM methodology with Tekla Structures. In another study by Lee et.al [29] labour productivity data is acquired and monitored with BIM tools, by matching data with a 3D model object. Even though the study focuses on labour performance the principles in the study can be used for any other resource management applications.

BIM carries a huge potential for cost control integration with possible solutions to cost-controlling issues like system incompatibilities, non-collaborative works, the workload of low-tech documentation etc. [24]. The studies related to cost control varies according to approaches, tools used, type of construction, and level of required detail. Different estimation methods and techniques are used for the cost control systems. The variety of approaches can be attributed to the cost control having different practices, tools, techniques, and needs of the users. Therefore, proposed methods and solutions for cost control integration are flexible and configurable, which addresses that variety.

4. Cost Management Survey

Apart from the state of the art of cost management in construction, a qualitative survey is also a strong tool in forming a better idea about the practical applications in the field. It can also aid in determining the challenges in the industry and the shortcomings of the existing approaches in that regard. For these reasons, a survey with 17 questions was formed. It is composed of two parts, namely QTO/cost estimation, and cost control. In total 20 responses are gathered. The formation of the survey and the results are presented below.

4.1 Forming the survey and application

Firstly, when forming the questionnaire, it is significant to have an introductory section that can give us an idea about the participant

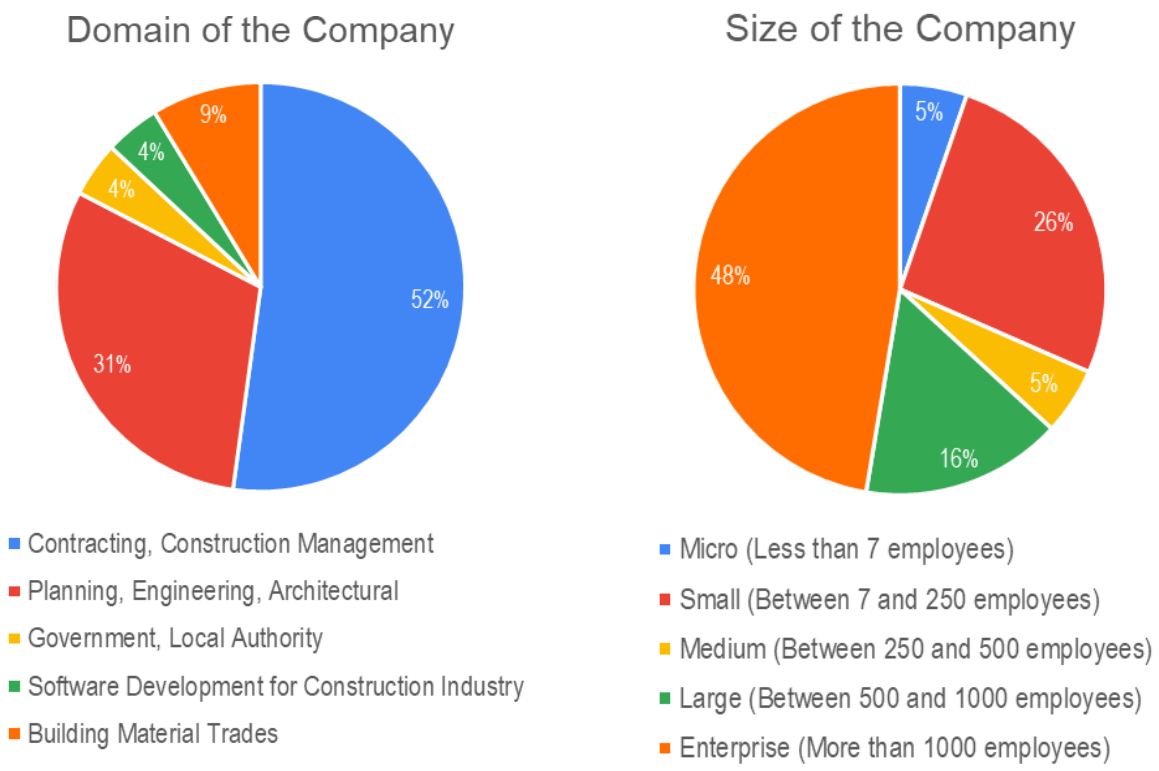

Fig. 3. Participant profile in relation to the domain of the company and the size of the company.

profile. Therefore, the first three questions are aiming to gather the contact information (email) of the participant, the domain, and the scale of the company that they are employed. This way, it is possible to assess the methods and tools in relation to the company profile.

Secondly, the questionnaire is divided into two main parts. Similar to the chronology of the application in the industry, the first part focuses on the tools, methods and problems related to QTO and cost estimation prior to the construction site, whereas the second part is focused on the cost control during the construction phase. By asking the participants about the tools and methods, it is possible to understand the level of digitalization and automation in this field, and the problems related to this issue. Each of these sections is then further divided into conventional applications and BIM, thus giving further information about the possible shortcomings of BIM applications in cost management. BIM here is used to describe a digital 3D model and the information embedded in the geometry.

The questionnaire is distributed through a QR code, and it is presented to the company representatives at Digital Bau Köln and Karrieretag Bauwirtschaft Wuppertal.

4.2 Results of the survey

In total 20 responses are gathered from various company representatives. The participant profile is shown below (see Figure 3). 52% of participants are working at companies with more than 1000 employees. Such construction enterprises are compelled to form internal systems to ensure team collaboration in different locations. Especially due to the regulations in place since 2017, companies are compelled to use BIM systems for projects with a budget over €100 million [30]. So, hypothetically the use of BIM integrated systems can be more commonly found in enterprises compared to smaller companies. However, the results do not show parallelism to this hypothesis.

Selected questions regarding QTO, and the cost estimation phase are presented below with the distribution of responses (see Figure 4). It can be seen that most of the participants are still working with PDF documents and 2D CAD interfaces that they receive from planning offices. This is a clear indication of the lack of digitalization in the construction industry as 2D drawings are not well suited to be used within automized QTO systems.

Another striking result is the most significant issues that need addressing according to the participants. The top three issues are listed (see Figure 5):

- Human errors due to manual processes,
- Quality of data exchange,
- The contradiction between documents and/or drawings.

These issues are all rooted in the lack of an automized system such as BIM.

When asked if data extracted from 3D models / BIM models could be a solution to the problems above, 52% of the participants strongly agreed, signalling the existing motivation to benefit from digital tools in the long run (see Figure 6).

More than half of the participants indicated that they are not using any BIM software(s) for QTO or cost estimation (see Figure 7 and Figure 8). When combined with the previous questions, it is clear that there is still a large gap in the industry for BIM tools in QTO and cost estimation. The following section is based on the results of the cost control part. In this section similar questions regarding tools, methods and problems in the cost control phase are asked of the participants. Selected results are presented below. The top three issues that need to be addressed regarding cost control are (see Figure 9):

- Disruptions in the process,
- Changes in the duration of the project,
- Lack of collaboration and isolated decision-making.

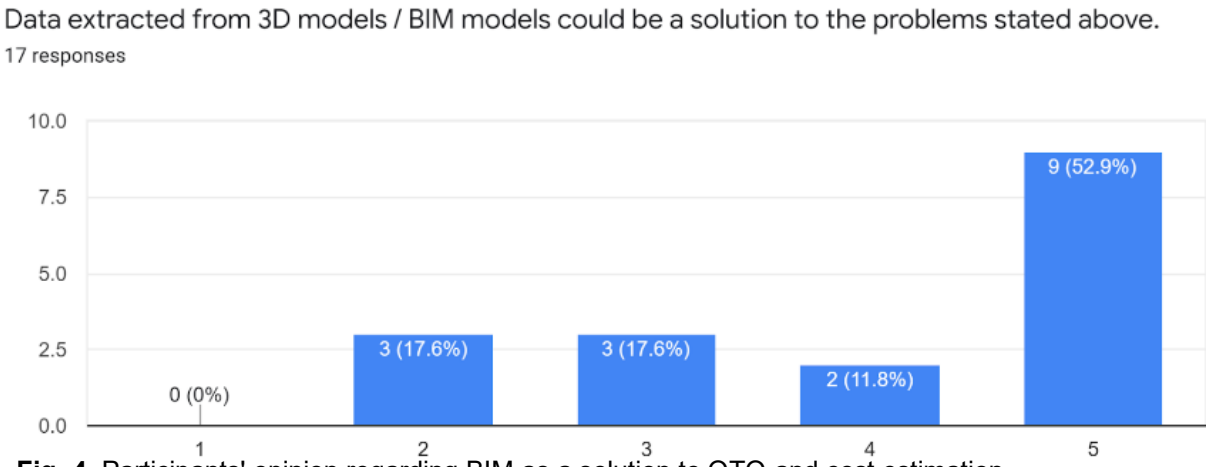

Fig. 4. Participants' opinion regarding BIM as a solution to QTO and cost estimation.

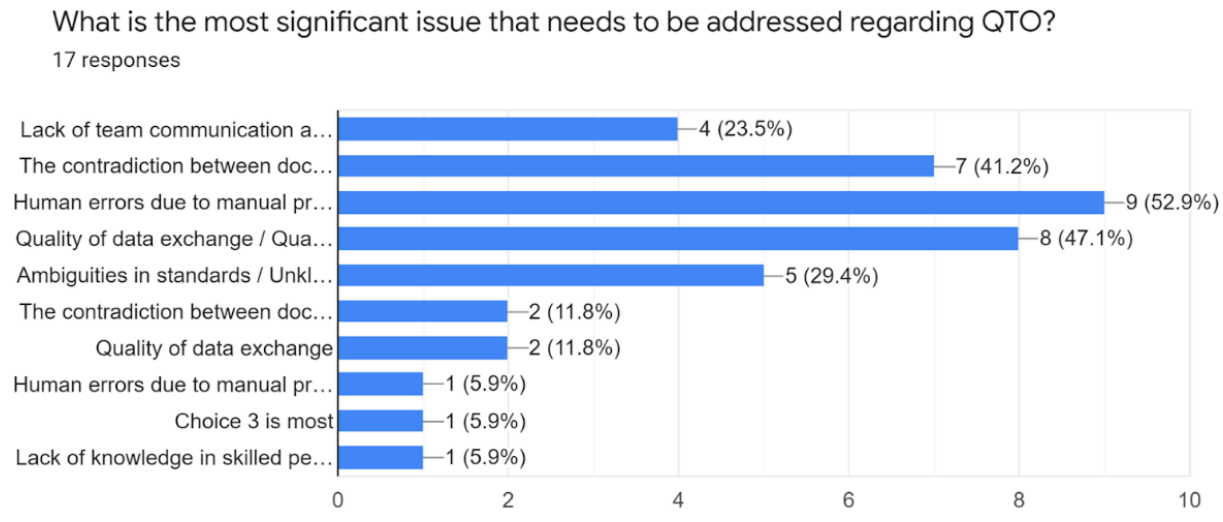

Fig. 5. Most significant issues that need to be addressed regarding QTO according to the participants.

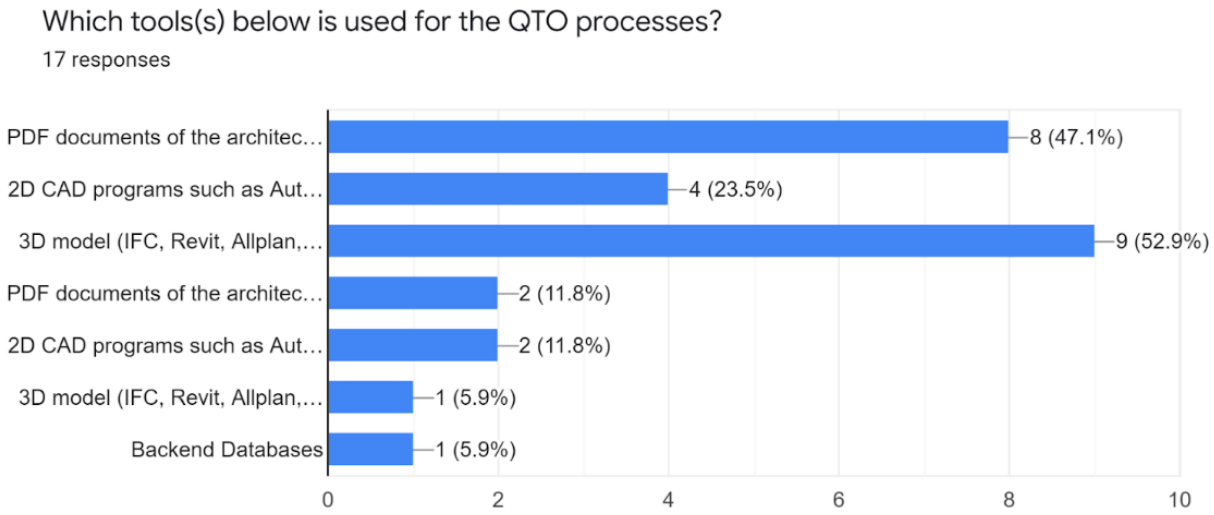

Fig. 8. Distribution of tools used for QTO processes according to the participants.

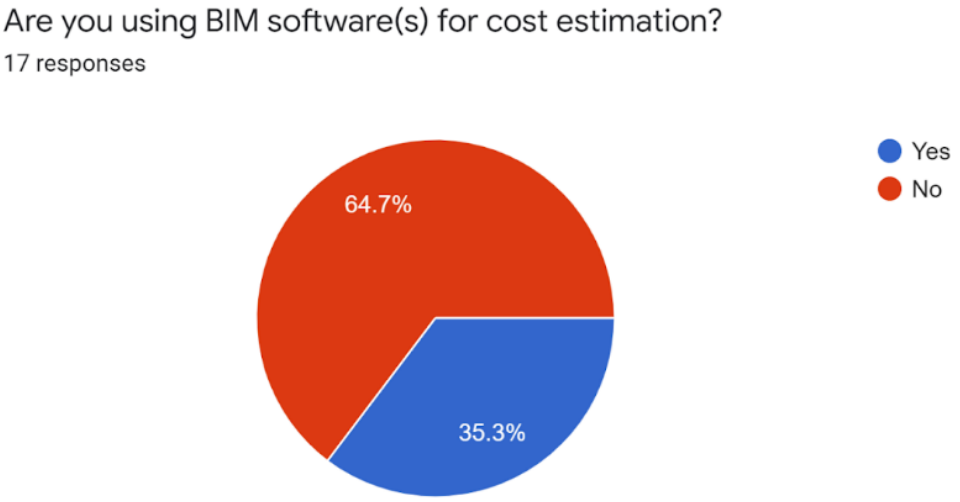

Fig. 7. Use of BIM in cost estimation according to the participants.

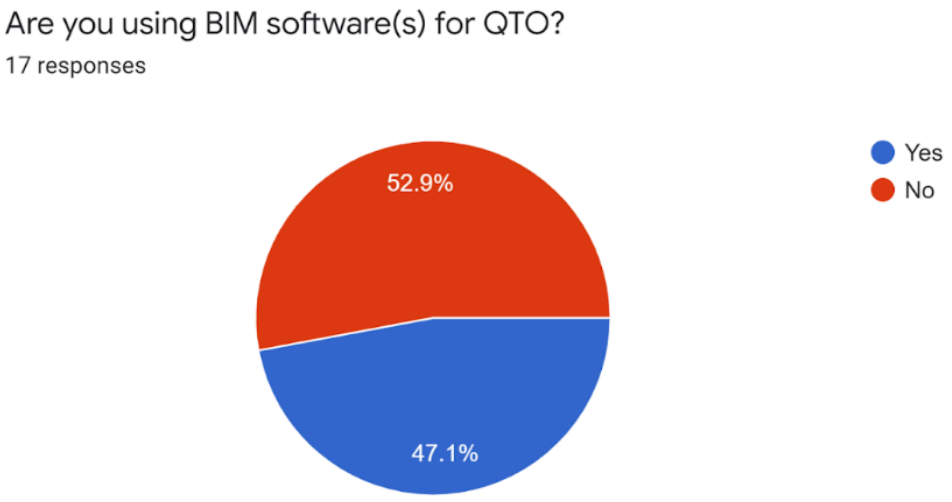

Fig. 6. Use of BIM in QTO according to the participants.

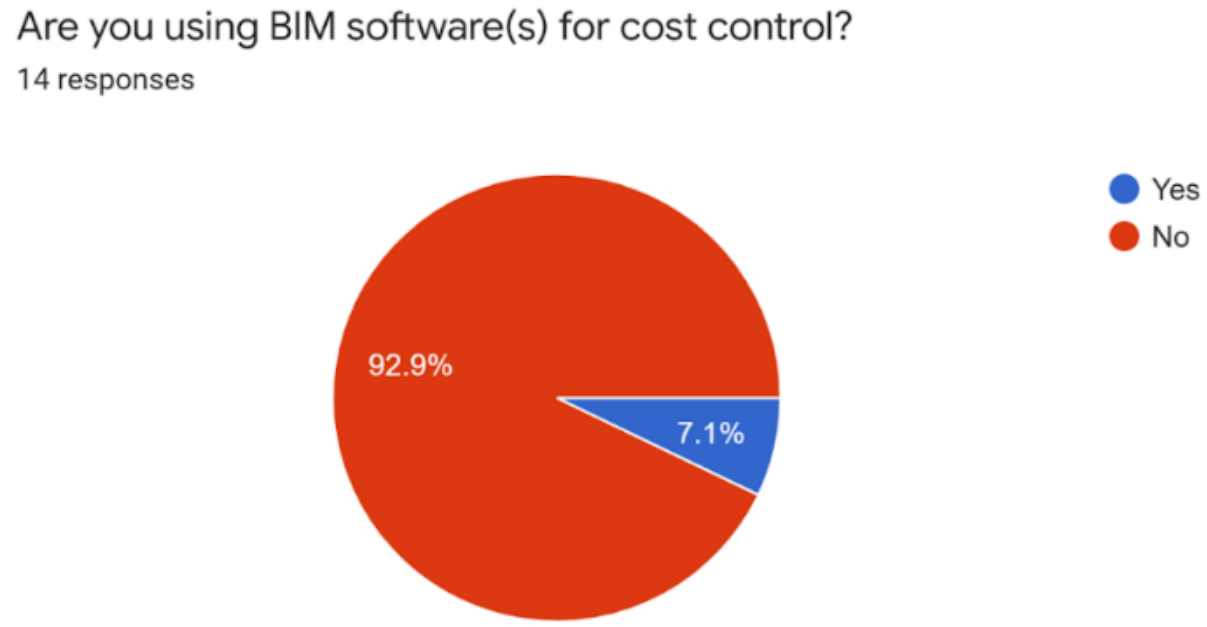

Fig. 10. Use of BIM in cost control according to the participants.

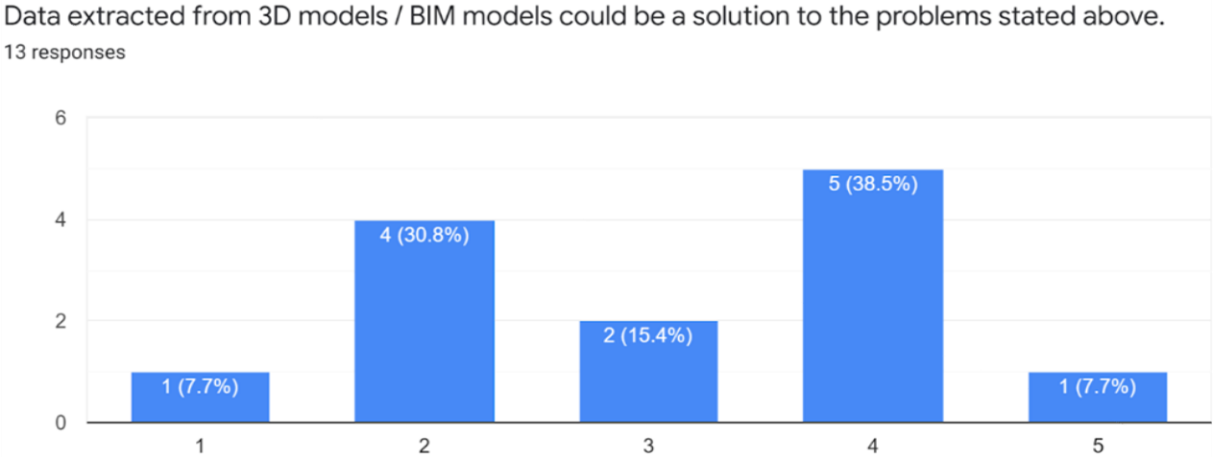

Fig. 9. Participants' opinion regarding BIM as a solution to cost control.

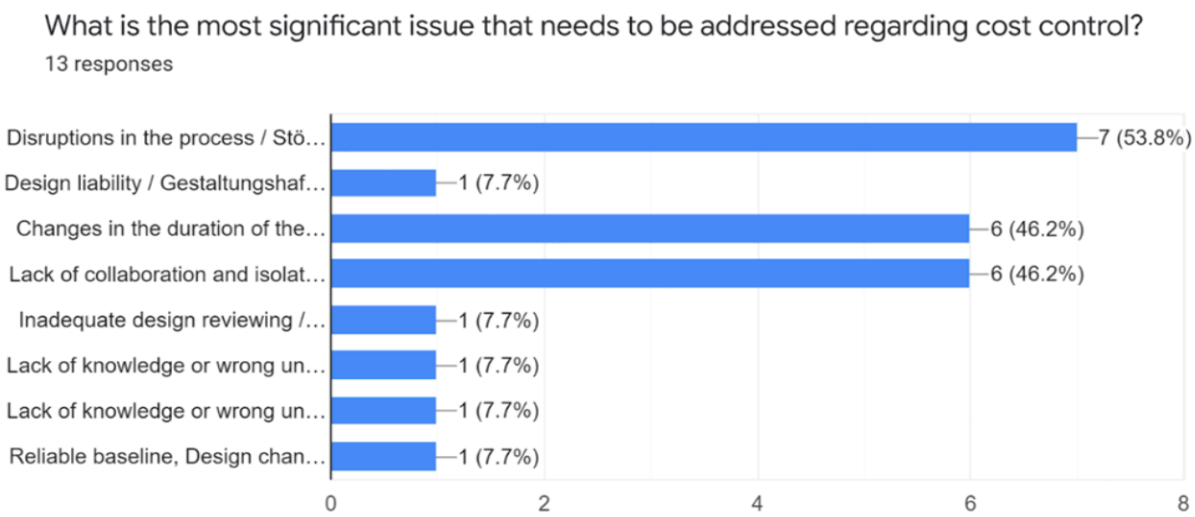

Fig. 11. Most significant issues that need to be addressed regarding cost control according to the participants.

Different from the previous section of the survey on QTO and cost estimation, BIM is not mainly viewed as the solution to these problems (see Figure 10). This may be due to the scarcity of BIM use in cost control processes (see Figure 11). 92% of the participants state that they are not using any BIM software(s) for cost control in their company. It is not possible to comprehend the benefits of automatization and to feel the lack of such tools without seeing the practical use.

4.3 Discussion of the survey results

Looking at the graphs in the previous sections, it is possible to make some deductions regarding cost management in the construction industry:

- Along the process, use of 3D/BIM models and viewing them as solutions to current problems decreases.
- There is no correlation between the size of the company and automation in cost management.
- VOB standard is used for QTO but no common standard or methodology is found for the next steps.
- PDF files are still used commonly for Quantity Take-off.
- Excel is still heavily used in cost control processes.
- Problems regarding cost control are well defined and agreed upon by the participants.
- The main problems regarding working with BIM are:
  Lack of skilled workers,
  Model quality,
  Lack of a common library for varying companies,
  Lack of specialists working on cost control.
- It is not easy to collect answers to such a specialized poll as there are not many people focused on cost management, especially the cost control part.
- There are many solutions focused on QTO and cost estimation, but very few solutions on cost control.

5. Software Analysis

5.1 Aim

While being aware of the current technology advancement rate, this chapter intends to update software comparisons regarding BIM 5D cost control solutions directly related to facilitating the connection between 3D building models and the budget during the construction phase.

The final objective is to understand the existing solutions in the market and the similarities and differences between them through the key features.

5.2 Definition of criteria

Based on past BIM 5D software analysis, a more compact amount of criteria parameters were defined to evaluate the scope of all chosen software.

These criteria parameters comprehend helpful uses across the pre-construction and construction phase which is the focus of this research.

Criteria parameters description

- Field input interface: Capacity to retrieve information from the ongoing construction in a user-friendly interface.
- Model sharing data: Information flow between model, budget, and cost control sheets.
- Support cloud applications: connection to an online database
- Interoperability: Facility of format software exchange.
- Value of completed activities: Capacity to display cost progress per activity.
- Cost overrun alert system: Feature to automatically generate a message to people in charge regarding cost control in the field and offices.
- Monitoring use of resources: Cost breakdown tracking included.
- Automatic changes cost estimation: Real-time quantification and updating from the model to the budget.

The authors are responsible for the content of the papers.

3D MODEL COST ESTIMATION AND CONTROL SOFTWARE USED IN CONSTRUCTION.						
PROVIDER /software 5D	BEXEL / BEXEL MAAGER	ACCA / Primus	RIB / ITWO	Causeway / CATO suite	Construsoft / VICO office	Autodesk / Navisworks
•Field input interface:	0.5	0.5	1	0	0	0
•Model sharing data	1	1	1	1	1	1
•Support cloud applications:	1	1	1	1	1	1
•Interoperability:	1	1	1	1	1	1
•Value of completed activities:	1	1	1	1	1	1
•Cost overrun alert system:	0.5	0	0.5	0	0	0
• Monitoring use of resources:	1	1	1	1	1	0
•Automatic changes cost estimation:	1	1	1	1	1	1
•Dashboard output interface:	1	0	0	0	1	0
TOTAL	8	6.5	7.5	6	7	5

Fig. 12. Software comparison table.

- Dashboard interface: Complete business intelligence reports in real-time.

Criteria parameters evaluation

According to the completion of the criteria parameters those who met 100% of the requirement, are graded by "1", partially implemented with a mean of "0.5" and no feature inside of the software related to the criteria parameter is graded with "0".

It is important to understand that many of this software also need a plan of implementation to accurately reach the desired performance in each parameter because often the input and output information comes from different professionals and standards which must be synchronized with these digital tools to provide a unique database which serves construction managers and cost managers to act and adjust more precisely the project parameters in order to generate savings as a return of the investment of the application of such software.

As the total sum of points shows BEXEL manager is the most complete option for private providers to companies that want to implement BIM 5D software in the construction phase. Despite the large list of features, it has a price for the single user of 2.400 € which means just a single part of investment besides professional capacitation, other necessary licenses, and extra time invested in change management for new workflows.

Finally, a tool that can meet all the requirements in the parameters analysed in the table above and still can be simple (user-friendly), flexible and affordable for any construction company regardless of its earning size is still missing in the market. The next chapter intends to show several approaches which can fill this space.

6. Approach

As an outcome of the literature review, the software comparison and the poll results, a project is proposed. There are much fewer existing solutions based on cost control compared to QTO and cost estimation. Therefore, the project focuses on a flexible workflow that creates a solution regarding cost control processes. The workflows of the two approaches (private and open-source) are presented below (see Figure 13 and Figure 14).

The flow aims for a user-friendly input and output interface that connects the cost

engineer working on the construction site and the client or project manager. This way, it will be possible to create intuitive displays that visualize the cost data on an IFC model or on a Revit model.

6.1 Database

The data plugged in by the engineer is then transferred to the database (see Appendix 1).

Excel and SQL are the best options for such a task. However, SQL is chosen as it works much more efficiently with relational tasks. The database can later be used for further applications when several project data are embedded.

Private Approach

The data plugged in by the engineer is going to be imported into Revit as Excel files.

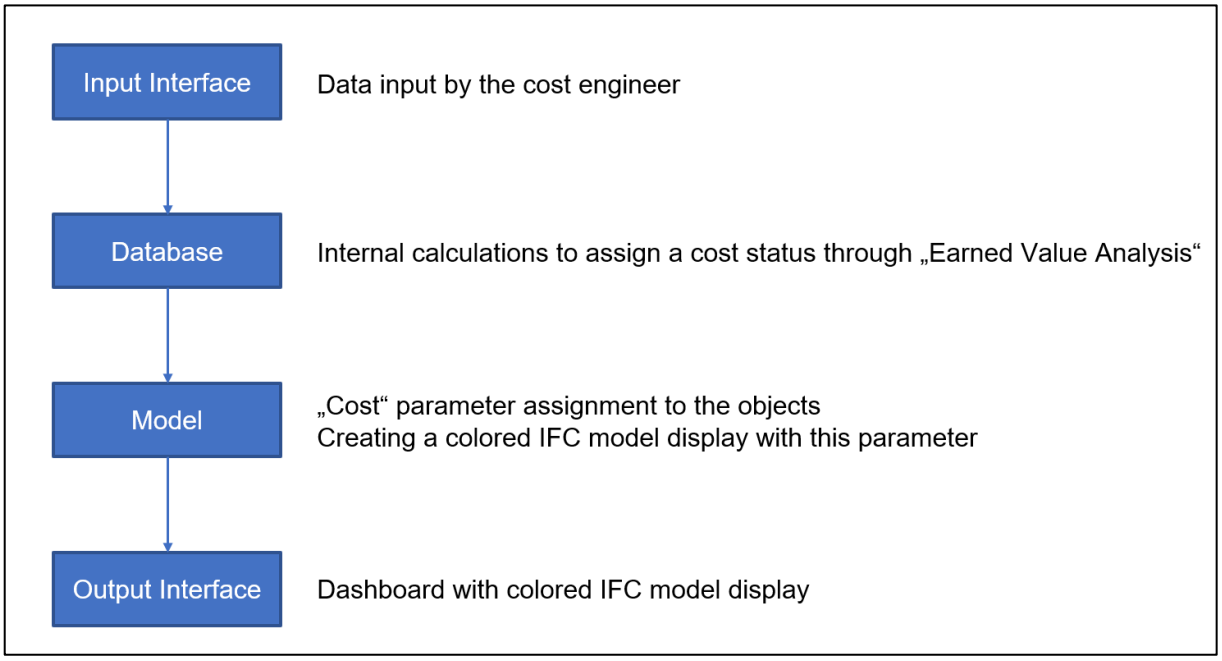

Fig. 13. Open-source project workflow.

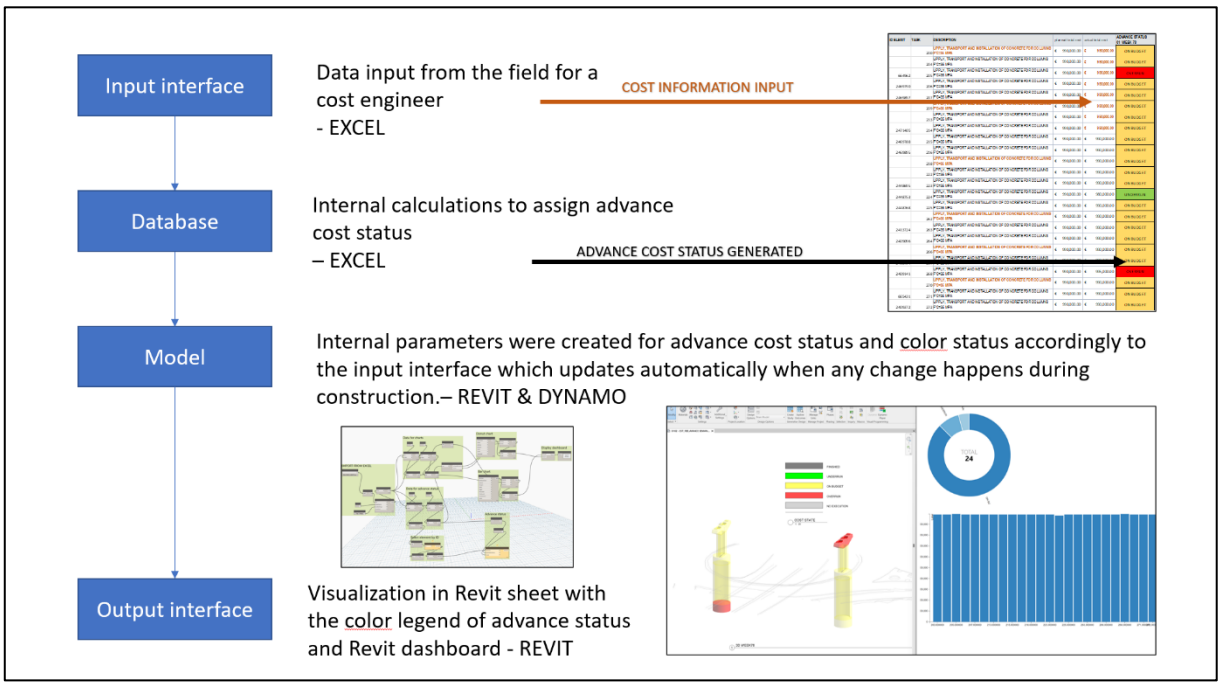

Fig. 14. Private software project workflow.

6.2 Parameter assignment to the model

To display the cost status of the building elements in a 3D model, it is necessary to assign a new parameter to these objects. As the cost parameter is not an existing IFC entity, a custom property assignment is needed. Currently, there are two working systems in this regard, the first done using open-source tools and the second using licensed tools.

Open-Source Approach

Cost status is assigned according to the comparison of "Actual Cost" and "Estimated Cost" in the database. After assigning the cost parameters, each IfcBuildingElement is given a colour representing its cost status. Building elements are coloured green if they are "under budget", blue if they are "on budget" and red if they are "over budget" (see Appendix 2).

Private Approach

Through the graphical programming tool Dynamo, the parameter for cost status is filled from imported Excel tables.

6.3 Output interface

The final step of the project is to create an output interface that the end user can utilize easily. Such an output interface comes in the form of a BIM-enabled dashboard which allows the user to easily visualize the model and corresponding cost-status to each element of the building. The main goal was to embed an IFC-viewer into the browser, which could display the cost status in colours. For this sake, a systematic approach was implemented to list probable software alternatives. Final filtering process lead to three alternatives: (1) PowerBI as an interactive data visualization environment + SeveUp as a BIM platform to import IFC data, (2) IfcOpenShell as an open source software library which allows working on IFC schema + Jupyter Notebook as a web-based interactive computing platform + Voilà which turns Jupyter notebooks into standalone web applications for making a dashboard, and (3) Autodesk Revit + Dynamo + Excel. Each of the three alternatives are thoroughly discussed and investigated within the following sections and eventually the decision upon the optimal alternative is taken.

Alternative I: PowerBI + SeveUp

Power BI service is a secure Microsoft hosted cloud service that lets users view dashboards, reports, and other Power BI apps. The idea was to embed an IFC-viewer into a BIM dashboard created on Power BI. To achieve such a goal, SeveUp App is an online platform allowing BIM actors to simply access and exploit BIM data and processes with data visualization. A new project was created containing the dashboard named "RDP BIM DASHBOARD", and the IFC model named "SoftSkills_cost_color.ifc" was imported as IFC 4 Reference View version for architecture. Now the model is ready to be exported as pbit. Extension which is supported by Power BI.

The file was then downloaded with the name "Viewer-assets", and opened with PowerBI. After all properties, assets, asset tree, QTO, and data service URL are evaluated and loaded automatically, the model was imported to the template.

After the model was loaded in Power BI desktop, the following shortcomings were observed:

1) Faulty in automatically importing queries such as AssetTreeSpatial which is the core for the IFC spatial hierarchical structure for the model according to BuildingSMART, as shown in the figure below.
2) Colours assigned according to cost status were not shown in the viewer.

After realizing these problems, it became clear the necessity to look for another alternative which can correctly import IFC Schema and show the colours assigned to each element according to cost status, which is the main aim of this approach.

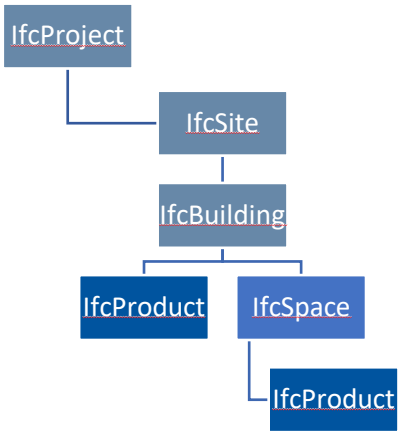

Fig. 14: IFC Spatial Tree showing model hierarchy.

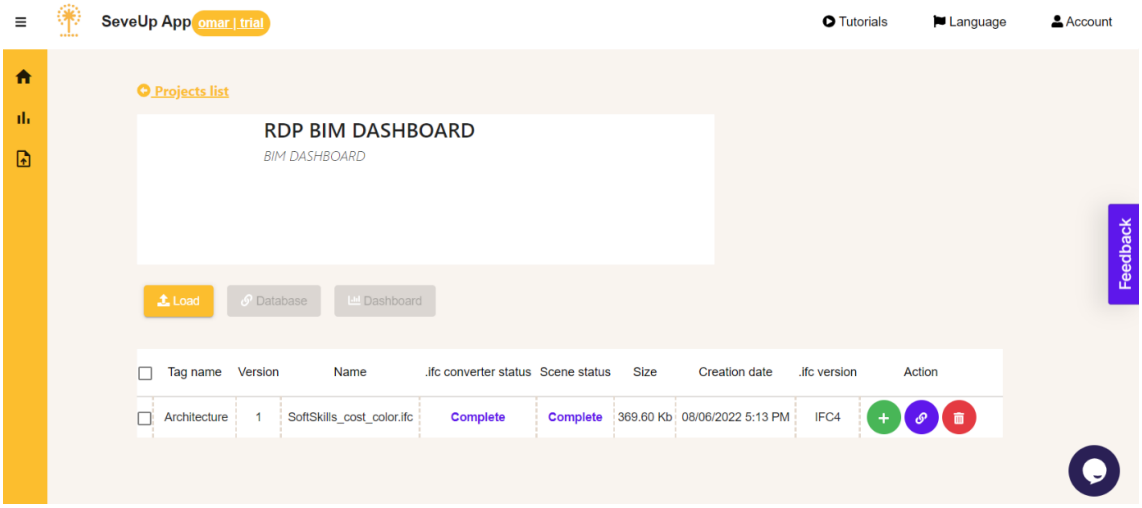

Fig. 15: RDP BIM DASHBOARD created on SeveUp App Platform.

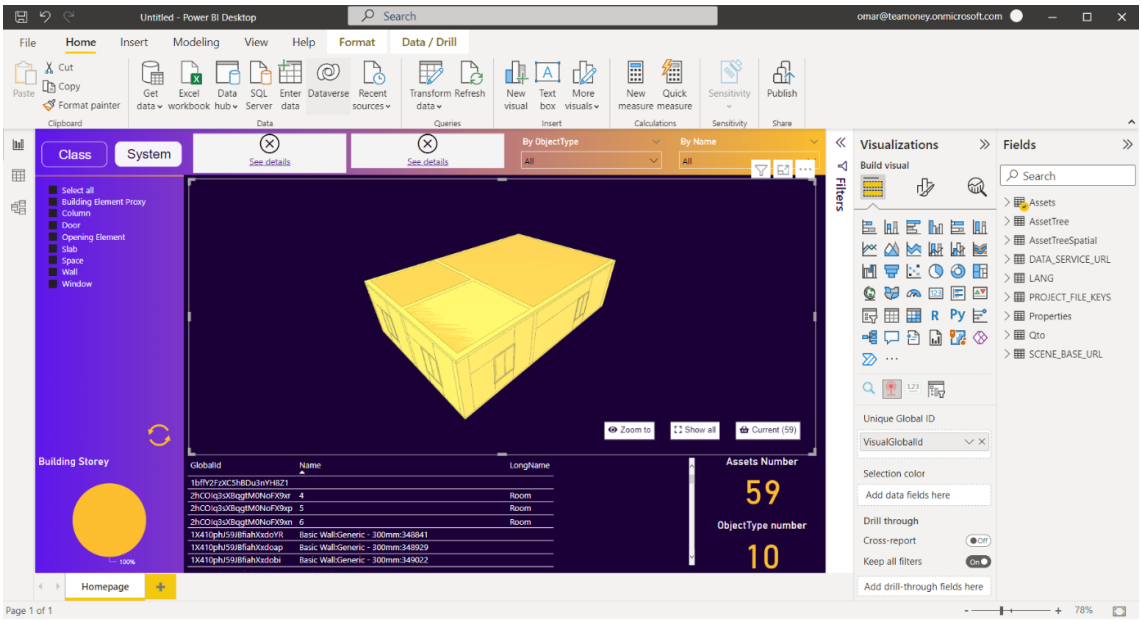

Fig. 16: RDP BIM dashboard imported to Power BI.

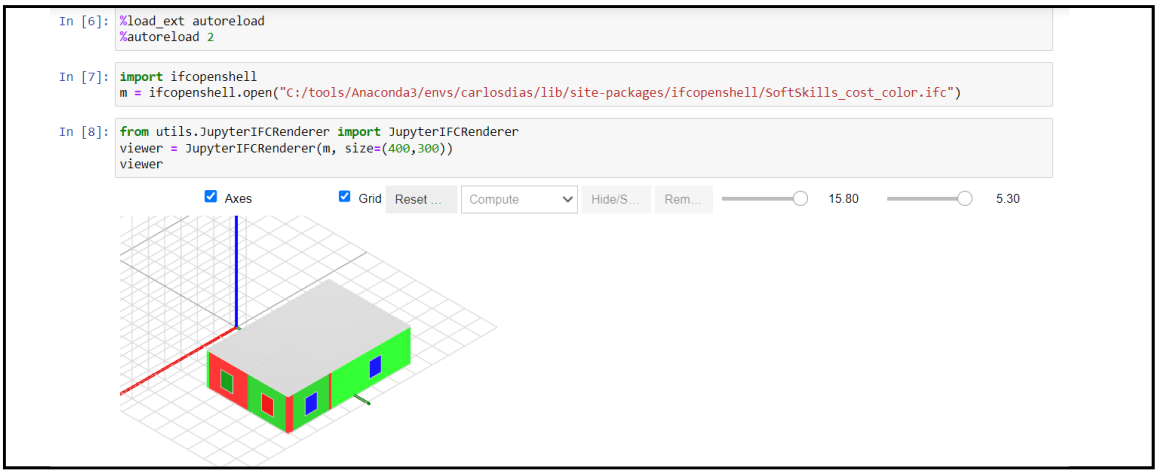

Fig. 18: IFC viewer showing the model with colors denoting cost-status of each element.

Alternative II: Jupyter Notebook + IfcOpenShell

Jupyter Notebook is a web-based interactive computing platform which promotes using IfcOpenShell as an open source software library which allows working on IFC schema. Jupyter Notebook was installed using Anoconda, and by using Anconda Powershell Prompt it was set to run via localhost. After installing Pandas package and other required packages, IfcOpenShell library was added. The interactive viewer for IFC models has been extended from Thomas Paviots' JupyterRenderer and offeres a number of functionalities. The viewer component is used to import and show the IFC model.

As can be seen from the above figure, the model is displayed with colours corresponding to cost status. Furthermore, cost data were imported as JSON format and are ready to be tabulated and accessed in the dashboard.

Using Folium made it possible to visualize data in Python by generating an interactive leaflet map. It enabled us pass rich vector/raster/HTML visualizations as markers on the map showing the location of the building. The location was set to the RWTH Construction and Robotics Reference Site.

Moreover, HTML header tags were added to make the dashboard more appealing and user friendly.

Using Voila enabled turning Jupyter notebooks into standalone web applications for making the dashboard. The output is shown in the next figure. From this point onwards, it became clear how this alternative satisfied all the requirements by being able to show the IFC model with intended colours and having all data easily manipulated by Python. The rest is a matter of styling and fixing the layout for ease of accessibility for the user.

Alternative III: Excel + dynamo + Archi-lab_Mandrill package

Using excel as a user input interface and database simultaneously, all information needed is summarized in collums where later on a dynamo script will take that data to fill the Revit model parameters to transform the model into a real-life database. Then, with the available filters for Revit visualization model can be alerted with colours of overrun, underrun or on budget legend. Finally using the same data imported to the model with help of a dynamo package called “Archi-lab_Mandrill” the information is transformed into the shape of a chart to be displayed in a comfortable dashboard which shows the principal stats of the advanced status of the sample project.

```
In [15]: import json
         with open("C:/tools/Anaconda3/envs/carlosdias/lib/site-packages/ifcopenshell/costdata.json") as f:
             data=json.load(f)

In [16]: data

Out[16]: {'IFCELEMENTS': [{'ID': '001',
             'Name': 'IfcWall',
             'Tasks': [{'ID': 'W001',
               'Name': 'Brick Laying',
               'Productivity': 5,
               'QType': 'NetVolume',
               'Ratio': 1,
               'UoM': 'm3',
               'Resources': [{'ID': 'L001',
                 'Name': 'Foreman',
                 'Quantity': 5,
                 'UnitPrice': 15,
                 'UoM': 'hr',
                 'Type': 'Labor'},
                {'ID': 'L002',
                 'Name': 'Skilled Labor',
                 'Quantity': 20,
                 'UnitPrice': 10,
                 'UoM': 'hr',
```

Fig. 19: JSON file for cost data imported to the dashboard.

```
In [20]: import folium

         m = folium.Map(location= [50.775345,6.083887], zoom_start=14)
         folium.Marker(
             [50.771450, 6.060900], popup="<i>Reference Site</i>").add_to(m)

         m
```

Out[20]:

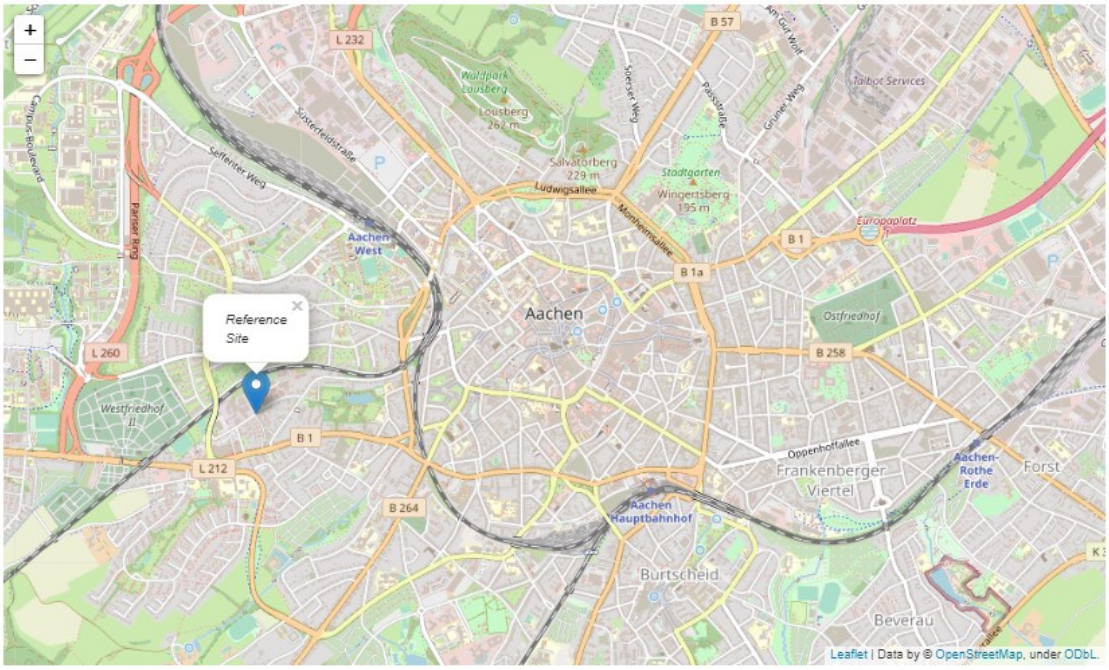

Fig. 20: An interactive map was generated to show the location of the building.

```
In [2]: from IPython.core.display import display, HTML
        display(HTML('<h1><center>RDP BIM DASHBOARD!</center></h1>'))
```

RDP BIM DASHBOARD!

```
In [3]: display(HTML('<p><h3><center>This is a BIM Visualization Dashboard made with Jupyter notebook & Voila</center></h3></p>'))
```

This is a BIM Visualization Dashboard made with Jupyter notebook & Voila

```
In [4]: display(HTML('<p><h4>The Dataset</h4></p>'))
```

The Dataset

Fig. 21: Adding HTML headers.

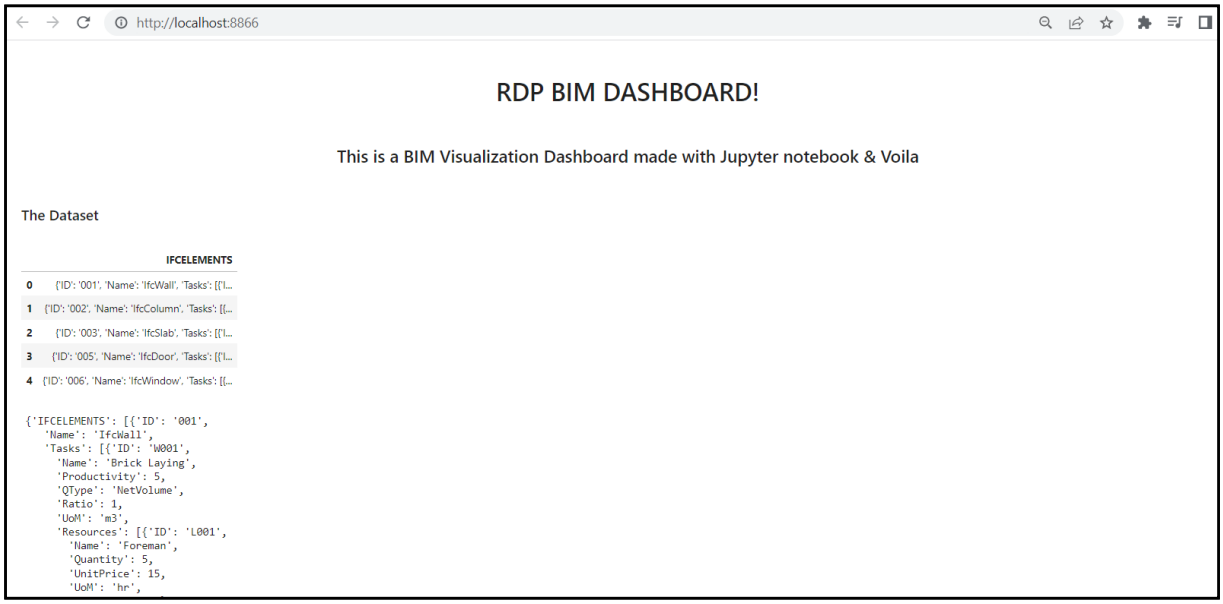

Fig. 22: Voilà was used to convert a Jupyter Notebook into an interactive dashboard and display it in a separate browser.

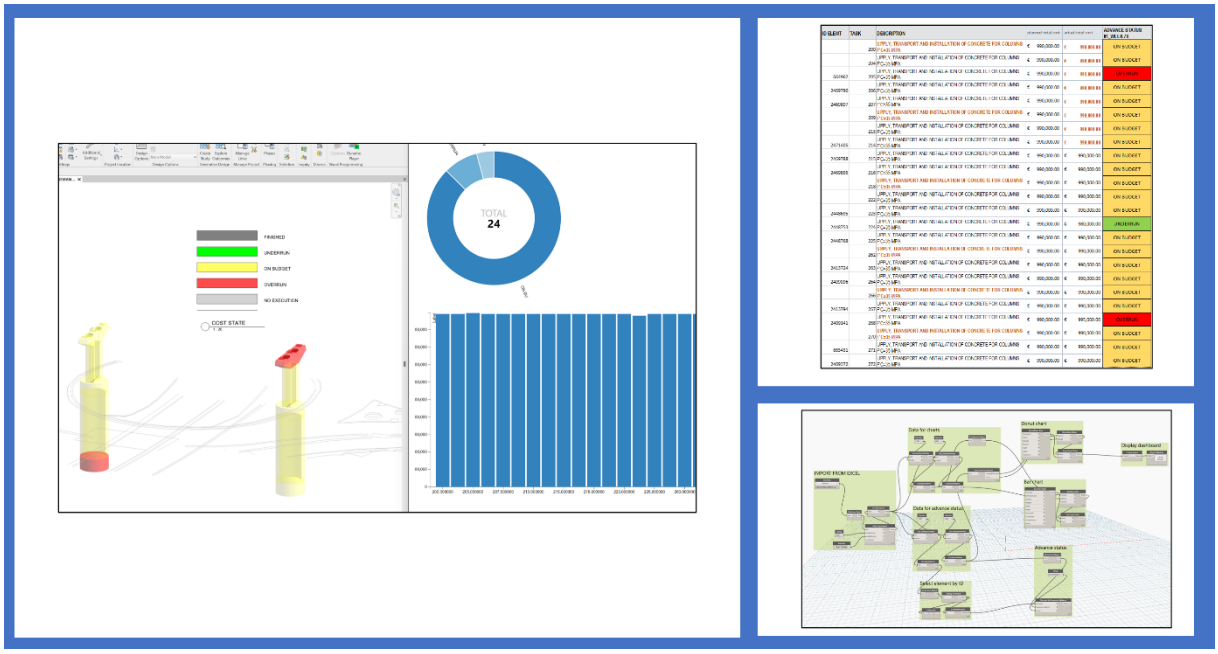

Fig. 23: Model displayed with dashboard charts with dynamo script included.

6.4 Results

As a result of this study, the initial aim was to achieve an open-source and flexible tool that can be used by the shareholders in a construction project. Currently, it is focused on the cost control phase and the visualization of cost status on an IFC model. However, it can be further developed to encompass various workflows. Additionally, with the private software approach, it can be concluded that a flexible tool such as Excel can be connected to industry standard BIM tools to generate a holistic and simple workflow for a construction company of any scale.

The softskills approach has introduced new means for exploiting BIM data and facilitating a flexible workflow which creates a solution regarding cost management processes. It was clear from the first alternative for creating a dashboard, section 6.3.1, the need for certified IFC software wherein robust implementation and correct applications for IFC2x3 and Coordination View 2.0 and IFC Reference view. It was clear how some software were not capable of importing the correct IFC Schema. There raises the necessity for standardization to enable the entire built asset industry to improve the sharing of information throughout the lifecycle of a building, and to boost interoperability between different disciplines, which is the core aim of BIM and IFC.

It became obvious how the use of IfcOpenShell library helped in building a digital platform and tools for the built environment. It allowed us to read, write and modify BIM models using IFC and we expanded beyond incorporating cost management and adding another dimension to the BIM spectrum, and by integrating other tools such as Jupyter Notebook and Voila, the dashboard was made possible and is to be even more improved in the near future by analysing more data and making it more user-friendly. It is then decided upon Alternative II as the optimal and most feasible, considering the points stated above.

7. Conclusion

A meticulous cost management approach is essential for construction, given the impact the construction industry has on the world economy. Through an analysis of the state of the art in cost management, this study presents possible solutions in various construction phases with BIM. It is a necessity to improve the cost management processes of construction projects to make quicker decisions and make timely adjustments to the project's performance. By doing so, major delays and overspending can be avoided. For this reason, concepts related to cost management in construction are introduced, poll results conducted with construction firm representatives are presented, the state of the art is discussed, and an approach is derived accordingly.

Even though there are many solutions for the pre-construction cost management phases of QTO and cost estimation, there are only a few solutions regarding cost control. Therefore, the application phase of this study focuses on cost control solutions, and it aims to create a mutual interface for construction site cost engineers and the end users such as clients or project managers. There are several studies are focusing on cost control, but it is possible to observe the lack of an integrated open-source solution with a flexible and user-friendly interface. As a result of the approach in this paper, an integrated system that can present the required information for decision-making in a single dashboard is created. The dashboard includes a 3D model coloured according to the cost status of the building elements in the database. Additionally, a private software approach is also applied to experiment with two different methodologies. As both of them are still in progress, there is ample room for improvement.

One of the main challenges was finding participants for the poll, especially engineers or architects who could answer the questions related to cost control. This is due to the fact that there are fewer professionals specializing in this particular field. The number of participants must be increased in future studies so that more solid deductions can be made.

Another challenge was the acquisition of realistic data that can represent all the aspects of a project in the industry. A sample BOQ is obtained from a German construction company alongside an IFC model. However, BOQ has turned out to be very complicated (1000 pages long only for shell construction) and often independent of the building elements in the IFC models, making it

The authors are responsible for the content of the papers.

inefficient to use it for the approach in this paper. Therefore, a simpler sample project is considered to be adequate for the purposes of this study at this stage.

The third biggest challenge was visualizing the model with the desired colours. It has been possible to display the model in the assigned colours only after removing the "IfcSurfaceStyleRendering" entity from the model as it overrides any visual preference.

In the future, a real-life project with a detailed BOQ, construction site receipts and a connected IFC model needs to be obtained from a contractor company. This way, a further prototype can be derived using a more realistic database.

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Appendix

Appendix 1

Database_01

```
import ifcopenshell
import json
from pprint import pprint
from qty import *
import sqlite3

connector=sqlite3.connect('Data/CostManagement.db')
curs=connector.cursor()
curs.execute(""" CREATE TABLE IF NOT EXISTS Summary (
  "ElementID"    INTEGER,
  "IfcRef"   TEXT,
   "Name" TEXT,
  "GuID"  TEXT,
   "PlannedValue" DOUBLE,
   "ActualValue" DOUBLE,
   "Currency" TEXT,
  PRIMARY KEY("ElementID" AUTOINCREMENT))""")

curs.execute("DELETE FROM Summary ")

with open('Data/costdata.json') as f:
    data=json.load(f)
    datas=data['IFCELEMENTS']

model=ifcopenshell.open("Data/DSSRDP(Schema4).ifc")
MonetaryUnit=model.create_entity('IfcMonetaryUnit',Currency='EUR')

def new_cost_val(valname,val):
        new_val=model.create_entity('IfcCostValue',AppliedValue=model.create_entity('IfcMeasureWithUnit',\
            ValueComponent=model.create_entity('IfcMonetaryMeasure',val),UnitComponent=MonetaryUnit))
        return new_val

for d in datas:
    ename=d['Name']
    elements=model.by_type(ename)
    tasks=d['Tasks']
    for element in elements:
        grandtotal=[]
        for task in tasks:
            t=model.create_entity('IfcTask',GlobalId=ifcopenshell.guid.new(),Name=task['Name'],Status='Not
Complete')
            resources=task['Resources']
            #get quantity of element
            definitions=element.IsDefinedBy
            for definition in definitions:
                if definition.is_a()=="IfcRelDefinesByProperties":
                    property_definition=definition.RelatingPropertyDefinition
                    if property_definition.is_a()=='IfcElementQuantity':
                        quantities=property_definition.Quantities
                        for quantity in quantities:
                            if quantity.Name==task['QType']:
                                if task['QType']=="NetVolume":

newQ=model.create_entity('IfcQuantityVolume',Name='Volume',VolumeValue=quantity.VolumeValue*task['Ratio']
)
                                if task['QType']=="NetSideArea":

newQ=model.create_entity('IfcQuantityArea',Name='Area',AreaValue=quantity.AreaValue*task['Ratio'])
                                if task['QType']=="OuterSurfaceArea":
```

```
newQ=model.create_entity('IfcQuantityArea',Name='SurfaceArea',AreaValue=quantity.AreaValue*task['Ratio'])
                    break
        elif task['QType']=="Weight":

newQ=model.create_entity("IfcQuantityWeight",Name='Weight',WeightValue=qty.netvolume(element).VolumeVal
ue*task['Ratio'])

        elif task['QType']=="Each":
                    newQ=model.create_entity("IfcQuantityCount",Name='Count',CountValue=1*task['Ratio'])
        values=[]
        for resource in resources:
            unitcost=resource['Quantity']*resource['UnitPrice']/task['Productivity']
            monetarymeasure=model.create_entity('IfcMonetaryMeasure',unitcost)

MeasureWithUnit=model.create_entity('IfcMeasureWithUnit',ValueComponent=monetarymeasure,UnitComponen
t=MonetaryUnit)
            val=model.create_entity('IfcCostValue',Name=resource['Name'],AppliedValue=MeasureWithUnit)
            values.append(val)
            resources=task['Resources']

c=model.create_entity('IfcCostItem',GlobalId=ifcopenshell.guid.new(),Name=t.Name,CostValues=values,CostQu
antities=[newQ])

        #link cost item to element

model.create_entity('IfcRelAssignstoControl',GlobalId=ifcopenshell.guid.new(),RelatingControl=t,RelatedObjects=
[c])
        model.create_entity('IfcRelAssignsToProduct',
GlobalId=ifcopenshell.guid.new(),RelatingProduct=element,RelatedObjects=[t])
        gradntotal=[]
        totalval=[]
        for x in c.CostValues:
            totalval.append(x.AppliedValue.ValueComponent.wrappedValue)

        if c.CostQuantities[0].is_a()=='IfcQuantityVolume':
            quan=c.CostQuantities[0].VolumeValue

        if c.CostQuantities[0].is_a()=='IfcQuantityWeight':
            quan=c.CostQuantities[0].WeightValue

        if c.CostQuantities[0].is_a()=='IfcQuantityArea':
            quan=c.CostQuantities[0].AreaValue

        if c.CostQuantities[0].is_a()=='IfcQuantityCount':
            quan=c.CostQuantities[0].CountValue

        totalcost=sum(totalval)*quan
        grandtotal.append(totalcost)

        print(f"Total cost of {task['Name']} for {element.Name} is {totalcost}")
    print(f"Total cost of {element.Name} with guid {element.GlobalId} is {sum(grandtotal)}")
    row=[]
    row.clear
    row=[(element.is_a(),element.Name,element.GlobalId,sum(grandtotal),0,"EUR")]
    curs.executemany("INSERT INTO Summary (IfcRef,Name,GuID,PlannedValue,ActualValue,Currency)
VALUES (?,?,?,?,?,?)", row)

curs.execute("SELECT SUM(PlannedValue) FROM Summary")
print(curs.fetchone())

connector.commit()
connector.close()
```

Database_02

```
import ifcopenshell

class qty():
    def __init__(self):
        pass

    def netarea(element):
        definitions=element.IsDefinedBy
        for definition in definitions:
            if definition.is_a()=="IfcRelDefinesByProperties":
                property_definition=definition.RelatingPropertyDefinition
                if property_definition.is_a()=='IfcElementQuantity':
                    quantities=property_definition.Quantities
                    for quantity in quantities:
                        if element.is_a()=='IfcWall':
                            if quantity.is_a()=='IfcQuantityArea' and quantity.Name=='NetSideArea':
                                break
                        if element.is_a()=='IfcColumn':
                            if quantity.is_a()=='IfcQuantityArea' and quantity.Name=='OuterSurfaceArea':
                                break
                    return quantity


    def netvolume(element):
        definitions=element.IsDefinedBy
        for definition in definitions:
            if definition.is_a()=="IfcRelDefinesByProperties":
                property_definition=definition.RelatingPropertyDefinition
                if property_definition.is_a()=='IfcElementQuantity':
                    quantities=property_definition.Quantities
                    for quantity in quantities:
                        if quantity.is_a()=='IfcQuantityVolume' and quantity.Name=='NetVolume':
                            break
                    return quantity

    def perimeter(element):
        definitions=element.IsDefinedBy
        for definition in definitions:
            if definition.is_a()=="IfcRelDefinesByProperties":
                property_definition=definition.RelatingPropertyDefinition
                if property_definition.is_a()=='IfcElementQuantity':
                    quantities=property_definition.Quantities
                    for quantity in quantities:
                        if quantity.is_a()=='IfcQuantityLength' and quantity.Name=='Perimeter':
                            break
                    return quantity

    def width(element):
        definitions=element.IsDefinedBy
        for definition in definitions:
            if definition.is_a()=="IfcRelDefinesByProperties":
                property_definition=definition.RelatingPropertyDefinition
                if property_definition.is_a()=='IfcElementQuantity':
                    quantities=property_definition.Quantities
                    for quantity in quantities:
                        if quantity.is_a()=='IfcQuantityLength' and quantity.Name=='Width':
                            break
                    return quantity
```

Appendix 2

Python code that works with IfcOpenShell library to pull the data from the database and assign colors to the building elements in the IFC file accordingly.

Main

```
from assign_cost_status import pull_data
from visualize import coloring

ifc_file_path = r'Data/SoftSkills.ifc'
export_path = 'Data/SoftSkills_cost.ifc'
export_path2 = 'Data/SoftSkills_cost_color.ifc'
data_file_path = "Data/CostManagement.db"


this_list = pull_data(data_file_path, ifc_file_path, export_path)
coloring(export_path, export_path2, this_list[0], this_list[1], this_list[2])
```


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Assign Cost Status

```
import ifcopenshell
from ifcopenshell import file
import pandas as pd
import sqlite3

def pull_data(data_file_path, ifc_file, export_path):
    index = 0

    # Read sqlite query results into a pandas DataFrame
    con = sqlite3.connect(data_file_path)
    df = pd.read_sql_query("select * from Summary", con)

    df.head()
    Array2d_result = df.values
    cells_status = []
    cells_id = []
    color_factor = []

    # Label each building ID with a cost status according to the data in the database
    for i in range(len(Array2d_result)):
        cells_id.append(Array2d_result[i][3])
        if (Array2d_result[i][4] - Array2d_result[i][5]) < Array2d_result[i][4] * (-0.05):
            cells_status.append("OVER BUDGET")
            color_factor.append(float(Array2d_result[i][4]/Array2d_result[i][5]))
        elif ((Array2d_result[i][4] * (-0.05)) < (Array2d_result[i][4] - Array2d_result[i][5]) < (Array2d_result[i][4] *
0.05)):
            if (Array2d_result[i][4] - Array2d_result[i][5] > 0):
                color_factor.append(Array2d_result[i][5]/Array2d_result[i][4])
            else:
                color_factor.append(float(Array2d_result[i][4])/Array2d_result[i][5])
            cells_status.append("ON BUDGET")
        else:
            cells_status.append("UNDER BUDGET")
            color_factor.append(float(Array2d_result[i][5])/Array2d_result[i][4])

    #read ifc file and get all the building elements into an array
    ifcfile: file = ifcopenshell.open(ifc_file)
    products = ifcfile.by_type("IfcBuildingElement")
    owner_history = ifcfile.by_type("IfcOwnerHistory")[0]
    building_elements =[]
    for i in products:
        building_elements.append(i)
    toDelete = ifcfile.by_type("IfcSurfaceStyleRendering")
    for a in toDelete:
        ifcfile.remove(a)

    #cross-reference the model and the excel values
    for i in building_elements:
        for j in cells_id:
            if j == i.GlobalId:
                property_values = [
                ifcfile.createIfcPropertySingleValue("Cost Status", "Cost Status",
ifcfile.create_entity("IfcText",cells_status[index]), None),]

                #assign the properties according to the excel table
                property_set = ifcfile.createIfcPropertySet(i.GlobalId, owner_history, "Cost Status ", None,
property_values)
                ifcfile.createIfcRelDefinesByProperties(i.GlobalId, owner_history, None, None, [i], property_set)
                index = index + 1
    #export
    ifcfile.write(export_path)
    return cells_status, cells_id, color_factor
```

Visualize

```
from ifcopenshell import file
import ifcopenshell.util.schema
import assign_cost_status
from assign_cost_status import pull_data

def coloring(export_path, export_path2, cells_status, cells_id, color_factor):
    shapes = []

    # pull the exported ifc with cost parameters
    ifcfile: file = ifcopenshell.open(export_path)
    products = ifcfile.by_type("IfcBuildingElement")

    for p in products:
        try:
            shapes.append(p.Representation.Representations)
        except:
            shapes.append(0)

    # color building elements according to their cost status
    for i in range(len(products)):
        for y in range(len(cells_id)):
            if products[i].GlobalId == cells_id[y]:
                if shapes[i] != 0:
                    if cells_status[y] == 'ON BUDGET':
                        IfcColourRgb_Blue = ifcfile.createIfcColourRgb('blue', 0.1, 0.1, color_factor[y])
                        IfcSurfaceStyleShading = ifcfile.createIfcSurfaceStyleShading(IfcColourRgb_Blue, .0)
                        IfcSurfaceStyle = ifcfile.createIfcSurfaceStyle(IfcColourRgb_Blue.Name, "BOTH",
(IfcSurfaceStyleShading,))
                        Assign = ifcfile.createIfcPresentationStyleAssignment((IfcSurfaceStyle,))
                        for s in range(len(shapes[i])):
                            items = shapes[i][s].Items
                            for item in items:
                                IfcStyledItem = ifcfile.createIfcStyledItem(item, [Assign], 'Label_On-Budget')
                    elif cells_status[y] == 'OVER BUDGET':
                        IfcColourRgb_Red = ifcfile.createIfcColourRgb('red', color_factor[y], 0.1, 0.1)
                        IfcSurfaceStyleShading = ifcfile.createIfcSurfaceStyleShading(IfcColourRgb_Red, .0)
                        IfcSurfaceStyle = ifcfile.createIfcSurfaceStyle(IfcColourRgb_Red.Name,
"BOTH",(IfcSurfaceStyleShading,))
                        Assign = ifcfile.createIfcPresentationStyleAssignment((IfcSurfaceStyle,))
                        items = shapes[i][0].Items
                        for s in range(len(shapes[i])):
                            items = shapes[i][s].Items
                            for item in items:
                                IfcStyledItem = ifcfile.createIfcStyledItem(item, [Assign], 'Label_Overrun')
                    else:
                        IfcColourRgb_Green = ifcfile.createIfcColourRgb('green', 0.1, color_factor[y], 0.1)
                        IfcSurfaceStyleShading = ifcfile.createIfcSurfaceStyleShading(IfcColourRgb_Green, .0)
                        IfcSurfaceStyle = ifcfile.createIfcSurfaceStyle(IfcColourRgb_Green.Name,
"BOTH",(IfcSurfaceStyleShading,))
                        Assign = ifcfile.createIfcPresentationStyleAssignment((IfcSurfaceStyle,))
                        items = shapes[i][0].Items
                        for s in range(len(shapes[i])):
                            items = shapes[i][s].Items
                            for item in items:
                                IfcStyledItem = ifcfile.createIfcStyledItem(item, [Assign], 'Label_Under-Budget')

    ifcfile.write(export_path2)

    return()
```


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Reuse of existing precast panels as a low carbon alternative - Design proposals through the use of digital tools

ABSTRACT

The reuse of building components from existing buildings is a great potential in the aim of reducing the Co2 emissions towards a more sustainable building construction industry.
The current stock of existing buildings of this typology is relatively large and it can be used as a resource from which the components can be reused. There is evidence of successfully completed building projects made out of existing concrete components and also attempts to use automation of the dismantling process through robotics implementation. The design discipline has an important role in order to properly plan, coordinate and implement this process. However, one issue associated with the design is the uncertainty related to the physical properties of the existing components when put in a new design context. This introduces additional constrains through the design process.
In order to have more freedom in the design and to put these components in various spatial configurations, a reliable assessment of their existing mechanical and geometrical properties is required. This information can be modeled as a digital asset and then can used by the designer in order to make the right design decisions in terms of both architecture design and structural integrity of the new design. This paper discuss and investigate how existing stock of prefabricated building panels can be used through BIM information to achieve the optimum architectural design configuration with the least carbon footprint for the environment. This research includes structure investigations and design experiments beside co2 emissions calculations to prove the hypothesis.

Keywords:– Assessment – Co2 emissions – Carbon footprint – Prefabricated panels– Information Modeling - Digital Model

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Image from Freepik

1. Introduction

1.1 Motivation

Building construction industry is responsible for a total of 38% of global energy-related emissions.[18] Decarbonizing the buildings and construction sector is currently a challenge addressed in a worldwide context in order to reach predefined objectives such as Paris Agreement commitment and the United Nations (UN) Sustainable Developments Goals (SDGs).[23]

Reusing existing concrete panels for new buildings is a study area of interest with the goal of reducing the overall greenhouse gas emissions caused by the building sector. As a general quantitative indicator, is worth mentioning that one m^3 reused panels consumes only 2.6 liters of heating oil in comparison to the production of 1 m3 of concrete which consumes 50-55 liters of heating oil.[8]

Several aspects such as the stock availability of this building typology, the dismantling properties of their components and their relatively good product quality, are the grounds of motivation for this paper, in which proposals are discussed focusing on practical methodologies and workflows in the design domain.

1.1 Problem statement

One of the challenges when designing with existing components is to find reliable structural schemes, compositions and arrangements which can integrate the element of precast panel in order to effectively reuse these components in new design contexts.

In the architectural point of view, the new design by using existing components must always produce solutions that do not violate the structural integrity of the new designed system.

When designing with such existing precast components, the architect has to strategically provision where to place these components in the new project arrangement. The new position of these wall panels in the future project must ensure that none of these components are overloaded. In other words, the existing panels should not withstand a load higher than they are designed for in their original design.

In the structural point of view, the design model for the existing component must have all the necessary parameters to allow for a structural design and calculations to be performed. Accurate as-built information of the component is required along with effective structural models and schemes which integrate the components in a structural system.

The description of the process for on-site deconstruction is not part of this paper but rather is considered as an already feasible task which has to be integrated into the planning and design process.

In order to achieve an efficient, low carbon and circular construction processes, the design task can play an important role by planning and provisioning that every component to be placed at the most efficient location in the project by fulfilling all the requirements. Therefore, intelligent conceptual design methods should be implemented by combining the technology of information, computational design and classical principles of engineering design.

1.2 Goal

The overall goal is to be able to achieve a sustainable and low carbon building typology by embracing the approach of adaptive and reuse for the precast building components.

The topics discussed in this paper propose ways how to use the process of on-site assessment and information modeling in combination with already available digital tools used in the design environment.

The overall principle is to use the information taken from site and to create digital properties and parameters for the physical building elements.

These parameters can be further used to create rule-based conceptual design and also structural design respectively for the architecture and structure discipline.

As shown in the following diagram, the proposed workflow imagines a scenario where a building has to be deconstructed and its building components (wall panels) will be reused in a new design.

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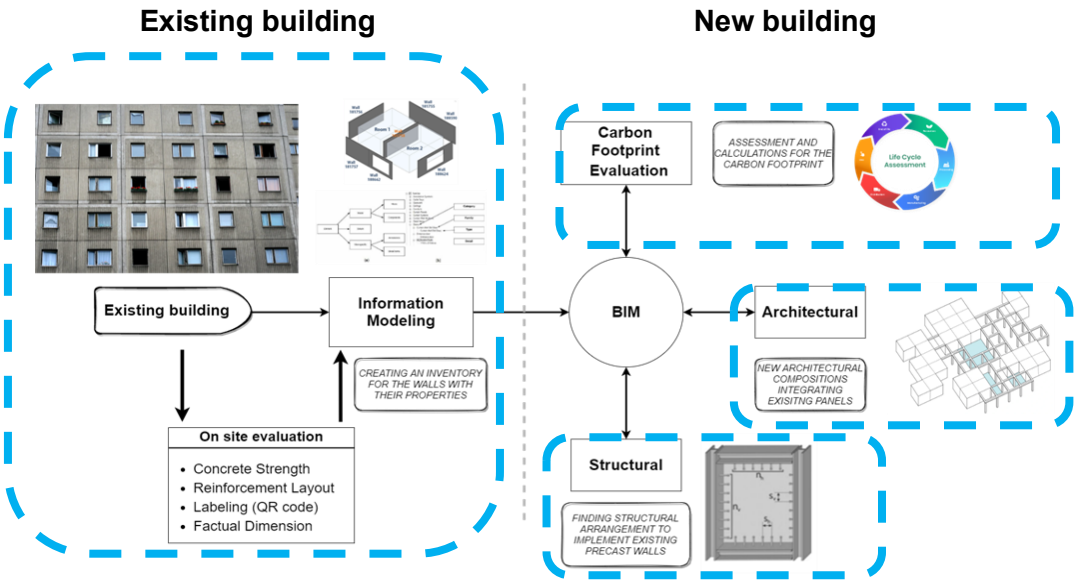

Fig. 1. Research goal diagram explaining the process from existing building till new building [1] [2] [3] [4] [5]

The process starts by collecting the information on site from the donor building, converting it in digital properties related to the prefabricated components.

Then, the information is transferred it to a design BIM model. Further, this BIM model is used in the design environment in order to evaluate the architectural and structural arrangements by taking control over the carbon footprint of each design option.

2. Research methods

The research method is focused mainly on literature research of existing papers, case studies of real-life projects, research related to prototype tests, research for the available technologies and state of the art software. Overall analysis with indicators is presented in terms of their usability, whether they apply to the architectural norms and the benefits on their dismantling and reuse with regards to Co2 emissions reduction. Then real executed projects are presented showing various ways on how this concept was implemented in new architectural context.

2.1 State of the art, literature research

The first part of literature research focuses on the state of the art concerning the existing prefabricated panels and their reuse. It is subdivided into research for existing stock of buildings and into research of existing case projects implementing the concept of panel reuse in new design. State of the art software and calculations tools are investigated in order to be utilized and implemented for a comparison analysis.

2.2 Concepts of panel reuse, literature research

The second part of the research is focused on the practical point of view from the design perspective. It describes the current work and evidence related to structural systems and recent development on some innovative systems which already implement infill walls. Research relating to structural domain is analyzed as a background for new discussions and proposals. In addition, conceptual design options are created to present the feasibility of the concept. Lastly, the current methodology of Life Cycle Assessment (LCA) is presented together with best practices for carbon footprint calculation. These will serve as a framework for calculating the footprint for different design options described in this paper.

2.3 Assessment

Structural Properties

This paragraph describes more technically the research findings and the parameters related to the components.

On-site process

Available tools and technologies are investigated, which would allow the assessment of necessary parameters from site environment.

Co2 Emission assessment

Research and methodology for calculating of carbon footprint is described through this chapter aligning to the Life Cycle Assessment concepts.

3. Results and Discussion

3.1 State of the Art on existing building stock

A great share of European housing was built with a large-panel system within the 1960s and 1970s.[6] During this time, for example in Germany, building blocks differ according to estate size as shown in figure 1 , with almost 800, 000 units of housing built for 2 million people in large estates having more than 2,500 blocks, 4-5 stories towers existed in up to 7500 flats estates and height up to 20 stories were in larger estates as Cologne-Chorweiler or Berlin's Märkisches Viertel.[7] Figure 1 shows the distribution of the panel housing system across Germany in different states.

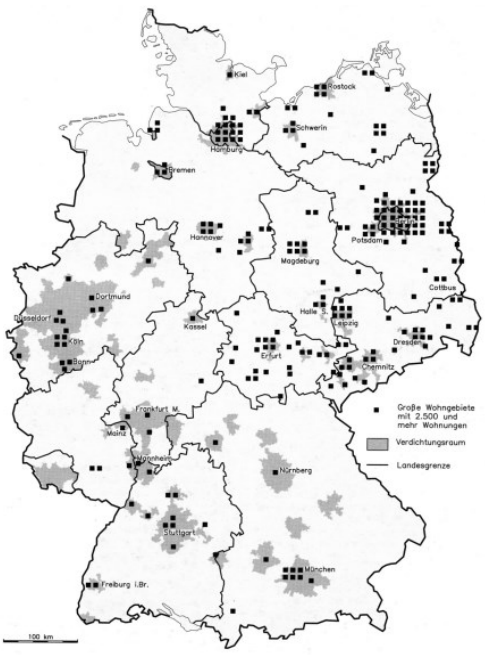

Fig. 2. Panel system housing distribution across Germany in the 1960s and 1970s [7]

East Germany has completely implemented prefabricated buildings as the dominant form of construction and to large residential complexes as the dominant urban model [7]. East Germany prefabricated buildings from 3 to 20 stories are commonly seen from the traditionally industrialized southern hill regions [7]. Starting in the 1970s, greenfield construction became easier and more economical, especially as land became more freely available through expropriation, as shown in Figure 2. [7]

Prefabricated concrete wasn't only for residential high blocks but also was used for production of business building [8].

A study conducted about Finnish panel system building was focused on the review of the existing prefabricated buildings and their standardized dimensions of the components. The main goal was to compare these dimensions with the current architectural design norms for dimensioning living spaces.[6]

Figure 3 shows a summarized table with the required dimensions of the components used as a standard in Finland since 1969. This guideline has remained in use in the construction of blocks of flats and offices ever since.[6]

Figure 4 shows main panel types from left to right: blind load-bearing panel; typical non-load-bearing panel with a normal window, and non-load-bearing balcony back wall panel [6]

The amount of different panel types are shown in the following Figure 5 according to panel typology and openings. Load-bearing panels are most often blind. Non-load-bearing panels almost always have a window, or a window with a door if they are balcony back walls [6].

3.2 State of the Art on Previous experiments

During this research several conducted experiments were studied focused on converting existing buildings panels into new building typologies and functions.

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Building part or structure	Dimension(s), mm
Floor height	2800
Room height	2500
Modular dimension, load-bearing structures	1200
Modular dimension, adjoining structures, horizontal direction	300
Modular dimension, adjoining structures, vertical direction	100
Load-bearing panel, possible width	1200, 2400, 3600
Non-load-bearing one-room panel, possible width	3000, 3300, 3600, 3900, 4200
Non-load-bearing two-room panel, possible width	6000, 6300, 6600, 6900, 7200
Hollow-core slab, width	1200
Hollow-core slab, maximum length	13000
Hollow-core slab, thickness	265
Load-bearing part of exterior sandwich panels, thickness	150
Load-bearing interior walls, thickness	180

Fig. 3. Table showing the standardized dimensions of the components in Finland 1969 [6]

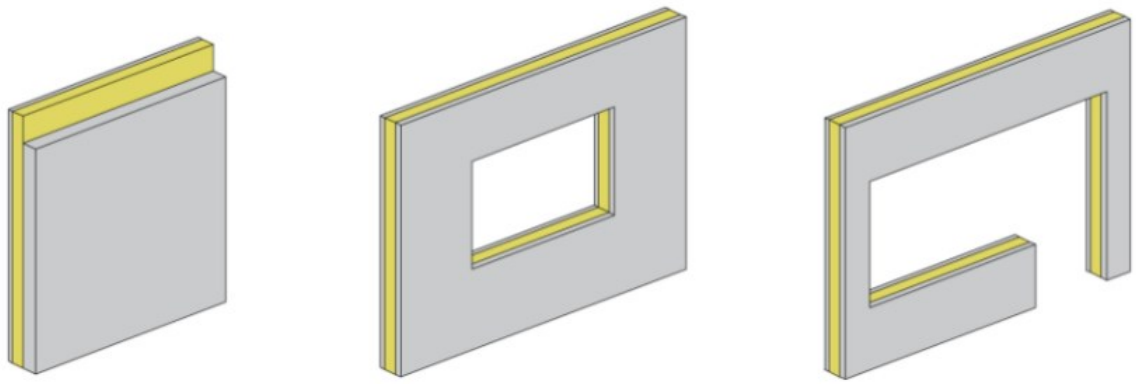

Fig. 4. Main panel's typology [6]

A test building was constructed from interior walls and prestressed concrete slabs of type WBS 70 [8].The first project was completed in October 2005 (200 square meters of living space) as shown in figure 6 . The demounting, processing, and remounting of the equipment took place within 12 days. Altogether, 118m³ of prefabricated concrete units were reused. This corresponds to an oil equivalent of 5900 liters.[8]

A prototype building was developed by Technical University of Berlin TUB which consists on a small scale building constructed with reused components for interior walls and slabs made of type WBS 70. These components had to be further treated through several processes such as concrete sawing and strengthening [24]. Figure 7 shows processes of component treatment and the final built prototype.

Another experimental project is a pilot house in Mehrow Berlin (Architecture bureau CONCLUS) [24].

It consists on a 200 m^2 building realized with wall panels taken from a donor building 8 km away (figure 8).

A similar pilot project by the same authors was developed in Karow Berlin [24].

It consists on a 180 m^2 house construction built with walls taken from another building. These walls were then covered with an ETIC (External thermal insulation composite) as shown in figure 9. Altogether, 245 m³ of prefabricated concrete units were reused.

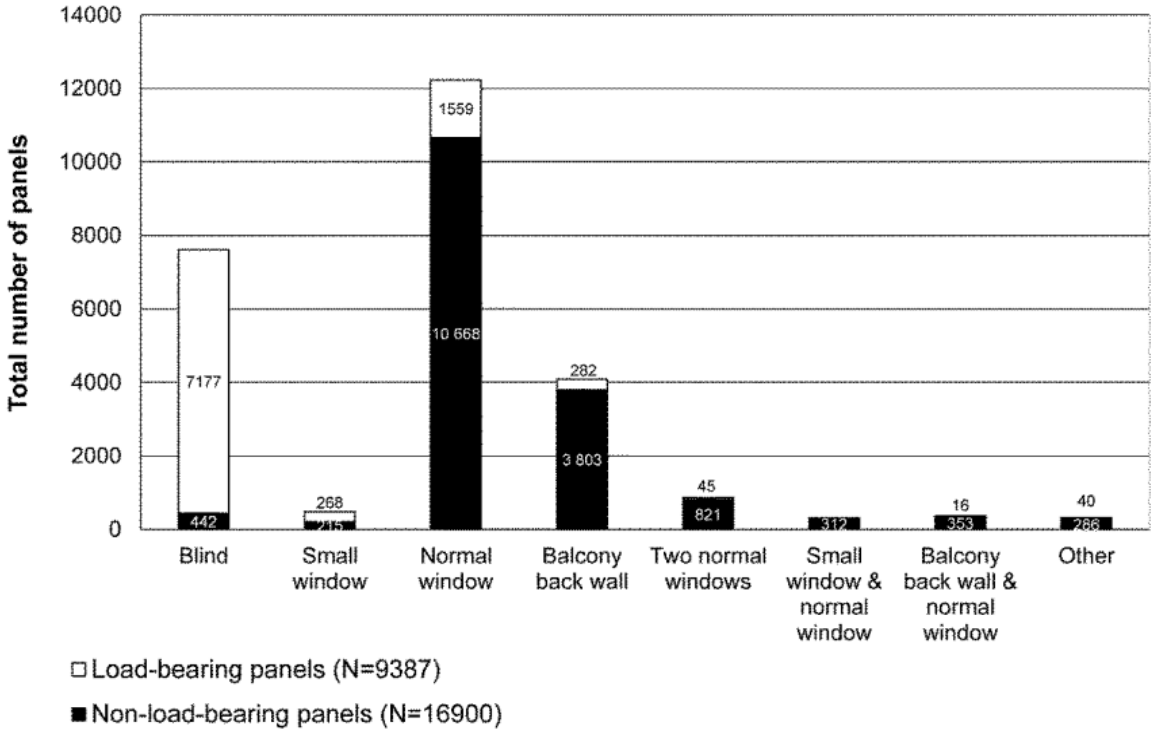

Fig. 5. Main panels Typology distribution according to load bearing and non-load bearing panels [6]

This corresponds to an oil equivalent of 12.250 liters. [8]

As part of a master thesis work from Alexandros Glias at TU Delft, an experimental design was performed integrating existing precast components into a new architectural design [25]. Figure 10 shows the reuse of existing precast beam-column frame as interior design elements while wall panels used as an exterior system.

Raahen Kummati neighborhood rehabilitation in Finland used existing panels and the connection between the concrete panels was opened using a chiseling robot. The result was a reduction of 36% in the financial cost of the project. [6]

The team of architects and engineers known as LID and GXN decided to use the principles of the circular economy, prefabricated architecture, and digital fabrication in order to transform and up-cycle many architecturally outdated buildings. [9]

The implementation of robotics may allow for the reuse of reclaimed building materials, followed by a treatment provisioned in designated facilities. The information assessed from this process may then be updated in a material passport [9]. Figure 14 illustrates the process from deconstructing of the panels to their further treatment and reconfigurations using robotics technology.

Another work suggesting for scientific steps to be followed toward the deconstruction of existing buildings is that of Ella Kaira in her master thesis about concrete reuse.

It focuses on three main specific steps such as:

1-Reviewing of existing architectural and structural drawings.

2-Inspecting structural systems and the number and typology of reusable elements and norms

3-Evaluating the cost of the deconstruction.

If all these factors result positively, then a form of the components catalogue including structural properties of the elements may be created. Finally, the data can be saved as BIM objects in a building design software.[10] Figure 13 briefly illustrates a specific precast component with its properties taken out from an existing building.

The authors are responsible for the content of the papers.



Fig. 6. New residential house out of high rise donor building [8]



Fig. 7.TU Berlin prototype. Steps from the processing of components to the final constructed prototype [24]



Fig. 8. Pilot house Mehrow. Steps from mounting of the carcass to the final completed building [24]



Fig. 9. Pilot house in Karow. Panel covering with ETIC insulation system [8] [24]

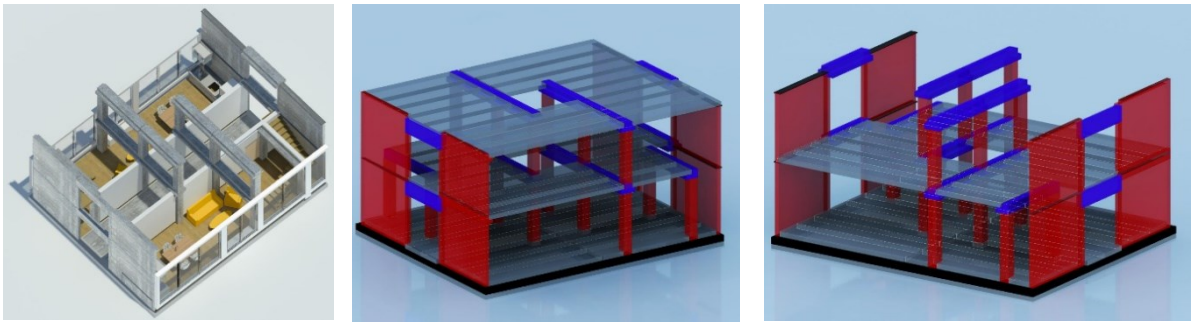

Figure 10. New design with existing precast beam, column and wall panels [25]

3.3 Topic 1 discussion. Geometrical reconfigurations of panels and the conceptual design in a BIM software.

An interesting field of application is the design scenario where the dismantled panel components are being reused in different geometrical configurations to create new architectural spaces and compositions.

As a common practice, the architects use the standardized shape of the panels and the modular nature of the original design to recreate new spaces and architectural elements.

An effective design principle during this process when working with bearing walls may be to ensure that the original span between two parallel bearing walls should not be exceeded in the new design. This is very



Fig. 11. Neighborhood rehabilitation in Finland [6]

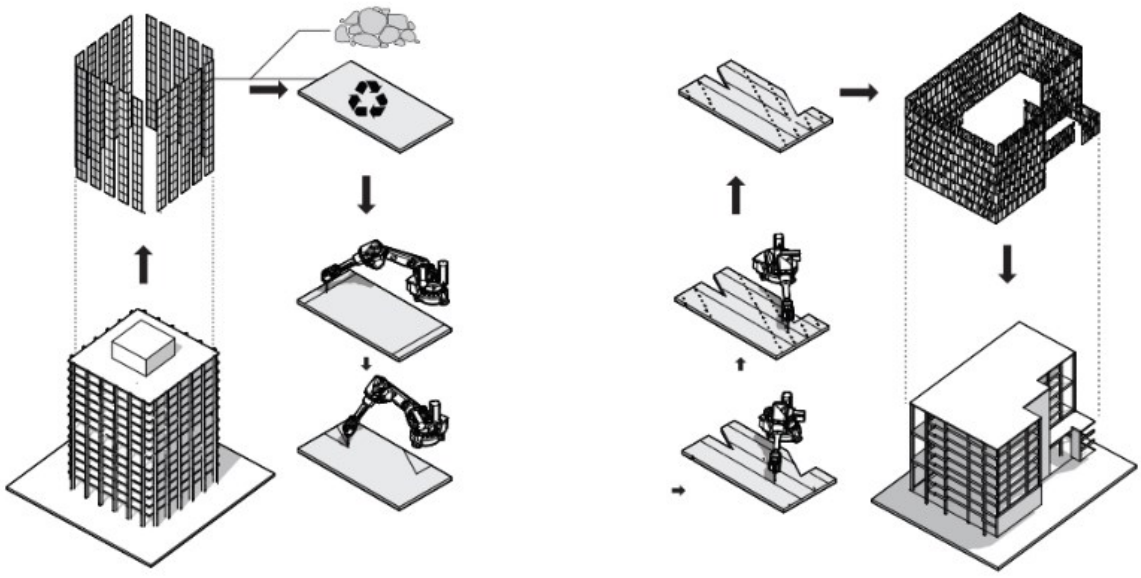

Fig. 12. Deconstruction and panel reuse process using robotics [9]

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important especially in the structural aspect because it ensures that the wall will have the same tributary width (or less) and as a result will not have to withstand larger load in the new scenario.

This paragraph discusses how to use a parameter in the wall building model which can be used by the architect during the conceptual design. More specific, this parameter should represent the estimated load capacity of the existing wall based on its tributary width and on the estimated loads from the original design.

From the existing project documentation, the design load of every bearing wall can be estimated and this parameter can be expressed in function of the walls' span dimensions and the surface load. When the wall is dismantled and put in new setting, the span dimensions and the surface load may change depending on the new design requirement. What remains constant is the estimated bearing load of the wall which should not be exceeded in the new design.

The proposal consists of converting the bearing load in a BIM parameter, which can be attached to every wall element and it can be used as a reference for a preliminary check during the new design.

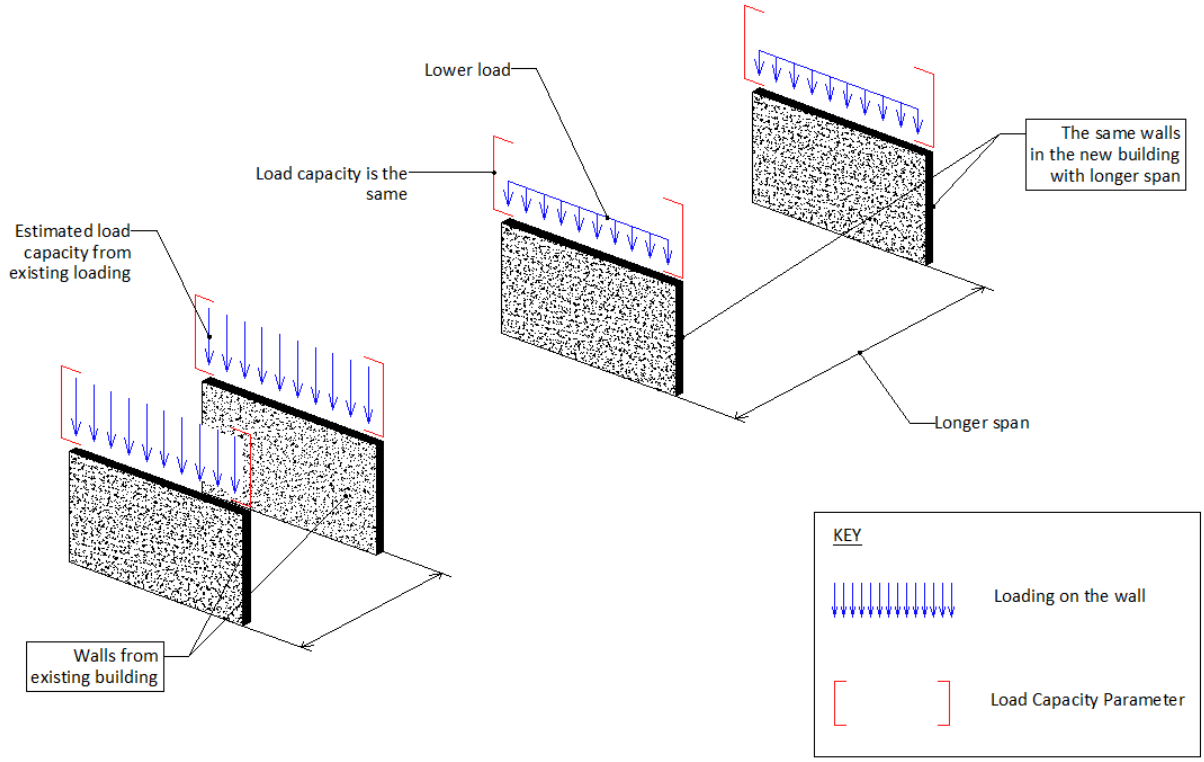

Fig. 14.a. The load capacity parameter in BIM model [Author]

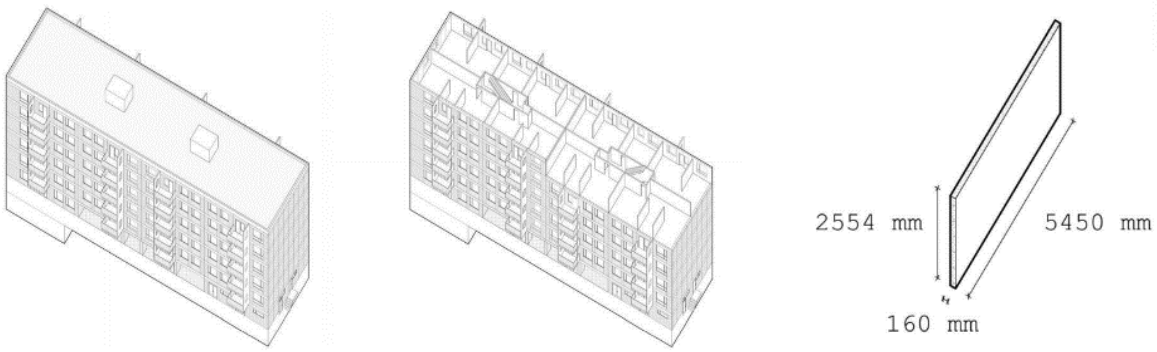

Fig. 13. Deconstruction building inventory analysis and dimensions [10]

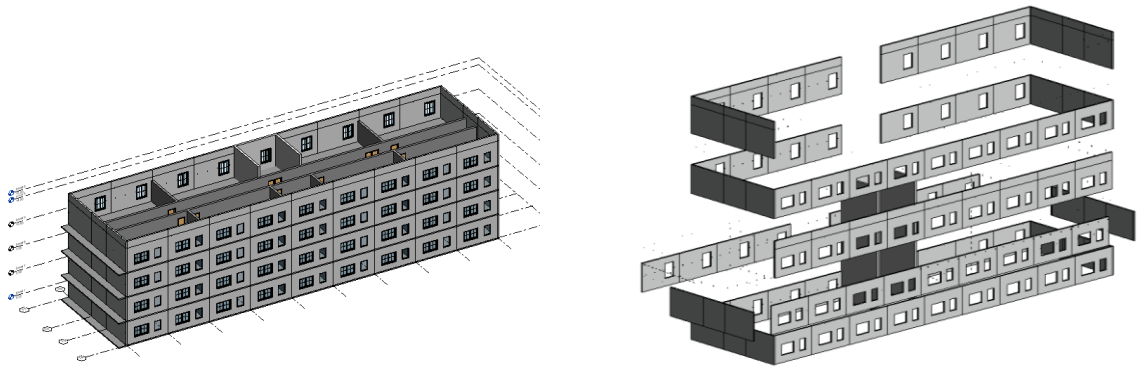

Fig. 14.b. Redesign process of precast panels [11] [Author]

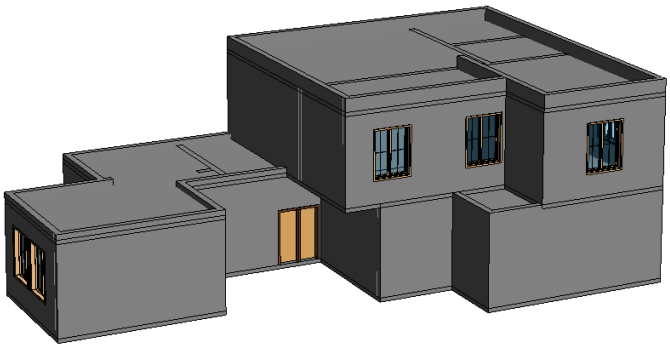

Fig. 14.c. New Building design from existing panels [Author]

A typical example may be when the walls in the new design have larger span dimensions compared to the original design but at the same time the surface load from the floor is lower because the floor construction in the new design is lighter than in the original one. In this scenario larger spans can be achieved between wall panels as long as the parameter of the estimated load is not exceeded.

The pictures in figure 14 schematically describe the creation of a two story building with panels taken out of an existing building. The last picture illustrates the use of this parameter in a 3D BIM model.

3.4 Topic 2 discussion. Structural systems integrating concrete panels

The second part of this paragraph presents structural solutions and considerations which involve the precast panel as part of the structural system.

While in the previous paragraph the focus was in the geometrical arrangement of the panels in the new design context, the topics presented in this paragraph describe situations when the concrete wall panel can be used as an integrate element of an overall structural system.

Proposals for practical structural systems are presented, implementing by the results from recent research into real project case scenarios.

General concept

One of the concepts introduced in this paper is that of hybrid wall structural systems. It consists on a wall system comprised of two different components, connected together to create a single system by combining their properties. More specifically, it focuses on **Hybrid Coupled Shear Wall System** which is a system consisting on a contour steel frame and on an infill concrete panel inside the surrounding frame [12].

It is a recent innovative structural solution which integrates both elements in order to create an efficient structural system able to withstand vertical and lateral loads. These components interact with each other not through rigid connections, but rather from

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dissipative connections, provisioned to undergo in the nonlinear range while keeping the concrete panel in the elastic range [12].

The reinforced concrete wall carries almost all the horizontal shear force while the overturning moments are partially resisted by steel columns in an axial compression-tension behavior [12].

This system focuses on a particular typology which has been recently developed as a product suitable to European market [13].

There is evidence of research and conducted experiments concluding that this system is viable in terms of structural design and analysis and current European Design Norms can be used in the design process.

This system also offers a large performance especially as a lateral resisting system, through the dissipative connections, which connect the infill concrete wall and surrounding steel frame.

In this way, the concrete infill wall is effectively protected against damage as the dissipative steel links yield long before the yielding of the wall, hence starting dissipating seismic energy while the wall is still in its elastic range [12].

Structure Analysis Design (Elastic---Hybrid design)

With regard to structural analysis, it is possible for the designer to create a structural analysis model of the component which can be modeled and calculated in a finite element software [12].

In order to perform this analysis and the design of the system, the most important parameters to consider are: number of reinforced concrete walls, thickness and length of reinforced concrete walls, length of the steel links and their connection type (rigid or pinned) [12].

Proposal for new implementation

The following paragraphs of this chapter discuss a proposal for an implementation of this system in a new context. The new concept consists on replacing the standard concrete infill panel described in the previous paragraph with a concrete panel typical from existing prefabricated buildings.

Based on the fact that the infill wall used during the research work for this system is a conventional precast wall, an adaption of this system is proposed by using an existing prefabricated wall as infill concrete wall instead of the typical wall.

Several parameters and wall properties are necessary for the design of such a system such as the factual concrete strength of the panel, reinforcement layout, geometrical dimensions as well as other structural parameter depending on the specific scope.

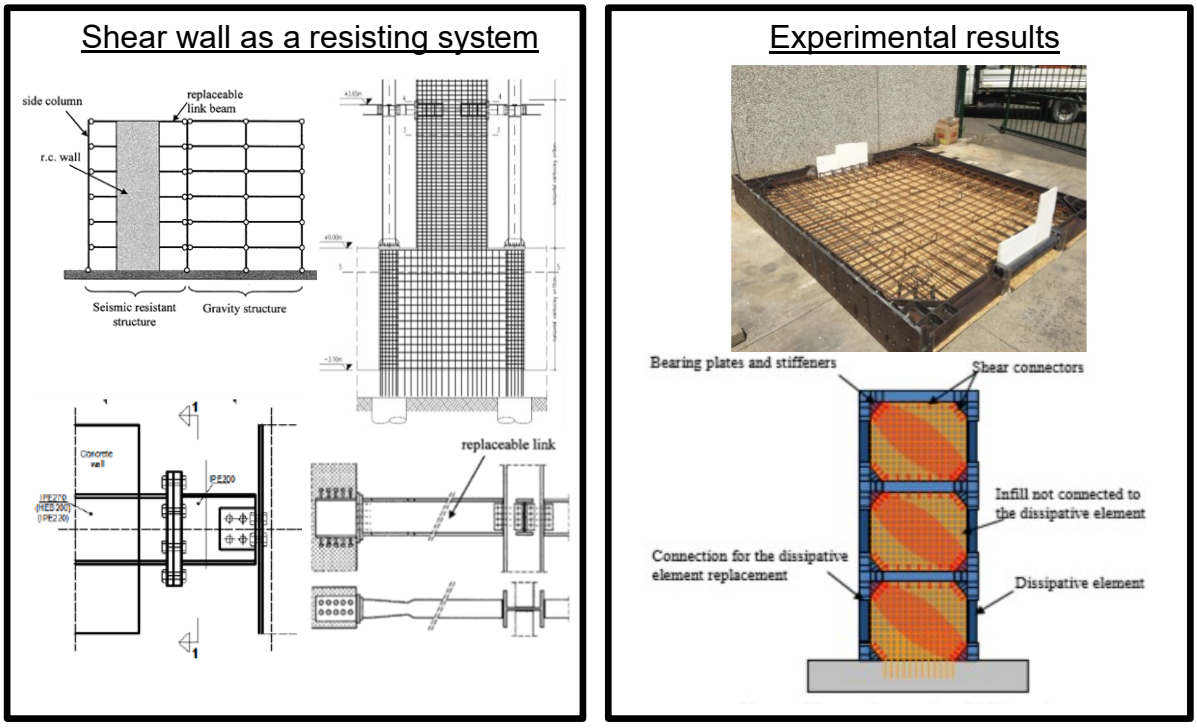

Fig. 15. Research for hybrid composite walls [12]

In the scenario of using existing panels, these parameters should be assessed on site and accurately stored for each component of the existing building.

The following paragraphs shows a proposal for implementing this process through already available tools and technology.

Process (QR-code for physical information assessment)

One important element for the feasibility of this process is the QR code element. This simple and cheap technology implementation used widely to store information, read and query it, may be a possible tool for this process.

The properties of existing panels, after being assessed on site can be stored digitally for every panel wall in the building along with a unique Id or label for each panel.

Considered as a physical object containing information, the QR codes can be attached to the walls storing the relevant information for that particular wall in terms of structural properties.

This method can allow for identifying of the components, tracking and creating inventory depending on the different stages from on-site assessment up to the next construction.

Lastly, the information contained in the QR code may be used in a digital BIM model as shown in figure 16, with a digital database of the components, while the properties of the walls assessed on site can be used as attributes in a BIM model in any Object-oriented software environment.

The assessment of this properties on site is proposed through a series of Non-Destructive Tests (NDT) as described in the following paragraphs.

Creating Digital Properties from Site to BIM model

Non-Destructive Tests / Automation perspective

There are a series of available Non-Destructive Tests (NDT) which can be used to assess the internal physical properties of the concrete walls necessary for a structural design.

Properties such as concrete strength, existing reinforcement layout and cover depth can be assessed on site by using tools like Schmmidt hammer test and Electromagnetic scanning devices respectively.

Also, the geometrical dimensions can be assessed by laser measurement devices.

A very promising field here is the potential of robotic automation of these previously described processes.

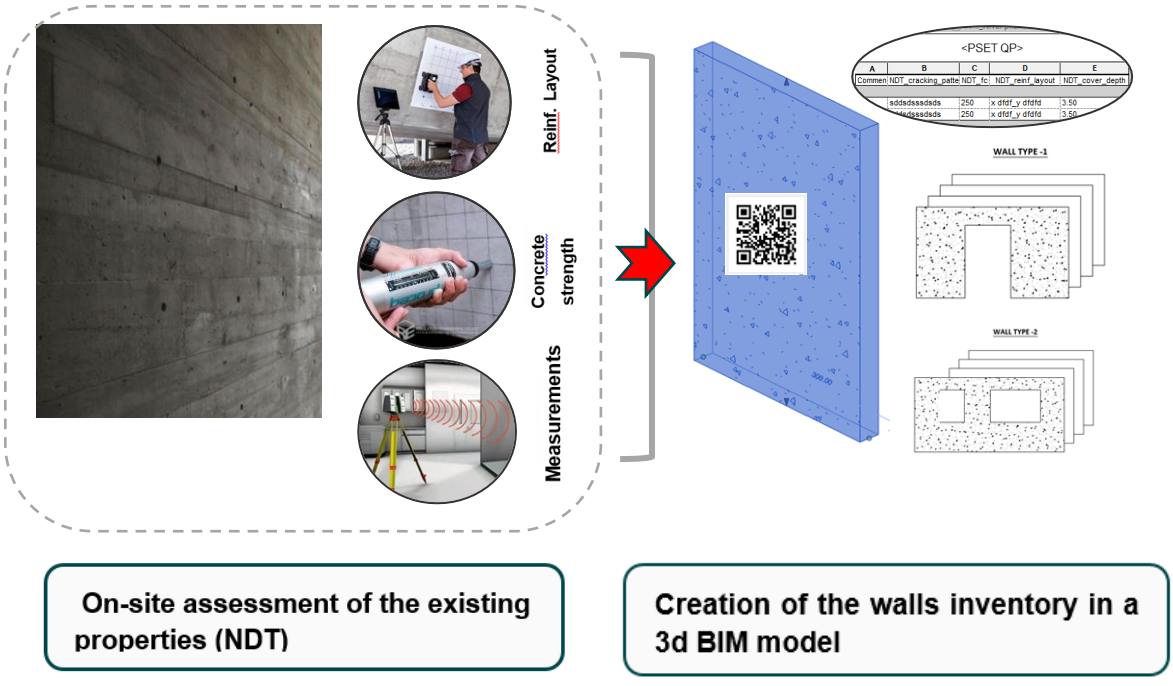

Fig. 16. Showing the process of from site assessment to the BIM model [18] [19]

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By using robotic implementation for the site assessment tasks, not only these processes will be completed quickly and effectively, but a higher quality can also be acquired for the results.

For example, a large number of test points can be measured and assessed for a single panel component, which otherwise would be non-feasible with current methods.

Proposed structural design implementations

This paragraph describes briefly the structural arrangement of the proposed system starting from the single module cell to the options of developing different structural schemas and arrangements.

The panel arrangement

Based on the factual dimensions of the existing concrete panel, a steel contour frame should be designed respecting the exiting wall configuration and allowing for the design of the steel connections at the interface of these two elements.

The design of the connections should comply with the dissipative design principles as described in the previous paragraphs and shown in Fig 16.

The connection should consist on several components such as the connections between steel link and concrete wall; the connection between steel link splices and replaceable part; the connection between steel link and steel side column [20].

3.5 Structural design of the component

The whole structure

Starting from the simple shear wall previously described, the structural arrangements can be further extended to other structural arrangements such as a multi-story shear wall, a dual frame arrangement which further allow for developing spatial configurations.

The presence of steel elements allows for flexibility in connecting with steel and concrete frames in the same time as shown in figure 18 and 19.

3.6 CO2 assessment

The final part of this paper is focused on the carbon footprint assessment and method of calculating it as part of the design process.

A comparison analysis is performed in this paper presenting two similar building structures but with different structural system where one of these systems integrates the existing precast panels.

The comparison is made in terms of carbon footprint values for the both scenarios which

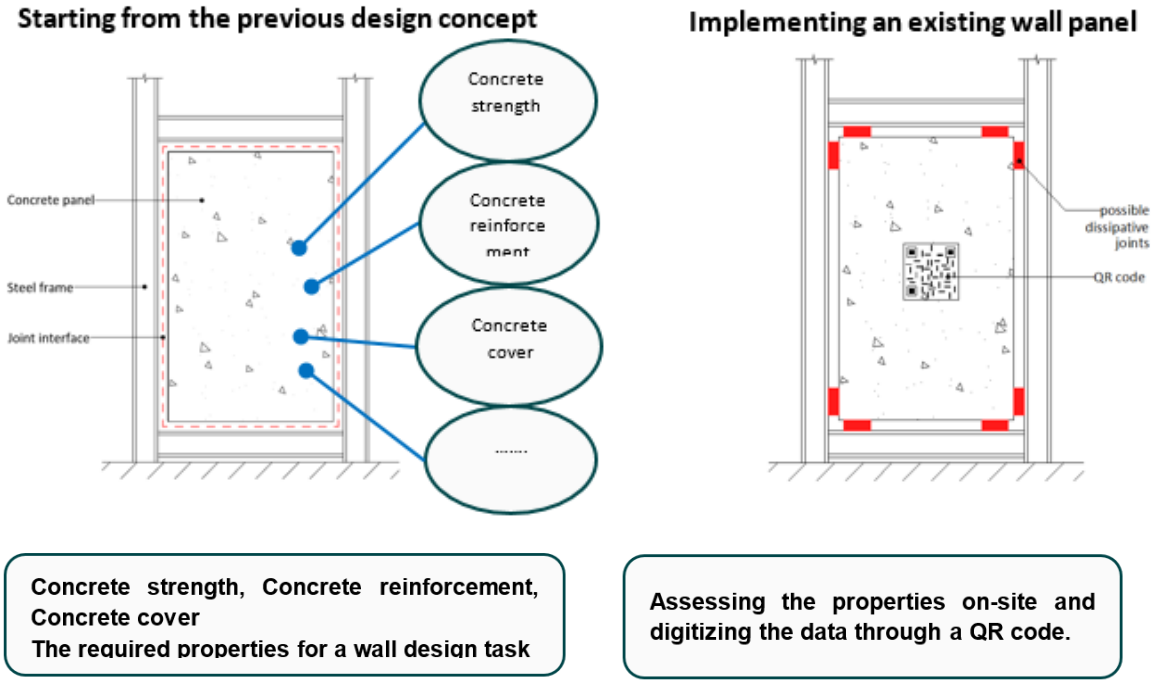


Fig.17. Structural design of the component [Author]

may be helpful for the designer to create a benchmark.

Although a full Life Cycle Analysis (LCA) is required in order to perform a throughout assessment of the environmental impact, this paper is focused on the carbon footprint category as a practical indicator, useful for decision-making during the planning and design stage.

Nevertheless, the following paragraphs give a very general overview of the LCA definition and concepts followed by the subset of the Carbon Footprint definition.

Description of LCA

LCA (Life Cycle Assessment) analyzes the impact on the environment throughout the entire process from production, distribution, and disposal, such as energy consumed to make raw materials and products, generation of pollutants and wastes, from the perspective of the cradle to the grave. It is mainly used as a tool to analyze and evaluate the impact on the environment that occurs during the life of a product. The figure below describes the framework and the main processes which drive the assessment analysis.

The first process of Goal and Scope Definition defines how big a part of product life cycle will be taken in assessment and to what end will assessment be serving. Then the inventory analysis (LCI) consists on data collection and calculation to quantify inputs and outputs of materials and energy associated with a product system under study [17]. The significance of potential environmental impacts of a product is analyzed in the third step based on life cycle

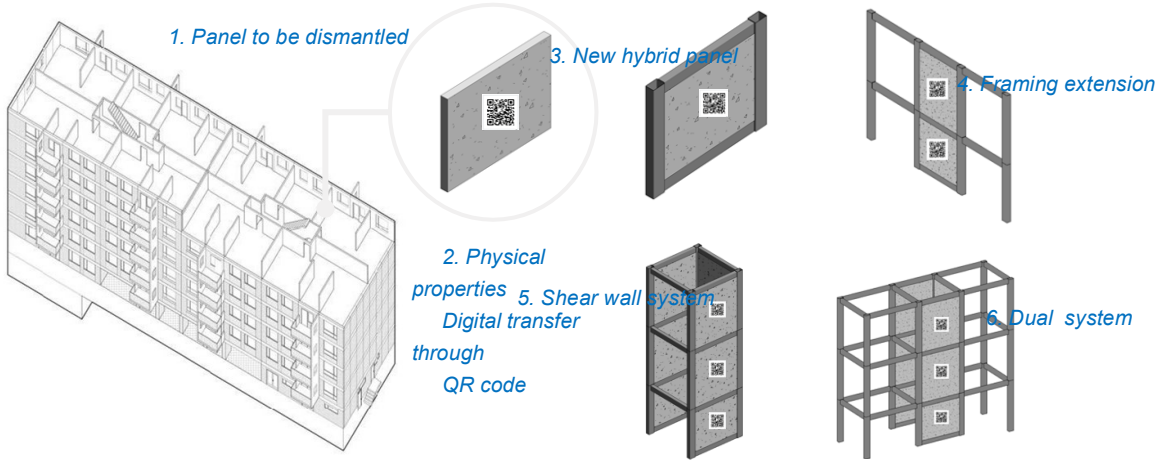


Fig. 18. Implementation illustration from deconstruction to design [10] [Author

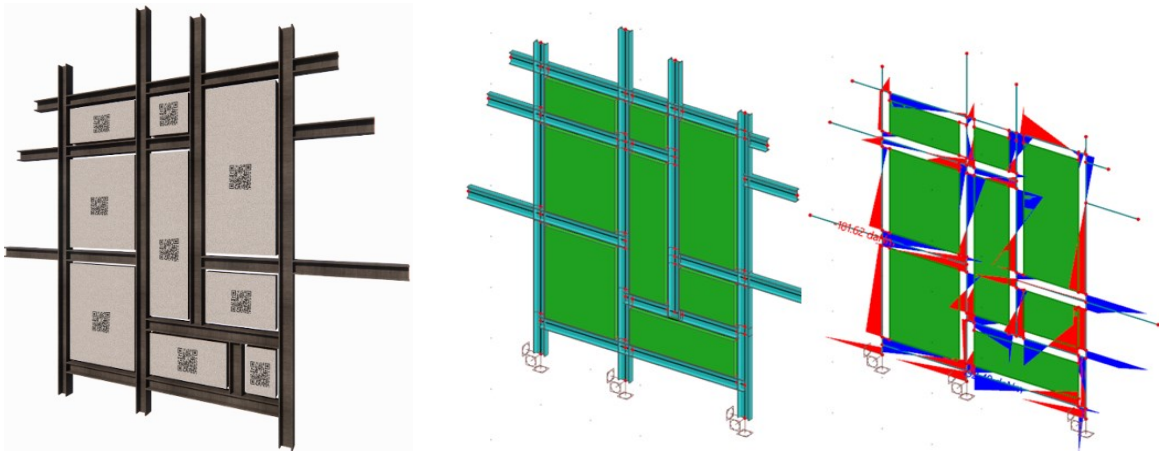


Fig. 19. Symbolic illustration design [Author]

inventory results. Lastly, the results of the assessments are analyzed with respect to various aspects such as completeness, sensitivity, and consistency. [17]

Stages

The calculation of carbon footprint is performed in relation to the life cycle stages of a building, which determine the process that takes into account the environmental assessment target of a construction project. These stages are divided into phases of material production and transport to site, construction process, use and end-of-life as shown in figure 21. [19]

Stage A1-A3. It represents raw material extraction, processing, manufacturing and related processes until the product leaves the factory door to the site, including the carbon emissions generated during transportation between these sections (cradle to gate).

Stage A4-A5. It represents the embodied carbon emitted during the transport of materials and products required to the site, and also the carbon emissions related to the materials used for installation or disposal, energy consumption, and transportation at the site.

Stage B1 – B7. It represents the Embodied Carbon emitted by energy generation from the

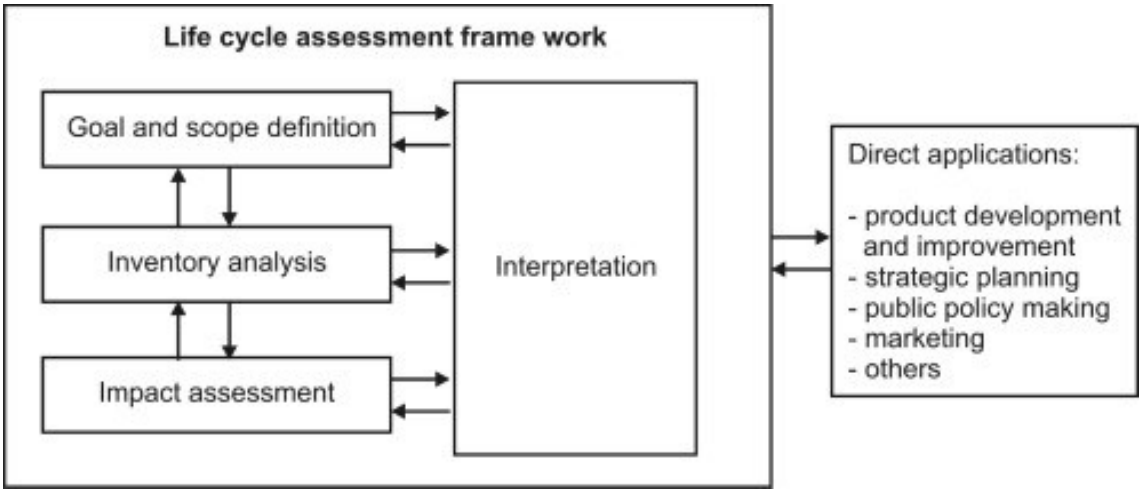


Fig. 20. Stages of an LCA according EN ISO 14040. [16]

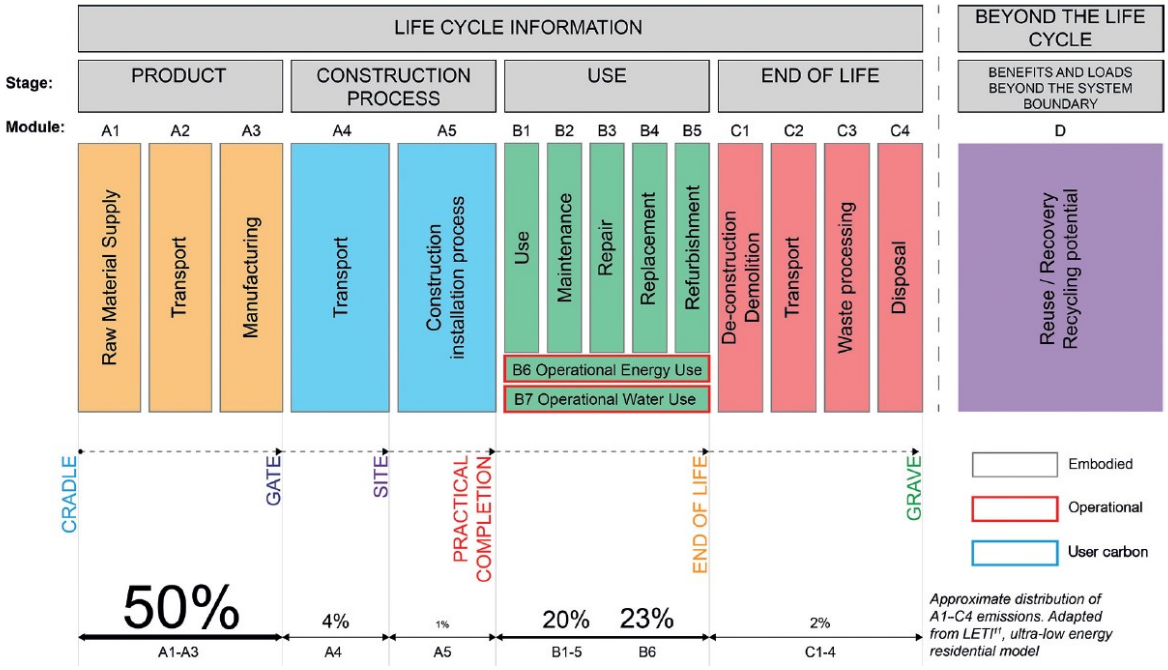


Fig. 21. BS EN 15978 Life cycle stages [20]

use, maintenance, repair, replacement, and operation of the building after construction is completed.

C1-C4. In this stage, the emission from the point of the end of the life of the building is shown. By default, the lifespan of the building is set to 60 years by default. [20]

The carbon footprint factor

The carbon footprint is the amount of carbon dioxide (CO2) emissions included in all activities of the people and entities (buildings, corporations, and nations). This includes those related to direct emissions.

The aspect covered in this paper is related only to Embodied Carbon Emissions. These are emissions generated during new construction, maintenance, and remodelling of buildings, including both carbon emissions from transportation and assembly of materials used in buildings, and carbon emissions from the demolition of existing structures as shown in figure 22.

Methodology of Carbon footprint Calculation

The fundamental principle of an embodied carbon calculation is to multiply the quantity of each material by a carbon factor for the life cycle modules being considered: material quantity (kg) × carbon factor (kgCO2e/kg) = embodied carbon (kgCO2e). The method of calculating embodied carbon goes through several steps which include the definition of the minimum scope of calculation, the inputs, the analysis step and the final results.

The minimum scope of calculation should include modules A1-A5 for basic substructure and superstructure elements. The calculation of carbon footprint will be focused on steps A1-A5, being as the most important part to considered to reduce carbon reduction. [20]

Second step consist on the inputs which are required to obtain the calculated value of the embedded carbon. The required input should be located according to each of these modules, which include material or product quantities, A1-A3 carbon factors and distance and mode emissions.

During the next steps an analysis is conducted with regard to accuracy of values, assumptions and the benchmark defined. Lastly the final output of results is completed. [20]

Based on this methodology, a comparison between two building systems is presented in

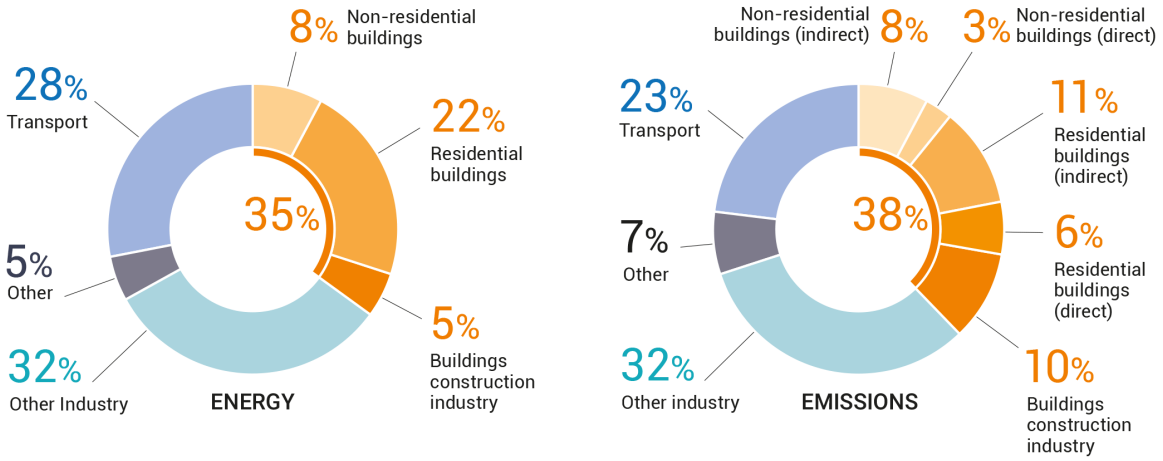


Fig. 22. Global share of buildings and construction final energy and emissions (2019) [18]

Material or product quantities	All stages	Building element replacement cycle	B4
A1–A3 carbon factors	A1–A3	Asset lifespan (reference study period)	B4
Distance and mode emissions intensity of transportation of materials to site	A4	Demolition and deconstruction emissions	C1
On site material wastage rates	A5	Distance and mode emissions intensity of transportation of materials away from site	C2
Site activities emissions	A5	End of life scenarios	C3 and C4

Fig. 23. Inputs required for A1–A5, Additional inputs for A–C [20]

the following paragraph with respective carbon footprint calculation for both options.

3.7 Comparison of the two building systems

In order to demonstrate the benefits of the new proposed structural system in terms of embodied carbon, two buildings are analyzed and compared. A conventional building structure with concrete column-beam frame structure is compared to a new building which implements the structural system discussed in topic 2 in this paper.

The buildings chosen are identical with regard to their floor area and number of floors. Also the buildings are very similar concerning their lateral load resisting performance verified in a separate analysis.

The calculation of the embodied carbon is done by using as an input, the material quantities of the structural elements for both buildings. Figure 23 shows the technical description of the two buildings and their parameters.

The new system is comprised of the precast panels connected with a steel column-frame to create a spatial dual system.

- Reference input values for the conventional building:

The required concrete volume for columns- 82.3 m^3

The required concrete volume for beams- 110 m^3

- Reference input values for the new building:

Volume of steel columns- 0.97 m^3

Volume of steel beams- 0.249 m^3

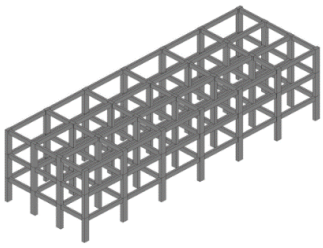
Volume ok steel contour frame- 0.984 m^3

Estimation transportation distance- 100 km

Figure 24 shows the structural arrangement of two buildings and their respective volume of quantities.

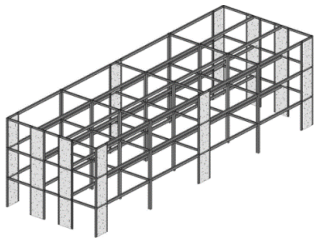
Figures 25 to 28 and figure 30 show the results of the calculations performed for the embodied carbon respectively for the two buildings presented in charts.

Figure 29 shows the additional value of carbon considering the transport distance. A distance of 100 km is chosen as the default value of the method.



- A conventional building with beam – Column frame as a vertical and Lateral LOD resting system.

CONVENTIONAL BUILDING		
Description	**Unit**	**Quantity**
Concrete for columns	m3	82.3
Concrete for beams	m3	110



- Building with Similar performance with New shear wall system

NEW BUILDING STRUCTURE		
Description	**Unit**	**Quantity**
1_Confining frame	m3	0.894
2_Precast walls (Transportation 100 km)	km	100
3_Other steel columns	m3	0.97
4_Steel beams	m3	0.249

Fig. 24. A conventional building with beam and similar performance with new shear wall system [Author]

The hypothetical scenario presented in this paper presumes a distance of 100 km between the distance of the donor building and the site of the proposed building.

The results show a clear difference in the embodied carbon values with the new system showing 60 % less carbon emissions.

Other from reusing the existing concrete panels as low carbon components, another factor influencing is also the choice of the structural system.

The use of the proposed system gives the possibility to use steel frame structure as vertical bearing elements, which cover large column-free spans in comparison to the other system. This factor together with a lighter weight of the structure contributes to the overall reduction of the embodied carbon as shown in figures below. Figure 29 shows the carbon calculation from the transport process. A value of 100 km is chosen for this calculation.

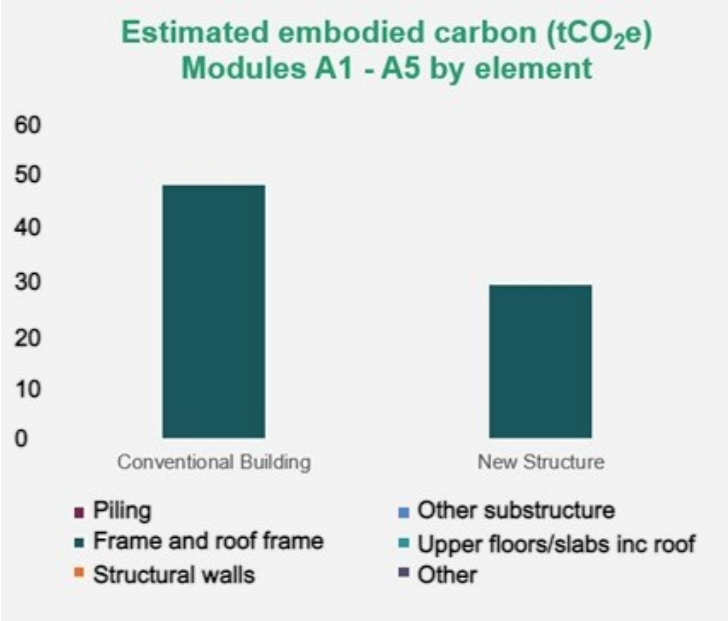


Fig. 25. Estimated embodied carbon Modules A1 – A5 and A – C [Author]

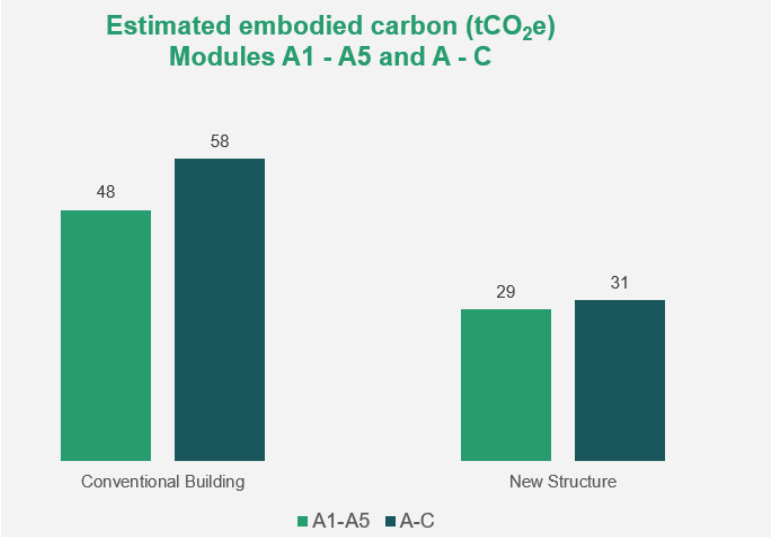


Fig. 26. Estimated embodied carbon Modules A1 – A5 by element [Author]

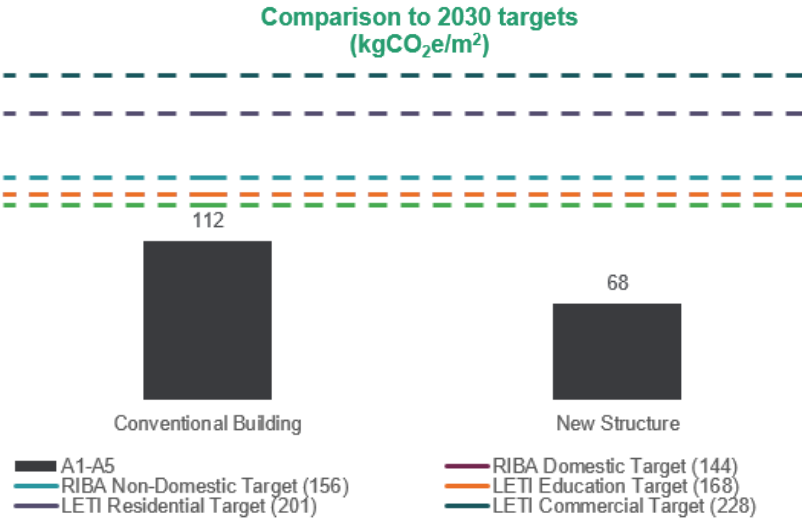


Fig. 27. Comparison to 2030 targets [Author]

Calculation of A4

	Distance by Road (km)	Distance by Sea (km)	Distance by Freight Air (km)	Distance by Rail (km)	A4 Value ($kgCO_2e/kg$)
Material Transport Distance:	100	0	0	0	0.011
Transport Emissions Factor, $kgCO_2e/kg$	0.10749	0.01614	0.53867	0.02782	

Fig. 29. Calculation of the A4 [Author]

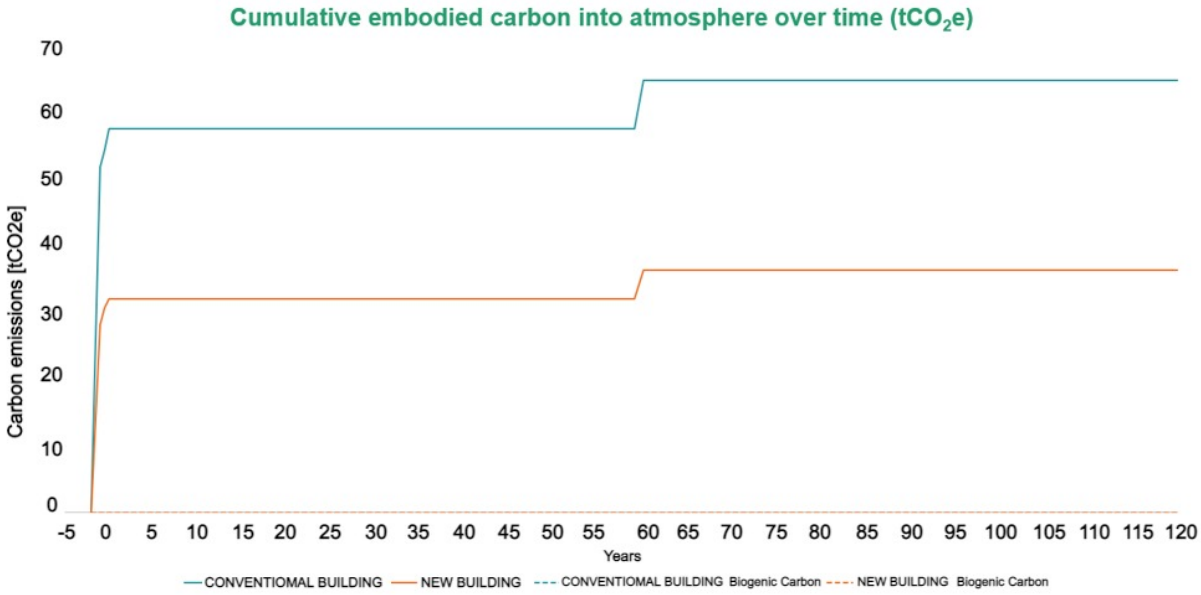


Fig. 30. Cumulative embodied carbon into atmosphere over time. The orange graph representing the new structure and the blue one representing the existing building [Author]

4. Conclusion

In this paper, the topic of deconstruction and redesign is discussed as a strategy for low carbon emissions. The typology presented was that of buildings with prefabricated concrete elements and the possibility of reusing their components for constructing new buildings.

In order to reduce the carbon footprint in new building project, this can be seen as a feasible alternative. There is a large building stock of this typology, which can serve as a donor resource pool in this scenario while there is successful precedence with pilot projects where automated technology was used as well.

The paper focuses on the planning and design discipline, which is believed to play an important role in this task, by accurately provisioning that every reused component is optimally designed and it fulfills in the best way the requirements of the project.

The biggest challenge in this task is to accurately estimate the physical properties of the existing components and how to use them as parameters in the design for their future role in the building.

It is possible that by using the digital technology for assessing the existing information, and modeling of information through BIM, some of the current design methods can be adopted, making possible the design with existing precast panels by a practicing designer.

Two specific methods were discussed in this paper.

The first is focused on the architecture design discipline and it describes how to design with an existing precast element not only in the geometrical point of view, but also by considering its structural properties. This can be achieved through the use of a parameter which represents the load bearing capacity. This parameter can then be used in a digital model for designing new buildings.

The second method is focused on the structural discipline and describes how to use the existing precast wall element as a structural component in a new design which is code-compliant. It consists on integrating the

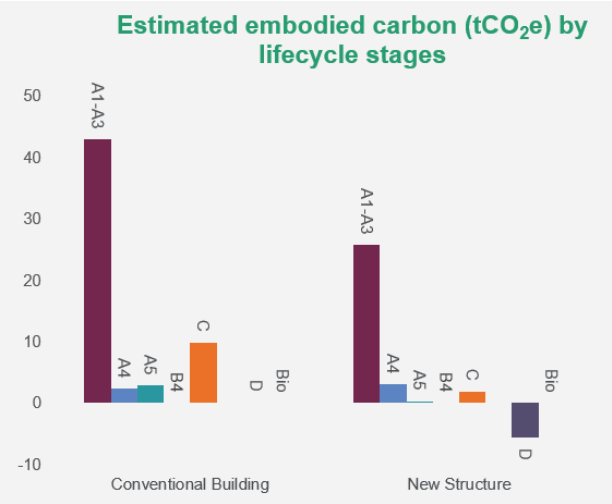


Fig. 28. Estimated embodied carbon by lifecycle stages [Author]

precast panel inside a flexible steel frame combining the properties of both members in a hybrid structural system.

Both methods rely on acquiring the existing information from on-site assessment and preparing it as an asset to be easily used in the new digital design environment.

Future work is required for this methods to be fully adapted by practicing designers especially in term of digital tools, how the digital information will be modeled and with regard to code compliance in the building design. Furthermore, concerning the site assessment processes, there is a potential for equipment automation and the use of robotic technology especially for non-destructive tests and geometrical measurements.

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Translucent Concrete Design Stimulation for Energy Efficiency

ABSTRACT

Translucent Concrete (TC) is currently emerging as one of the most innovative and sustainable construction materials due to its unique properties and applications. However, for this material to reach its full potential and its intended place in the market some challenges must be overcome. This paper aims to encourage the use of Translucent concrete by facilitating its integration into the design process. In the first chapter, a general overview of TC's history, its market, and its application is presented. Then a specific relevant application, namely the translucent building's envelope, is discussed. In the third chapter, different fabrication processes are introduced, and how they could influence TC's overall cost and availability. Then the paper will touch on the sustainability contribution of the TC material, comparing it with other relevant material and analyzing the existing use case studies. Finally, an overview of energy efficiency analysis software in literature is used as building knowledge for proposing a user-friendly early design phase open-to-use design tool that enables architects to integrate TC in daylight and thermal simulations for indoor spaces.

Keywords: Translucent concrete (TC), Light transmitting concrete (LTC), Optical fiber (OF), Translucent concrete panels (TCP), Fabrication, Energy efficiency, Energy performance, Daylighting analysis.

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Image from rawpixel.com on Freepik

1. Introduction

Over the last few decades, energy conservation has gained worldwide attention due to the intensifying energy crisis [1]. One of the major causes of the energy and co2-emission crisis is the amount of energy used by commercial and residential buildings. Buildings consume almost 30% of total energy globally and are accounted for 27% of energy-related co2 global emissions according to a report from 2021[2] Heating, Ventilation and Air Conditioning (HVAC) systems are the most energy-consuming service in buildings with 38% of the whole consuming sum [3]. It is notable to mention that about 93% of this percentage goes for space heating [4]. Even Though HVAC is the biggest energy consumer, according to the US department of energy, artificial lighting is responsible for 15% of global electricity consumption and 5% of worldwide greenhouse gas emissions [5] due to the fact that electric energy is derived primarily from thermal power plants that are not clean sources and contribute to greenhouse gas emissions [6].

An innovation like Light-transmitting concrete (LTC) also called Translucent concrete (TC) captures and delivers sunlight to illuminate the interior spaces inside the buildings, which not only creates a healthy environment for human occupations but also reduces our dependence on artificial lighting and reduces heating loads [6].

TC is a concrete-based building material, that has light transmitting capabilities gained by incorporating light-guiding elements during manufacturing [7]. In other words, light-guiding elements serve as channels that transmit light between the two surfaces of the concrete.

Among its many applications, TC was found to be highly useful as a sustainable material for building envelopes by permitting natural sunlight to penetrate the building, as well as in partition walls for light transition between interior spaces, thus increasing illumination levels and uniformity of light. [7]. Research shows that using TC can reduce light energy utilization by up to 50%, without compromising its compressive strength [8]. On the other hand, Using TC panels can help reduce the heating loads during winter since solar radiation can assist with heating the room.

Motivation

Translucent concrete is currently emerging as one of the most innovative construction materials with a potential for a significant sustainable impact on the building industry due to its unique light transmitting properties and applications. Therefore, it has piqued our interest to further study it. However, for this material to reach its full potential and its intended place in the market some challenges must be overcome.

Research Goal

This research aims to study the state-of-the-art fabrication process, marketplace, and applications of TC while focusing on its sustainability contribution and positive impact potential on buildings energy performance by analyzing the previous studies on this topic and defining the obstacles that limit the use of TC as a sustainable building material, in order to propose a solution for TC future integration enhancement in the industry and future development.

2. Research Methods

This paper focuses on the novel building material “Translucent concrete” as an energy saving material and its potential input to green buildings and sustainability. Several bold points will be discussed in the results section of the paper in order to provide the reader with an understanding of the state of the art, the advantages, and the challenges associated with the material. Next, the findings will be analyzed in the discussion part, along with a solution proposal. The research method in this paper includes both qualitative and quantitative data, the data was collected from articles, books, and journals from different scientific database platforms. Also, a market analysis was made by visiting the websites and the social media profiles of the big players. Patent research was conducted in the patent center of the RWTH to participants to question their interests in the material (see Fig.1). And finally, an interview was made with the world’s biggest supplier of TC to get state-of-the-art information regarding the market

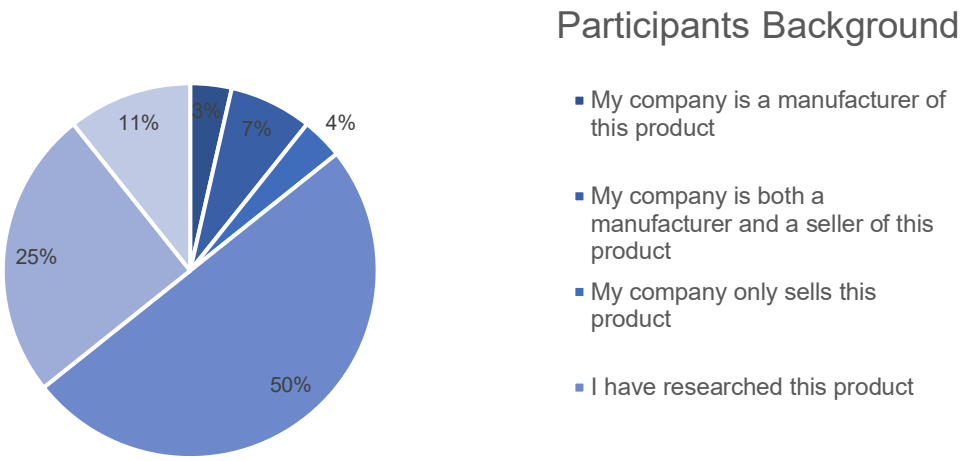


Fig.1. Online survey participants backgrounds

size, the fabrication processes, the applications, and the material cost.

3. Results

3.1 State of the art

Translucent Concrete (TC) is a concrete-based building material with light-Transmissive properties due to embedded light optical elements. It is also known in the market and in the research as Transparent concrete, Light-transmitting concrete, LiTraCon, and Light transparent cement mortar. If a Translucent concrete element is illuminated on one side by an artificial or natural light source, the light passes through the element and creates the effect of a transparent concrete element [8].

History

TC was first mentioned in a 1935 Canadian patent or in a 1922 United States Patent. The production of TC began to surface on the markets in the 1990s. The first industrial property rights to produce light-conducting concrete elements using fibers were registered in Japan already in 1985. The ideas from Japan were taken up in 2001 by the architects Áron Losonczi from Hungary and Andreas Bittis from Aachen [9].

Market

The market for translucent concrete is still in its infancy. Indepth research and development efforts are being made to commercialize the product for numerous uses. According to Translucent Concrete Market Global Forecast to 2024, the market size is projected to grow of 80% between 2019 and 2024, where one of the top and leading producers of translucent concrete in Europe is LUCEM GmbH (Germany) [10].

During our personal interview with one of the industry partners they commented that “It is a niche market, not a market with mass production because it is very customized and individualized for certain markets and for certain customers”.

Applications

The applications of TC can be categorized by their function (see Fig.2), for example:

- Saving energy: Exterior walls, Façade Panels (minimizing the need for artificial lighting by allowing daylight into indoor spaces, avoiding heat transfer while maintaining privacy).
- Road lighting: sidewalks, lane markers, and speed bumps.
- Dark spots illumination: staircases, tunnels, and subway stations. [11]
- Aesthetic purposes (mostly used): Facades, indoor and outdoor furniture, stairs, and logos[12] The world’s first façade featuring Translucent concrete by

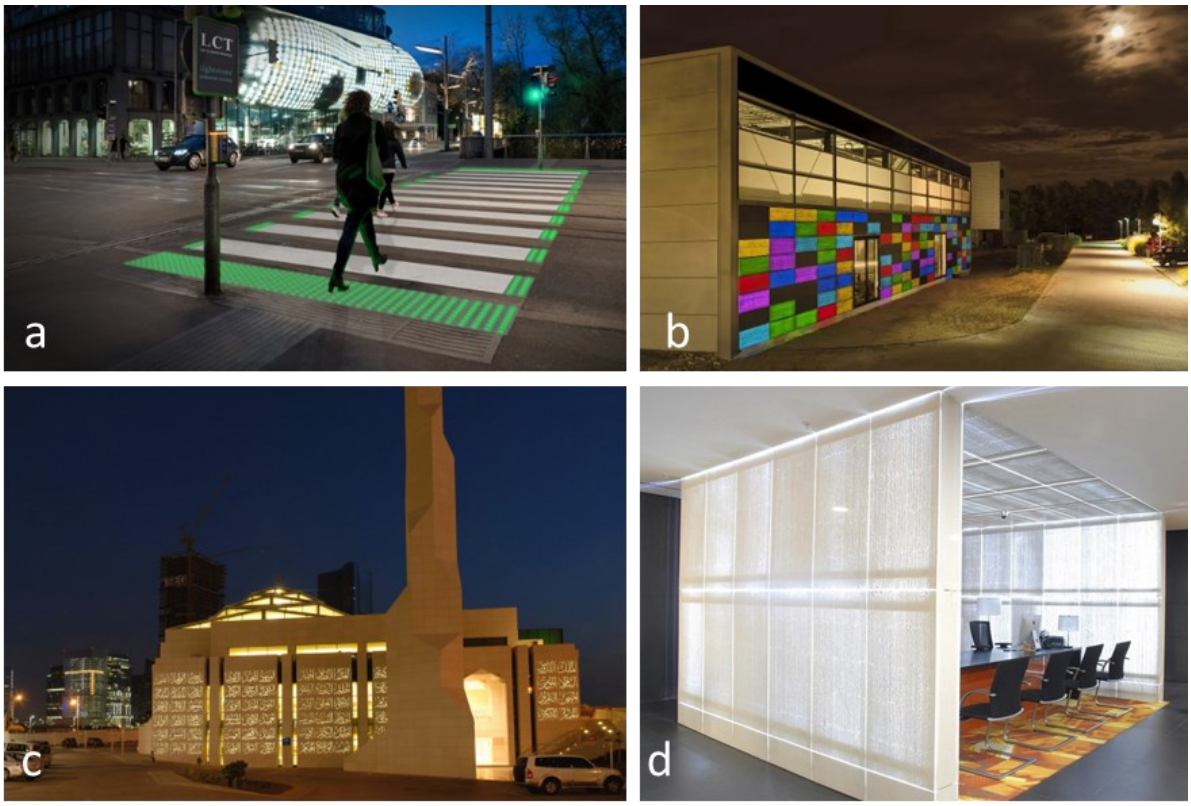


Fig.2. Application of TC: (a) walkways by LUCEM LICHBETON, Germany; (b) The world's first façade featuring Translucent concrete in Aachen, Germany, completed in 2012; (c) Al Aziz Mosque in Abu Dhabi; (d) the walls and partitions in Bank of Geogia [8]-[13]

LUCEM, has been used on the RWTH Aachen University in Germany [13].

3.2 Translucent Building Envelopes

Building envelopes are one of the most beneficial uses of TC. Since through them the interior spaces can be illuminated and heated in the winter by sunlight[12]. However, the properties of the wall can greatly vary depending on the TC components and the wall layers. This section covers the TC walls and their various properties and components.

Materials and components

TC is classified according to the type of translucent material used. Each type of light-guiding material has its degree of translucency, strength, and thermal conductivity, which will directly influence the overall performance of TC [8]. The most used materials are:

- optical fiber (plastic & glass) (see Fig.3),
- glass aggregates (or waste glass) (see Fig.4),
- rods (plastic & glass) (see Fig.5), and
- transparent resins (see Fig.6) [8].

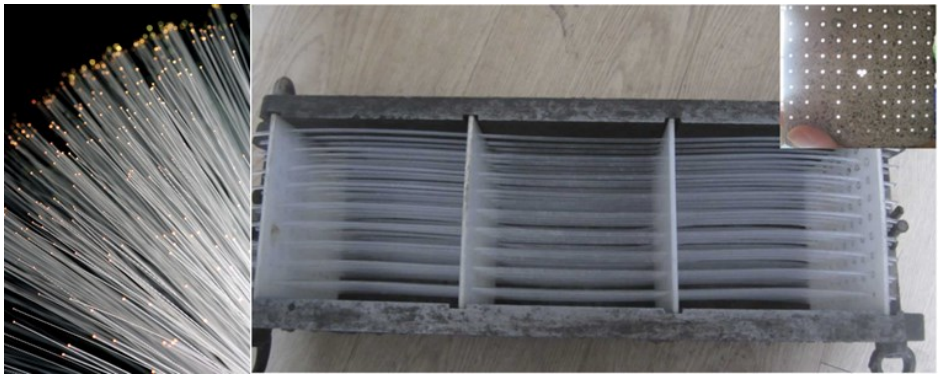


Fig.3. Optical Fibers [15]

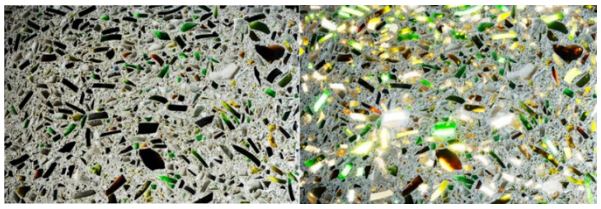


Fig.4. LTC with glass aggregates (unilluminated left & illuminated right) [16]

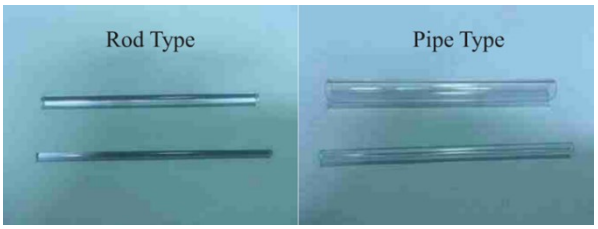


Fig.5. Glass & plastic rods [17]

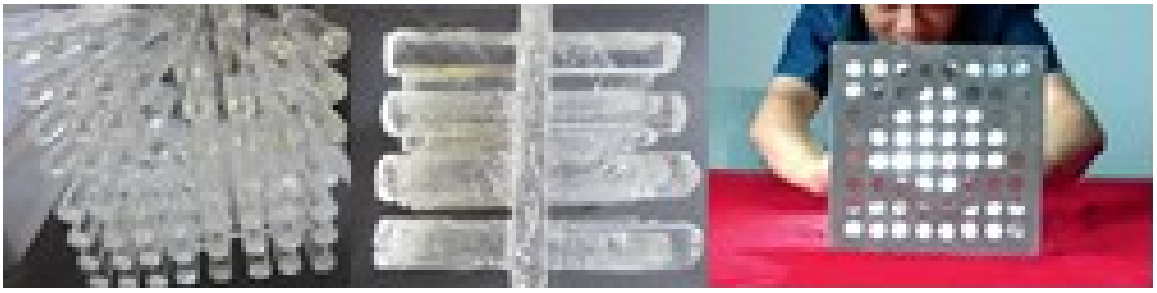


Fig.6. Resin (left & middle), resin translucent concrete (right) [17]

Using a suitable concrete or cement mixture, each of these materials builds a different TC type with different properties. However, the common point between all the TC types is that they all use a concrete mixture that does not impair the light-guiding elements' functionality. In general, the concrete mixture is composed of:

- cement (normally Portland cement),
- aggregate (fine aggregate with max size particles range of 0.6– 4.75 mm and coarse aggregate with max size particles range of 10–12 mm), and
- water [14].

Light transmitting properties

Optical fibers take the most interest in research and market among all light-guiding materials thus, in the production of TC, it is the most used light-guiding material. This is mainly due to its excellent light transmittance properties even when light incident at an angle exceeding 60 degrees [8]. This section explains how optical fibers transmit light through translucent building envelopes. The optical fiber consists of three main components: (see Fig.7)

- the core which is responsible for transmitting the light.
- the cladding which is responsible for guiding the light.
- the coating is responsible for protecting the fiber.

Depending on the size of the core diameter the fiber can be identified as a single-mode or a multi-mode fiber. The size of the diameter of the core has a directly proportional relationship with the light capacity and flow into the core and an inversely proportional relationship with the quality of the transmitted light. This is due to the dispersion of light passing through the different modes of the fiber with different refractive indexes. This problem can happen in step-index fibers. As a way of countering that gradient-index fibers are used where the refractive index is gradually increased from the edges to the core for a better blending of light [5].

Structural properties

In general, TC can be used as a load-bearing or non-bearing wall, however the incorporation of the translucent elements can reduce the concrete's compressive strength. However, within 5% optical fiber inclusion in the concrete mixture, the reduction of the concrete's compressive strength normally will not be more than 20% compared with the reference concrete. Aside from that, TC should not be used as tensile strength carrying element since TC normally includes no reinforcement. Furthermore, it is important to mention that the increment in fiber volumetric fraction leads to a descending trend in compressive strength. The larger the fiber diameter is the concrete's compressive strength will increase [8].

3.3 Fabrication process

Considering that TC is still a niche product targeting a particular market segment, it is a custom-made product that is fabricated either manually or semi-automatically with the potential for mass production. The fabrication process depends on the TC target application. Following are detailed descriptions of both existing fabrication processes.

Manual process

1. Mold preparation based on the target panel dimensions and quantity and polymer craft clay is placed at the sides and bottom of the mold and leveled.
2. Fibers are arranged in the formwork in the desired pattern according to design.
3. Concrete mix is slowly and carefully poured into the mold.
4. Vibration tables are used during pouring to avoid accumulation in the mixture.
5. After the concrete has been cured for 24 hours, the polymer clay is removed then the mold is removed.
6. Excess length of fibers is cut to size.
7. The TC block is cut according to target dimensions and the surfaces are prepared according to the target finish. [18] (see Fig.8)

Another way of manual fabrication is performed using textile fabrics (see Fig.9), which simplifies and accelerates the production of the TC elements many times over using individual fibers [9]. Following is a description of how textile fabrics can be used for TC fabrication.

1. 1.Mold preparation.
2. A thin layer of concrete is cast.
3. Optic fiber textile is positioned during the concreting process in a layer-by-layer structure.
4. The next layer of concrete is cast, then the next optic fiber textile is placed, and so on until the whole mold has been filled.
5. The mixture is left to harden. The resulting concrete block has then continuous fibers in the longitudinal direction.
6. The concrete block is cut into individual smaller blocks and panels.
7. To achieve optimum light conduction, the block or panel surface must be polished on both sides [9]. (see Fig.10)

Semi-automated

Semi-automated processes involve automating in one or more steps of the previous described process. According to our interview with the industry, the optical fibers can be placed into the mold robotically, saving a lot of time and labor by placing, for example, 300000 optical fibers per square meter. In the

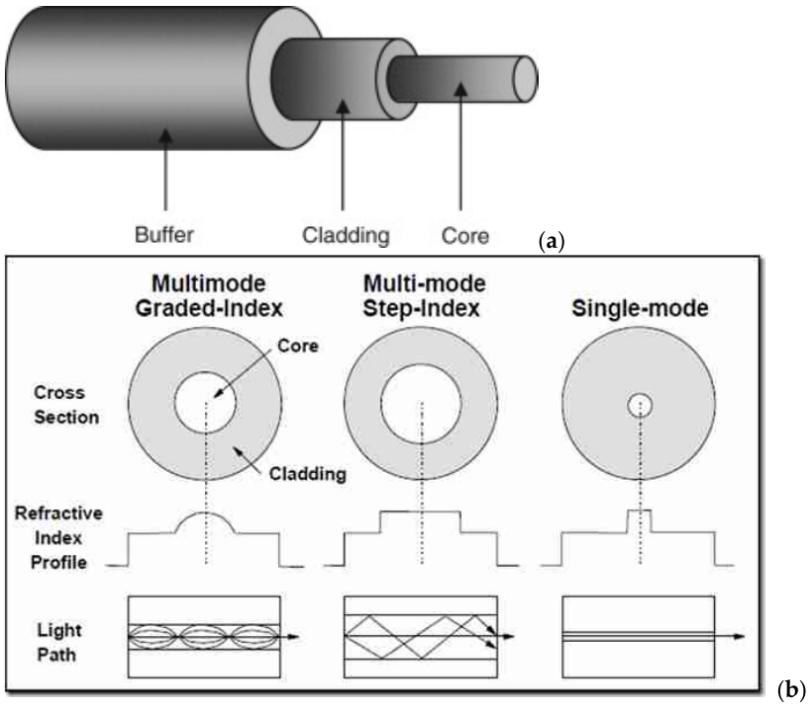


Fig.7. a) Optical fiber structure, b) types of the Optical fibers [7]

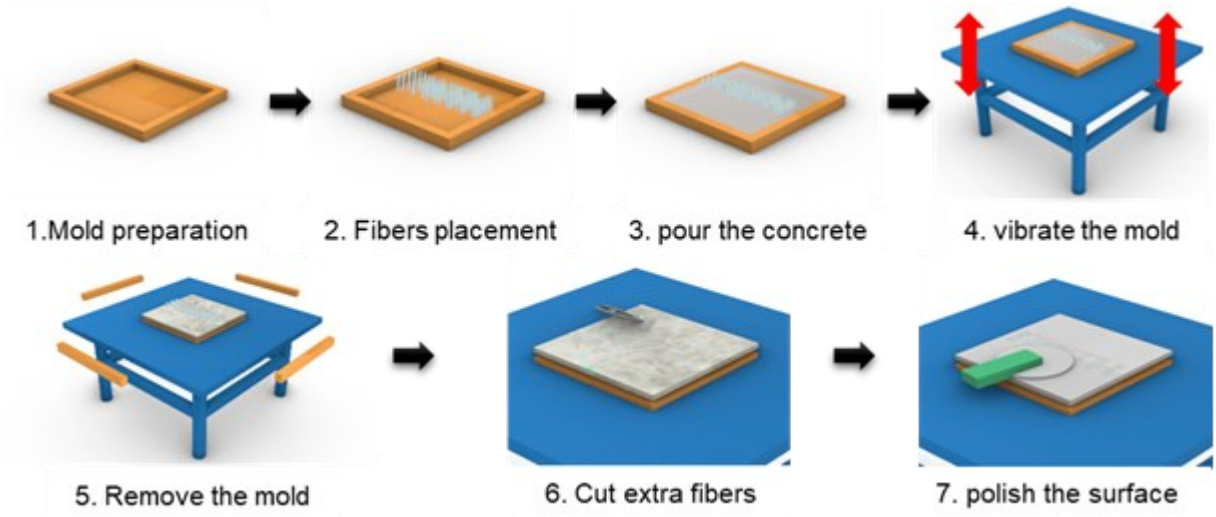


Fig.8. TC manual fabrication process



Fig.9. Light transmitting textile fabrics

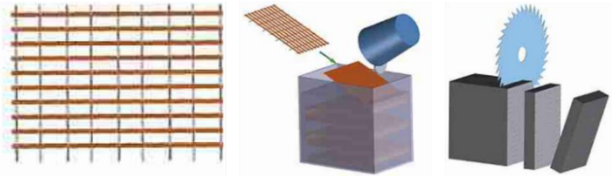


Fig.10. TC fabrication process with textile fabrics

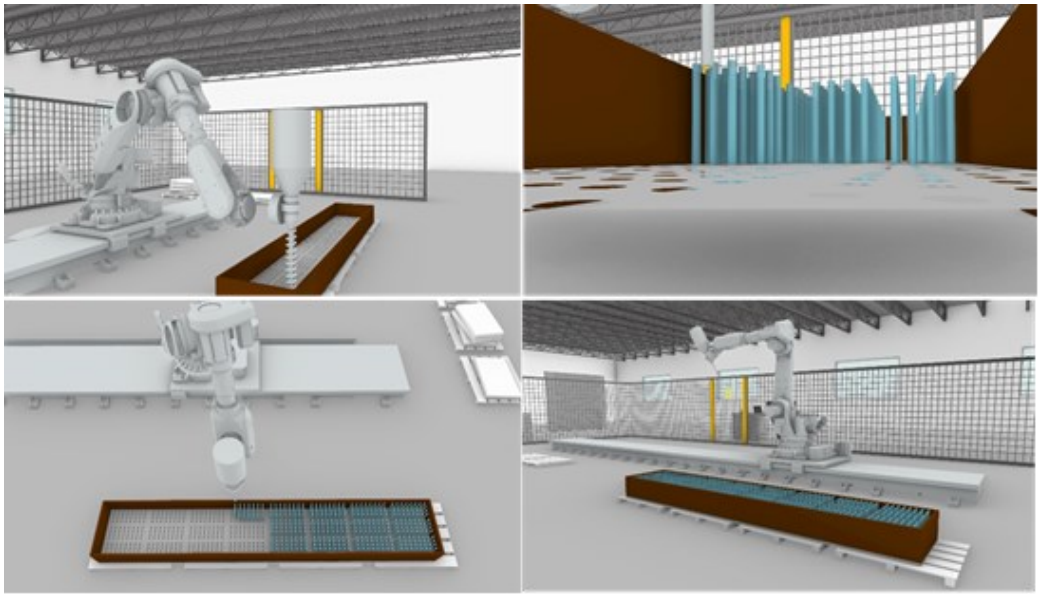


Fig.11 Stimulation shows using a robotic arm for a TC semi-automated manufacturing process

light of this information and our personal interview with TC manufacturer, we created a stimulation considering using a robotic arm for a TC semi-automated fabrication process (see Fig.11)

3.4 Recent innovation

Digital concrete

The digital concrete display is an application of translucent concrete where many embedded optical fibers transmit data



Fig.12. Digital concrete [19]

through high-strength translucent concrete surfaces. The data can be fed by cables or through a wireless connection. Despite inspiring many creative indoor application ideas, digital concrete displays really shine in outdoor applications. Due to its durability and weatherproofing capabilities compared to ordinary screen displays it can be implemented in hazardous areas or public spaces. It can also be used for floor displays due to its ability for withstanding weight [19].(see Fig.12)

3D printed Translucent concrete (HTRANS)

Jose Ramón Albiol Ibáez and Miguel Sánchez López, two researchers from the Universitat Politècnica de València (UPV) [20], have created and patented two new products that have the potential to change the building industry. The first patent is "HTRANS" that enables 3D-printed designs to be integrated inside TC. Second patent is "Tem LED" where they incorporate permanent or intermittent lighting elements inside the TC, using low-emission LED light sources powered by batteries charged through an external power supply or by wireless charging devices [21].

3.5 Sustainability contribution

The TC panels capability of transmitting day light makes them suitable for energy efficient uilding envelopes. The use of these panels in a building can be considered a step forward in saving energy and earning LEED credits, which presently require daylighting for at least 75% of the occupied spaces [6].

According to our conducted online survey most of the participants believe that TC has a high potential to be effective in saving energy, but it's not widely used yet. (See Fig.14)

Case study

The innovative translucent concrete sandwich panel with dynamic control of light transmission, known as "Brightwall" (see Fig.15), was developed under funding from

the EU. It has significant potential in terms of architecture and aesthetics, and it also

satisfies key requirements for indoor climate and

energy efficiency. The new material's main use is to construct Translucent exterior walls in new construction and restorations [23].

Through simulations, it was discovered that installing the Brightwall solution in place of traditional brick walls in buildings can result in significant energy savings in the usage of artificial lighting, cooling, and heating [24].



Fig.13. 3D printed Translucent concrete [22]

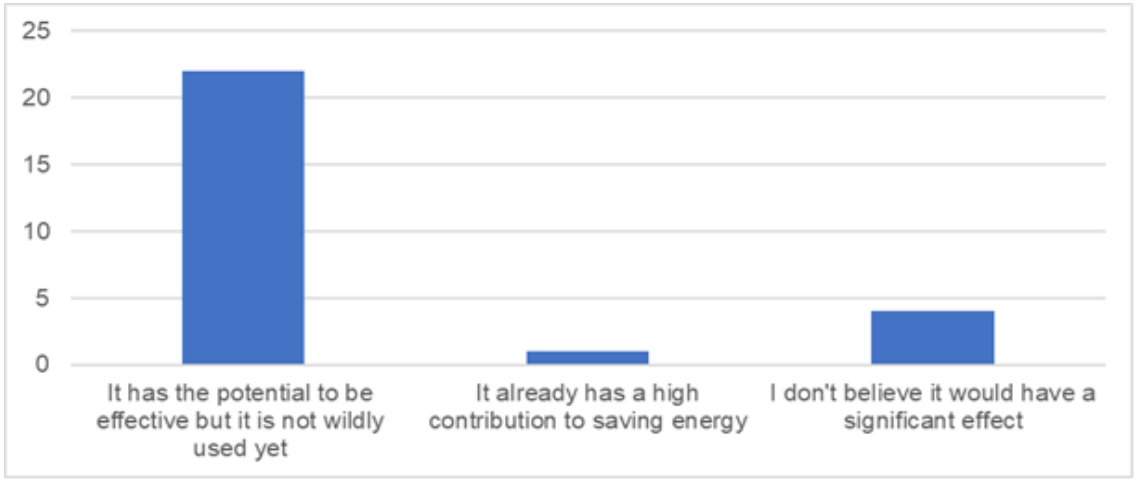


Fig.14. TC sustainability contribution



Fig.15. The Brightwall project [23]

Comparison with other building envelopes

Experimental and computational investigations were carried out by Baofeng Huang utilizing a one-room office building model to examine the electricity consumption of the TCP (Translucent Concrete Panel) for usage in building envelopes. The north, west, and east sides of this room were made of an uninsulated masonry wall. The south side of the building was reserved for envelopes, such as a window, glass curtain wall, and TC panel (See Table 1).

Three sample cities from the cold, moderate, and tropical temperature zones, namely Stockholm, Nanjing, and Singapore, were chosen to study power use and financial costs (electricity and material cost) (See Table 1).

The model with a TCP envelope had the lowest electricity consumption, financial cost, and payback period, according to the simulation findings [25].

Current TC Walls

Owing to the lack of study, LTCP's current applications tend to be aesthetic, but its multifunctional potential is still in its infancy. Table 2 illustrates the common engineering applications of LTCP. **[25]**

3.6 Building Performance Analysis software

Light transmitting performance and energy-saving of plastic optical fiber transparent concrete products

Juan Shen and Zhi Zhou document in their research paper a study that aims to evaluate the performance of Translucent plastic optical fiber transparent concrete product (PTCP) of their own development. The study is

The authors are responsible for the content of the papers.

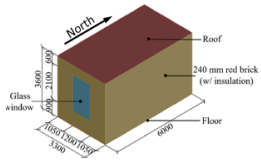
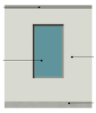
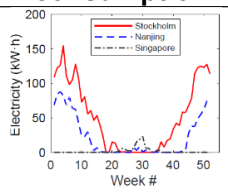
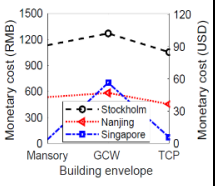
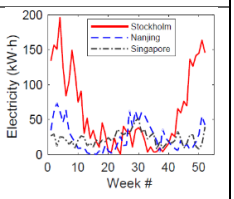
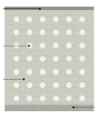
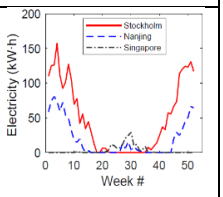
Model	Wall Type		Electricity consumption	Monetary cost	Payback (Year)
	Masonry wall with opening				-
	Glass curtain wall				Stockholm 4.63 Nanjing 13.02 Singapore 2.97
	TC panel				Stockholm -3.60 Nanjing -3.54 Singapore 1.18

Table.1. Examination model of electricity consumption & cost for the same room model but different the Masonry wall, glass curtain wall & translucent concrete panel [25]

Year	Project/Building	Dimension (mm)	Light material	Wall Type
2004	European Gate, Hungary	3500 × 3500	Optical fiber	Monument
2010	Italy Pavilion, Shanghai	1000 × 500 × 50	Polymethyl methacrylate resin	Facade
2011	Bank of Georgia, Tbilisi	1200 × 600 × 15	Optical fiber	Façade and partition wall
2012	LUCEM Media Façade, Germany	1200 × 600 × 15(30)	Optical fiber	Facade
2015	Al Aziz Mosque, AbuDhabi	1800 × 1400 × 40	Optical fiber	Facade

Table.2. The common engineering applications of LTCP [25]

performed on a model of a room that is built with t heir developed translucent concrete [26].

Software used:

ZEMAX optical design software was used to predict the light transmittance abilities of their developed translucent concrete.

Autodesk Ecotect building energy simulator software (not available since 2015) was used to evaluate the energy-saving effect of using the developed translucent concrete on the building

Study results:

30% increase in average daylighting.

40% increase in lighting uniformity.

20% reduction in energy consumption.

Evaluating energy consumption saving from translucent concrete building envelope

A. Ahuja et al. in their research paper a study that combines daylight and thermal analyses to determine the optimal optical fibers volumetric ratio in a translucent concrete panel in terms of saving energy [27].

Software used:

Developed custom code that estimates the energy loads resulted from the use of a translucent concrete system.

Study results:

Increasing the volumetric ratio of optical fibers in the translucent concrete panels result in:

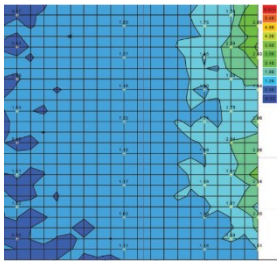


Fig.16. Daylight distribution in a common room [26].

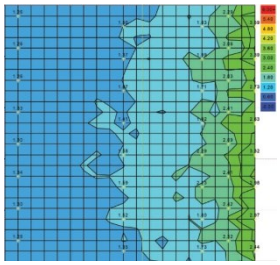


Fig.17. Daylight distribution in the PTCP room [26].

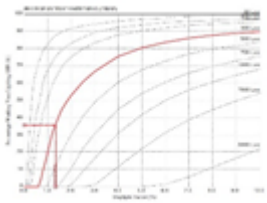


Fig.18. Energy-saving in a common room [26].

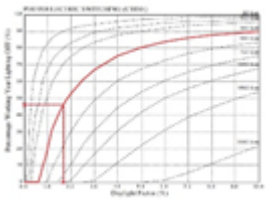


Fig.19. Energy-saving in the PTCP room [26].

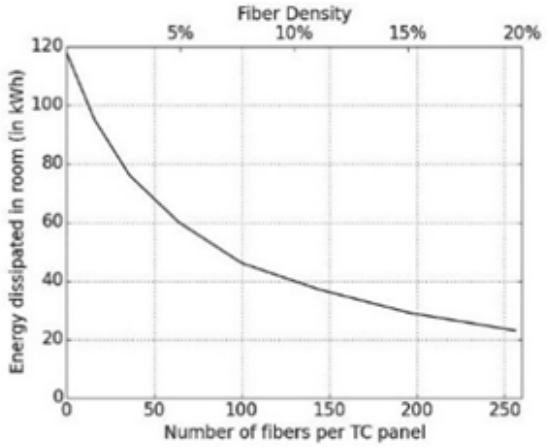


Fig.20. Heat gain and FO volumetric ratios [27].

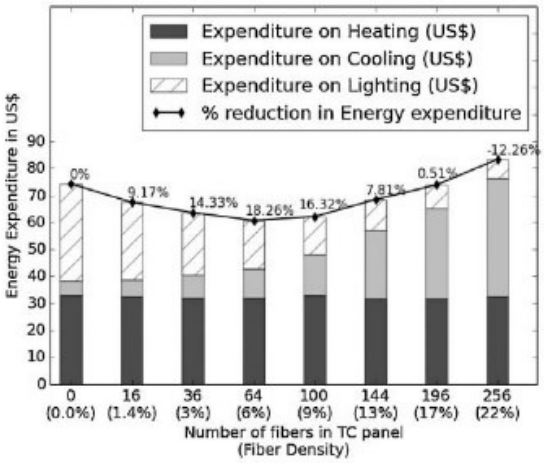


Fig.21. Energy cost due to the use of TC [27].

- Increase in heat gain therefore increasing the cooling loads on the HVAC system.
- Increase daylight illumination sufficiency therefore saving energy needed for artificial lighting.

Increasing the volumetric ratio of optical fibers in the translucent concrete panels result in:

- Increase in heat gain therefore increasing the cooling loads on the HVAC system.
- Increase daylight illumination sufficiency therefore saving energy needed for artificial lighting.

6% Fiber optics (FO) volumetric ratio of a south facing translucent concrete wall resulted in 18% reduction of energy usage compared to a room with no access to daylight.

The present-day software for analyzing building physics (e. g. Energy- Plus) are limited to materials that are either opaque (e. g. walls or partitions) or transparent (e. g. windows). Hence, it became necessary as part of this research to develop a software.

4. Discussion

4.1 Challenges

TC is not yet widely used in the construction industry[8], according to the conducted online survey the biggest obstacle facing the spread of TC is the high cost (see Fig.22).

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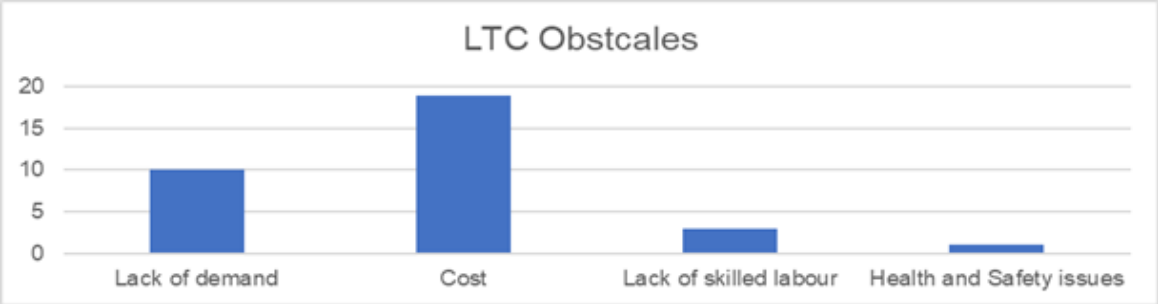

Fig.22. TC obstacles according to the online survey

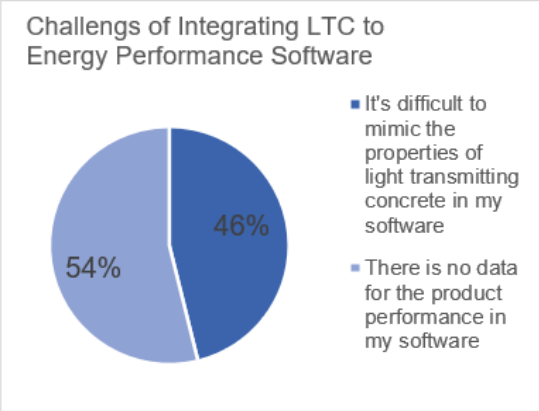

Fig.23. Challenges of Integrating TC to Energy Performance

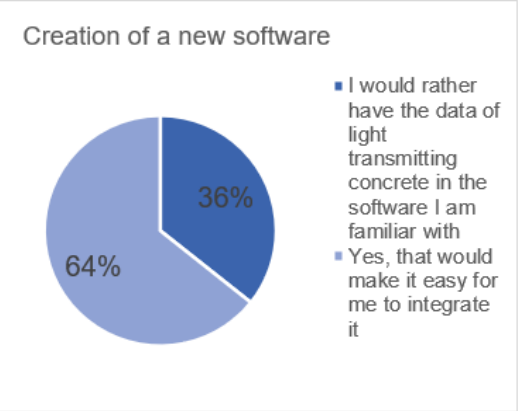

Fig.24. Creation of a new software proposal

This was confirmed by the industry partners during the interview, while correcting the common misconception that the cost of the optical fiber is the main reason behind the high cost of the TC, the industry partner stated that it's the complexity of the fabrication process is what rises the cost of the product. The second obstacle is lack of demand of TC compared to other products. Despite the high potential for TC to be used as a green building material due to its high capability of saving energy, it has only been used for aesthetic purposes. When asked in the conducted questionnaire, most of the engineers put the absence of TC material in their energy performance software data-bases and the difficulty of mimicking the properties of such materials as the main challenges facing them when trying to integrate TC in their energy performance simulations. The results of the questionnaire also shows a preference by the engineers of not using an additional software just for simulating TC but rather have the TC option in their already known software or as an add-on plugin (see Fig.23 & 24). Facilitating the integration of the TC in the energy performance analysis will surely encourage designers to integrate such innovative material in their early design phase therefore, increasing its demand.

5. Proposal

Goal

This proposal aims to encourage the use of Translucent concrete as a sustainable building envelope material for saving energy by facilitating its integration in the design process.

Idea

A User-friendly early design phase open-to-use design tool for architects that integrates Translucent concrete properties in daylight and thermal simulations and analysis for indoor spaces.

LTC Tool (Light Transmitting Concrete Daylight and Thermal Simulation Tool)

- The LTC Tool can be a stand-alone software or a plug-in for other software.
- The LTC Tool can be used as a plug-in for other building energy performance

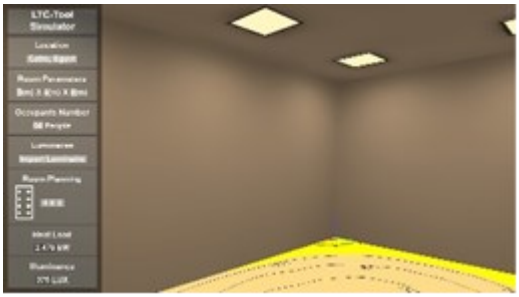

Fig.25. LTC-Tool UI concept for Luminaires.



Fig.26. LTC-Tool UI concept for façade openings.

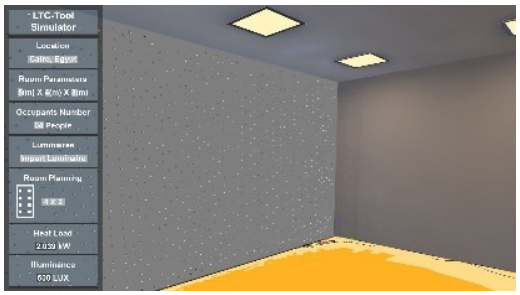

Fig.27. LTC-Tool UI concept for adding LTC Panel

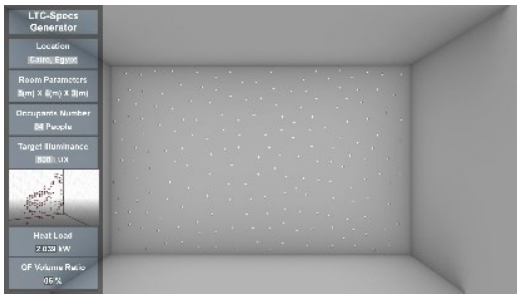

Fig.28. LTC-Tool Specs Generator UI concept.

software for a full energy performance analysis by energy modeling professionals.

Price and Funding

- LTC Tool will be a free software open for all types of users.
- The development of the LTC Tool will be funded by partners in the industry of Translucent concrete.
- The partners in return can have their catalogs of products available for planning by users.

LTC Tool-Modelling

- The user will be able to import 3D models in a range of different formats or build their model from scratch.
- The user will be able to surf and choose between a variety of Translucent concrete materials files provided from different partner manufacturers and use them in his project.
- The provided TC materials files will contain the TC specifications that will help the user test the effect of integrating TC and enable him to choose the most suitable product for his project.

LTC Tool-Analysis and Simulations

Based on different factors and specified data the user will be able to perform daylight and/or thermal analysis and/or simulations while integrating the effects of using Translucent concrete.

LTC Tool-Specs Generator

- The LTC Tool will be able to generate and suggest a custom-designed Translucent concrete surface with suitable specifications based on the target result set by the user.
- The LTC Tool will be able to generate a specification sheet for the custom Translucent concrete and use it to request the custom-made product from manufacturers.

6. Conclusion

This paper the illustrates the TC state of the art, applications, fabrication process, sustainability contribution, the main obstacles that limit the spread of this product and the attempts to increase its usability for TC future integration in the building industry and development.

General opinion of manufacturers of the product recognizes the positive potential of

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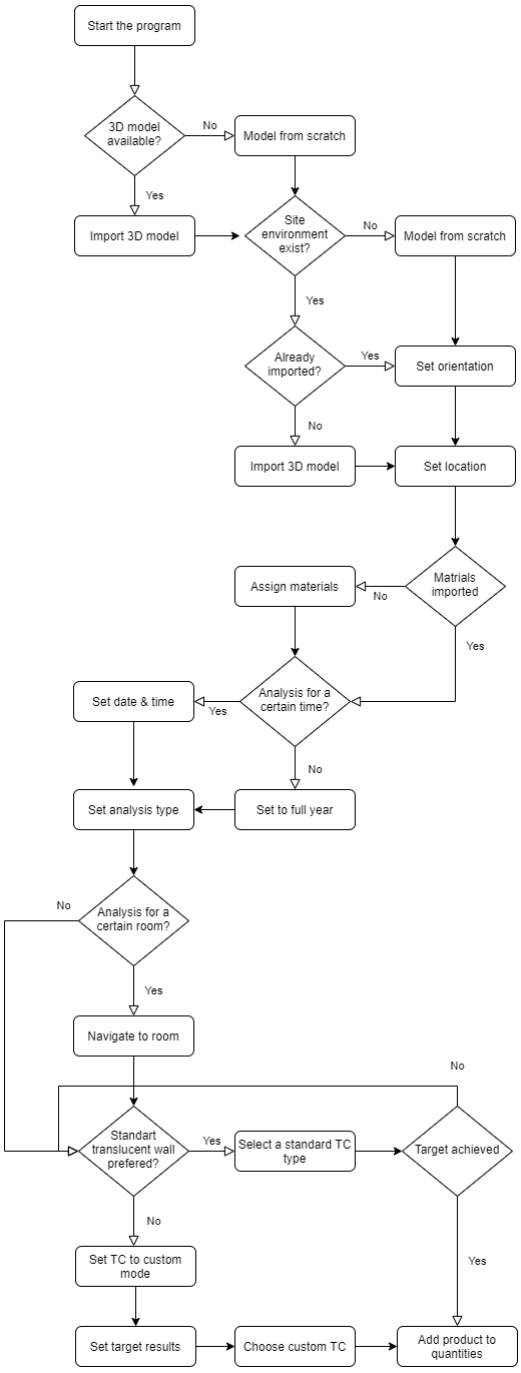

Fig.29. LTC-Tool informal UX flow diagram.

TC as a sustainable product. The development of TC panels was prompted by the interest in using alternative lighting sources. However, they have only been used for aesthetic purposes, even though most people acknowledge their high potential for sustainability contributions and their high capability of saving energy.

The main obstacle that limits the spread of TC is mainly its high cost (due to the lack of labor, complicated fabrication process, and the cost of optical fibers), which directly affects the demand on this product.

The difficulty of integrating TC in the building energy efficiency analysis software, is also one of the obstacles that limits architects, engineers, and designers from integrating TC in their projects as they do not have enough data for the product performance, and it is also difficult to mimic the properties of TC in the existing energy efficiency software. Jjhjuiu8, this paper aims to encourage the use of Translucent concrete by facilitating its integration in the design process.

A User-friendly early design phase open-to-use design tool for architects that integrates Translucent concrete in daylight and thermal simulations for indoor spaces is proposed.

Overall, TC simulation modeling should receive more focus in future study to provide a thorough understanding and recognition of TC performance for application in the construction sector. In addition to the light transmittance performance of TC, factors for thermal comfort and energy conservation should be given more attention in the simulation examination of future research.

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CRISTÓBAL DÍAZ MUÑOZ, ERICH DOMME, FILIPE SILVEIRA LEÃO, SYED ALI ZARGHAM KAZMI

Bridge management using sensor-aided NFTs

ABSTRACT

Bridge management is a significant topic in the field of Bridge Engineering. While new bridge monitoring and inspection methodologies are emerging, the amount of data generated, the data management, and the security of information are becoming key aspects to be considered. The objective of the present study is to describe the current challenges and opportunities concerning bridge management and propose an adapted bridge management concept by considering the use of sensor-aided NFTs. To accomplish that, this paper summarizes the most important characteristics of bridge management systems and reviews the role of sensors in Structure Management Systems (SHM). Furthermore, it is also presented a review of the main concepts concerning blockchain, smart contracts, and NFTs. Finally, this research illustrates the proposed sensor-aided NFT solution by describing the use of fiber optic sensor for corrosion detection in reinforced concrete bridges.

Keywords: Bridge management, sensors, NFTs, corrosion, optical fibers, blockchain

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Image from Mikael Blomkvist

1. Introduction

A growing awareness of the degradation and underperformance of civil infrastructure systems has existed since the early 1980s. Considering this scenario, bridge management stands out due to the importance of bridges in transportation infrastructure and in the global economy.

The importance of the topic, the potential impact on the construction industry, and the enormous horizon of applications are the major motivators of this work. This study aims to discuss key concepts involving bridge management and its main process and technologies, in order to identify the main problems and challenges concerning this crucial activity. Moreover, the research intends to propose an adapted bridge management scheme through the use of sensor-aided NFTs, and describe all the aspects involved on it.

2. Research Methods

This paper discusses key aspects of bridge management in combination with the main challenges and opportunities that involve the topic. In addition, this study aims to propose an adapted scheme using sensor-aided NFTs which may tackle important problems presented in Bridge Management Systems. For that, this paper follows the subsequent strategic scheme:

I. Literature review of bridge management and its main components.
II. General outline of the current sensors used in Structural Health Monitoring (SHM) systems.
III. Introduction about key concepts for this study: blockchain, smart contracts, and Non-Fungible Tokens (NFTs).
IV. Sensor-aided NFT solution.

3. Results and Discussions

3.1 Bridge Management

To begin with, it is necessary to understand what an asset management system is. The formal definition, based on ISO 55000:2014, states that “it is a set of interrelated and interacting elements of an organization, the function of which is to establish the asset management policy and asset management objectives, as well as the processes needed to achieve those objectives” [1]. Therefore, by extending this definition to bridge management, the bridges belonging to highways are the assets which need to be managed. Consequently, the management objectives correspond to the bridge conditions that must be met during the bridges’ operational phase. Furthermore, the asset management policy in combination and its related processes are, in this context, key elements that are considered necessary to reach the bridge management objectives. The most important bridge management processes, such as inspection, monitoring, and maintenance, are further discussed in this study.

In this perspective, it is important to remember that bridges are key assets in highway engineering, since they allow us to connect strategic points, optimizing construction budgets, travel times and urban planning logistics [2]. However, they are also considered a high-risk asset because any negligence or error in any of the stages of its life cycle (design, construction, and operation) can directly affect the normal operation of the highway or, even worse, threaten people's lives. That is why bridge maintenance is a key point to protect the safety of users as well as to extend the useful life and social profitability of the infrastructure project.
In some cases, one single company (e.g. road authority) is responsible for the management of several bridges at the same time, during the bridges’ operation stages. Due to the complexity of the analysis and the number of bridges, the amount of data collected might be enormous, which makes bridge management a very challenging process.

Because of that, many companies have used Bridge Management Systems (BMSs) as an important tool capable of helping agencies (companies) to meet their objectives such as Structural Health Monitoring (SHM), maintenance, inspection planning, and repairs.
In fact, BMSs are functional at a range of levels (executive, planning, administrative, maintenance) for: (i) collecting inventory data in a systematic and organize way; (ii) carrying

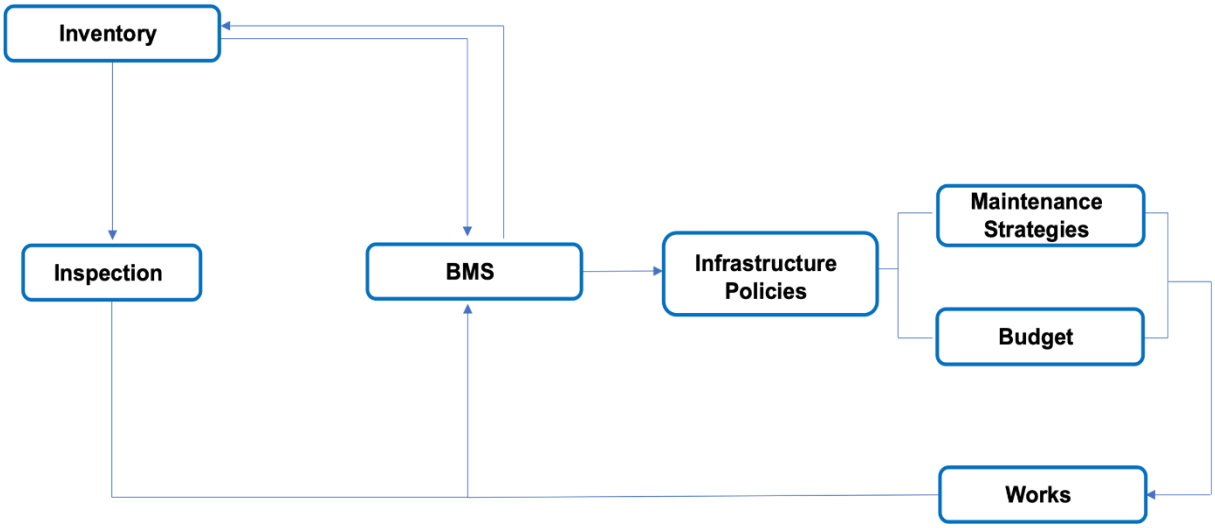

Fig. 1. Bridge Management System Diagram

out inspections and damage assessment; (iii) planning repair and maintenance schedule; (iv) allocating funds [3].

A simple way to explain the operation of Bridge Management Systems (BMSs) is according to the diagram of Figure 1. The inventory is the starting point in any BMSs, each bridge registered in the inventory should ideally possess concerns identification (geographical position, road, etc.), technical data (geometry, materials, structural system, etc.) and maintenance data (condition, inspections, monitoring, etc.) [4].

Inspections are frequently defined as the main power sources of BMSs, since they are the only process being periodically conducted by bridge specialists [5]. The main objective of the inspection is to register defects and damages that might affect the safety and usability of the bridges or reduce the structure service life by increasing the degree of deterioration [5]. Due to the importance of inspections in bridge management, each country generally publishes instructions about how companies must perform the tasks. Some guidelines are very extensive, but usually the level of detail required depends on the condition and age of each bridge. The most basic inspections, which are the most frequently performed, are visual inspections, without elevation means or traffic cuts. Through this process, the inspectors generate a report with the evaluation of all the inspected elements and summarize the general condition of the bridge by a numerical index, which is normally named as Condition Value (CV). The CV is calculated according to the infrastructure management policies defined by the highway administration entity.

The CV depends on the methodology adopted by each managing entity or according to the regulations imposed by each country. In the UK, for example, the CV varies from 1 to 5, and these values reflect the group of defects of the element which is being analyzed. Additionally, the UK`s methodology assigns a weight "*W*", ranging from 5 to 10, to each element [5]. The condition value, thus, is the first step to define the maintenance strategies in the BMSs. It is important to mention that the condition value is a key pointer of the general condition of bridges, but this indicator itself is not enough to determine which intervention strategy needs to take place or even which bridge needs to be prioritized. Normally, other factors are considered when prioritizing bridge interventions, such as the importance of the structure to the road network, budget, the traffic over the bridge, and so on.

Despite all the different methodologies and regulations around the world, the use of BMSs has become more and more popular when it comes to planning and executing bridge management tasks. It is crucial, however, to keep in mind that the BMS is a tool which needs to be tested and reviewed from time to time. Regardless of the use of a BMS, the following questions should always be considered in a bridge management planning:

- What is the real condition of the bridge?

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- How much would it cost to bring the existing old bridges to the state of acceptable performance?
- Is there enough information available about the bridges for an adequate intervention? [5]

Bridge Management Challenges and Problems

As previously stated, site inspections are extremely important to bridge assessments and usually involve teams of experts in this field. During site inspections, the responsible for the task collects valuable information about the structure and becomes familiar with the bridge`s physical layout and characteristics. A recurrent problem is that most of the current inspection methodologies involve a long working time, due to the fact that bridges are large-sized structures, so each inspection is not usually a quick task. In addition, the total number of bridges in the network is also a relevant factor, since it defines the workload and the inspection plan to be performed.

On the other hand, it is important to remember that inspections depend on the human eye, thus, there is always the probability of human errors. A clear example is when in 2005 the U.S. Federal Highway Agency (FHWA) stated that 28% of their 595,000 bridges are rated deficiently. Only a portion of it (about 15%) has structural reasons and in Europe this figure varies around 10% [6]. This is a strong indicator that the accuracy of the inspections is relative and arbitrary. In some cases, therefore, the bridge inspector might not notice severe defects during the inspection due to poor luminosity or bad weather conditions, for example. However, the opposite case can also happen, where a bridge inspector may overestimate the damage of the structure due to reasons like lack of experience. This sort of situation directly affects bridge management planning, controlling and execution.

A problem not often mentioned in the research scenario corresponds to the security and traceability of the information managed in a BMS, which is an important point when it comes to identifying responsibilities in collapse events. As an example, there is the well-known case of the Genoa Bridge in Italy (2018), where involved parties stated that “there is now fierce debate in Italy over whether the company did in fact do enough” while the company in charge argues that they “promptly fulfilled the concession obligations” [7]. In such cases, the causes and also the responsibilities of this event could be determined with a BMS with a proper data management technology capable of providing historical data (traceability) in a transparent and incorruptible manner. In fact, nowadays, it is common that many entities manage the technical information of bridges only through PDF files, which are easily modifiable. In the worst scenarios, sometimes entities responsible for the bridge management do not have any kind of documented data, which was the case reported in Chile where it was noticed the non-existence of a database of more than 6772 bridges [8].

Finally, regarding the implementation of BMSs, it is common that many entities limit themselves only to the creation of the inventory, which avoids that many countries use BMSs to make decisions about the risk status of their bridges. Countries like Belgium, France, Germany, and Ireland, for instance, base their decisions on engineering judgment [3], transforming the BMSs only into an information repository. Another frequent problem occurs in the planning stage of a new highway project when it is decided to reuse existing infrastructure. When that happens, it is common to have in the operation stage old bridges of which there is no information regarding construction drawings, reinforcement projects or even the last maintenance works done. This lack of documentation, or sometimes the poor documentation available might generate considerable problems for the future entity that will manage the structure.

Opportunities for improvement

The bridge inspection process is a time-consuming and usually a not very accurate process, as per the above-mentioned reasons. Therefore, one of the biggest challenges for bridge management is to increase the reliability of the data collected as well as its proper documentation. This is, however, a complex task and probably will never reach the desired standards since it is a task that depends on the human eye. For that reason, many researchers and companies are seeking automated solutions which can help to mitigate human errors. To illustrate, the use

of drones, digital twins or different BIM solutions are gaining space in the industry, but these solutions are still very dependent on human interaction.

Nevertheless, emerging techniques based on near-continuous monitoring of certain response characteristics of a bridge (e.g., vibration responses, operational deflection shape, deflection measurement) are quickly becoming popular. The principle of these techniques involves tracking changes in the material and geometric features of engineering structures like bridges over time by observing and analyzing a system using periodically sampled response measurements. Thus, if any of the observed values exceed a certain threshold, the system alerts the need for inspection or maintenance. This condition-based inspection technique is recognized by the industry as Structural Health Monitoring using sensors [9].

The continuous monitoring of bridges could reduce the uncertainty, arbitrary and time-consuming aspects of today's inspection process by automating the production of reports and, consequently, the management of this data. However, it is important to emphasize that Structural Health Monitoring using sensors does not imply replacing a visual inspection, instead the system would help to optimize resources, indicating only when a detailed inspection is necessary.

On the other hand, incorporating continuous monitoring systems into the BMSs opens the door to optimize data management with new technologies available for this

Physical quantity	Sensor	Market research	Applications
Displacement	Linear variable differential transformer (LVDT) [12] Long gauge fiber optics Optical Laser	TE connectivity	Industrial automation, Turbines, satellites etc.
Acceleration	Piezoelectric accelerometer [13] Capacitive accelerometer Force balanced accelerometer Micro electro-mechanical systems (MEMS)	Brüel & Kjær	Shock/vibrations tester, Dynamic response testing etc.
Strain	Electrical resistance strain gauges Vibration wire sensors Bragg grating fiber optics [14] Long gauge fiber optics (Interferometry)	FiberCore	High voltage and high current sensing systems, Temperature sensor for oil and gas reservoirs etc.
Force	Electrical resistance load cells Piezoelectric load cells [15]	Kistler	Medical devices, fire alarms etc.
Temperature	Electrical resistance thermometers Thermocouples [16] Thermistors Fiber optics-based sensor	Chromalox	Steam kettle temperature control, Oven control etc.

Table 1. Table captions should be placed above the tables – adapted from [11].

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purpose, such as NFTs. This would provide greater transparency and decentralization of information, avoiding possible problems of corruption and improper manipulation of this data. Therefore, during this research study, the feasibility of using monitoring sensors in conjunction with NTFs for bridge management will be analyzed in more detail.

3.2 Sensors for Bridge Health Monitoring (BHM)

If we look back into history, Warren Johnson's thermostat, which he invented in 1883. He called the device an "electric tele-thermoscope" [10]. It was a bi-metal coiled thermostat with a mercury switch, which could be used to ring a bell to alert the fireman to open or close the heating damper. In the 1940s, the first motion sensor was created. The implementations of first vibration-based damage detection in bridges came during the 80's and used as a rule identified modal parameters for damage identification. During the 1990s several laboratory experiments were performed in beams and bridge models.

The Structural Health Monitoring process starts with the measurement of relevant physical quantities in the structure, and it is usually achieved by sensors [11]. Some of the most commonly used sensor types and their manufacturers are listed in Table 1.

3.3 Blockchain and Non-Fungible Tokens (NFTs)

Since the paper has already explained the bridge management process, its current state of the art and also provided an insight into the common sensor systems for bridge monitoring, it is now time to talk about the last technical aspect of this paper - the sensor-aided NFTs (Non-Fungible Tokens). Before we can explain sensor-aided NFTs and investigate their potential additional value for the construction industry, we first need to establish a uniform knowledge foundation. For this purpose, this study provides overviews and definitions of blockchain, smart contracts, NFTs in general while explaining how the typical NFTs differ from dynamic NFTs. Therefore, all one after the other, starting with the topic of blockchain.

Blockchain

Blockchain is on everyone's lips these days. Since 2008, the topic has gained significant interest and popularity with the development of the first cryptocurrency, Bitcoin, by Satoshi Nakamoto [17]. It is not known much about Satoshi Nakamoto, it could be a single person or a group of people, the anonymity is still there today. However, it was Satoshi Nakamoto who made the topic public with the help of the Bitcoin which he developed. Before Satoshi Nakamoto, there was David Chaum, who in 1982 described a blockchain-like protocol based on cryptography for the first time [18]. However, it is usually the case that an idea or a thought is only taken up again years later and thereby creates something that is capable of changing the world - like Bitcoin.

The BaFin, the Federal Financial Supervisory Authority in Germany, defines blockchain technology as follows: "Blockchains are falsification-proof, distributed data structures in which transactions are recorded in chronological order, traceable, unchangeable and without a central authority. With blockchain technology, ownership relationships can be secured and regulated more directly and efficiently than before, as a complete and unchangeable data record creates the basis for this" [19].

In simple terms, this means that data, documents, and transactions are recorded and managed as if by a ledger. In the case of Bitcoin, each "block" in the blockchain contains information about the sender, the receiver, the number of coins transferred and the block-specific digital fingerprint, the hash. Each block therefore contains: Information, its own personal hash but also the hash of the previous block, because as soon as something changes in a block, this leads to a new block. The continuous deposit of the previous block creates a "chain" - The Blockchain. However, anyone can view the stored data and validate it. This leads to the three fundamental characteristics of a true blockchain: decentralization, peer-to-peer network, and distributed storage of data.

Decentralization

Decentralization is achieved by a blockchain by distributing the underlying network to numerous nodes, i.e., users or computing devices, so there must be no

centralized authority. In the best case, the ownership of the blockchain network is in the hands of its users, comparable to a swarm intelligence. Decentralization also has the advantage that if there were a central structure and it failed, the entire network would collapse; in decentralized form, it functions as long as one node is still active. Another advantage of decentralized networks is the quick identification of hacker attacks and how to avoid them. To successfully falsify data and, therefore, infiltrate corrupted information into the network, it requires an attack on a significantly high proportion of nodes in the network - and this has proved to be extremely difficult. Infiltrations by a single user are detected immediately and if the changed data does not match the majority of data already present, it is instantly classified as corrupted, so the blockchain does not include this data in the network.

Peer-to-peer network

Peer-to-peer network describes the function of direct exchange between users on a blockchain. With peer-to-peer, there is no need for a "middleman" at all. Thus, each node can carry out transactions of data or finances directly to another node without intermediates. Only by eliminating the necessity of an intermediary on transactions, the chances of falsifications tend to reduce. In general, the fewer intersections, the less susceptible a system is to corruption.

Distributed database

Distributed database is the way data is stored on the Blockchain. Namely, data is backed up on the hardware of the blockchain nodes, not as for example with a cloud, where the data is centralized. The distribution naturally increases security, since attacks, as already described in "decentralization", must be carried out on numerous nodes in order to be successful.

Smart Contracts

This section aims to provide an overview about smart contracts and the technologies linked to them. For that, it is important to mention that smart contracts cannot be created on the Bitcoin blockchain, it was never meant for that. The largest blockchain after Bitcoin that supports this technology is the Ethereum blockchain and this study will refer to it in the following. Of course, there are other blockchains, or sub-layers of the main Ethereum blockchain, that support smart contracts and more, but these will not be considered in order to provide a simpler overview of the topic.

The International Business Machines Corporation (IBM) defines Smart Contracts as follows: “Smart contracts are simply programs stored in a blockchain that are executed when certain conditions are met. They are typically used to automate the legal execution of a contract so that all parties have instant certainty of the outcome without the need to involve an intermediary or waste time. They can also automate a workflow and trigger the next action when the conditions are met” [20].

In simple terms, a smart contract is based on basic "if...then..." commands that are stored in the code of a blockchain. The decentralized network executes the order in the background, but only if predefined conditions are met and verified. The result of such an executable task might be applied to many different purposes, as for example to release funds, to rent out a car or to simply sign a contract. Once the transaction is complete, the blockchain is updated. This means that the transaction cannot be changed and only the parties who have been authorized can see the results. In a smart contract, as many conditions can be set as necessary to convince participants that the task will be completed satisfactorily. To set the terms, participants must determine how transactions and their data will be represented on the blockchain, agree on the "if...then..." rules that govern those transactions, explore any possible exceptions, and define a framework for resolving disputes.

NFTs (Non-Fungible Tokens)

NFTs are tokens that can be used, for instance, to represent ownership of unique objects. Nowadays, this can be used to tokenize things like art, collectors' items, or even real estate, especially known through the media. There can only ever be one official owner and the tokens are secured by the Ethereum blockchain. It is not possible to change the proof of ownership or insert a copy of a similar NFT into what already exists [21].

NFT stands for Non-Fungible Token, and the term, non-Fungible, comes from economics and is used for things like furniture,

a song file or a computer. As mentioned before, an equivalent exchange is not possible because they are unique [21].

In contrast, fungible objects can be easily replaced. They are determined by their values and not by their unique properties. ETH or euros, for example, are fungible, because 1€ or 1 ETH is exchangeable for another euro or ETH [21].

Whether a token is fungible, like a coin such as Ether, or non-fungible, like NFTs, it is defined on the blockchain using smart contract standards. Fungible tokens are described by the ERC20 standard [22] while non-fungible tokens are described by the ERC721 standard [23] and integrate. The creation or minting process is superficially composed of the following steps:

- A new block is created
- Information is validated
- Information is recorded in the blockchain

NFT's Features

NFTs offer the possibility to assign or claim any unique object. Therefore, a NFT can only belong to one owner at a time. Ownership rights are managed through the unique *ID* and metadata that no other token can replicate, while the traceability is provided via the Ethereum blockchain as a public record. Thus, it is always possible to differentiate who is the owner and who is the creator of an NFT.

As an NFT owner, it is always possible to prove the ownership of the NFT. Proof of ownership is determined with the help of the personal wallet, as the public address of the wallet is transferred when an NFT is obtained. The combination of token holding, and private wallet key proves ownership of the NFT.

The public key of the content creator serves as a certificate of authenticity for acquired NFTs, as the public key of the creator is a fixed component of the token history. In addition, the creator`s key can be used to prove the authenticity of the NFT, so it is possible to distinguish between the original and a counterfeit.

And most importantly, the original NFT cannot be manipulated by anyone in any way [21].

3.4 Study setting and context

Bridge management, as previously described, is the activity of controlling and administrating resources to maintain operational bridges.

This study aims to understand the current limitations of bridge management and suggest an adapted bridge inspection scheme through the use of sensor-aided NFTs. The main idea behind the use of NFTs is to identify if such technology may help Bridge Management to become more reliable, transparent, and effective.

As illustrated before, there are a number of sensors that have been used to measure relevant physical quantities in bridges. Thus, in order to understand the feasibility of the proposed sensor-aided NFT solution in this paper, we will focus this study on a specific type of sensor used for a specific purpose: fiber optic sensors (FOS) for corrosion detection in reinforced concrete bridges.

3.5 Study design

As previously mentioned, this study aims to suggest the use of sensor-aided NFTs to improve the bridge management documentation, data collection and data management. For that, the use of fiber optic sensors (FOS) for corrosion detection in reinforced concrete bridges are analyzed. In the next section and before introducing the proposed sensor aided NFT solution, this paper covers important concepts about corrosion in reinforced concrete bridges, the use of FOS in Structural Health Monitoring (SHM).

Corrosion in reinforced concrete bridge

Concrete bridges are probably one of the most important structures ever created. These structures play an essential role in transportation network systems globally, and of course, in people's daily lives. In this scenario, corrosion of steel in reinforced concrete structures is a major problem all around the world. In fact, corrosion is the most common cause of premature degradation of reinforced concrete structures [24]. Including maintenance, repair, replacement, and construction costs, the annual direct cost of corrosion in highway bridges alone in the

United States is estimated to be $8.3 billion [25].

The corrosion of steel in reinforced concrete bridges is, therefore, an important issue that needs to be properly addressed. Proper maintenance and investigation can extend the concrete`s bridge lifetime.

The actions required to check the condition and the durability of the structures are results of the chemical, physical and biological deterioration processes, which have a constant impact on them [26]. The action of oxidizing agents, acids, salts, or bacteria are some examples, therefore. These worsening processes modify their strength, stiffness therefore these properties have a major influence on their safety and functionality.

Fiber Optical Sensors in bridge Structural Health Monitoring (SHM)

Optical fiber sensors are emerging as a superior nondestructive means for evaluating the condition of concrete structures. Optical-fiber-sensor-based instrumentation has been shown to be extremely attractive for the in-situ health monitoring, diagnostics, and control of civil infrastructure. In contrast to existing nondestructive evaluation techniques, optical fibers are able to detect minute variations in structural conditions through remote measurements. [26]

Fibers and Corrosion

The most prevalent cause of reinforced concrete structure deterioration and failure is chloride-induced corrosion of its embedded steel [27]. For this reason, many researchers around the world are studying and developing ways to improve bridge SHM through the use of sensors capable of identifying corrosion in particular sections of structures, such as reinforced concrete bridges. Considering the sensing systems utilized to identify corrosion in structures, the use of fiber optic-based sensors is considered a reasonable alternative. This is mainly because certain fibers can be cast into the concrete-rebar matrix combination and tolerate a very alkaline environment [28].

Operating principle of optical fiber sensors

In this study, we are analyzing the use of optical fiber sensors aimed at monitoring and controlling the corrosion phenomenon. Most of the sensors employed for this purpose are governed by electrochemical principles, according to the literature now in existence.

Isolated transmit and receive fibers have been used in this demonstrated 'twin-fiber' technique. In order to achieve the required outcome, spectrally broadband light is joined into an optical fiber which afterward illuminates the region under measurement. The color modulation of the broadband input

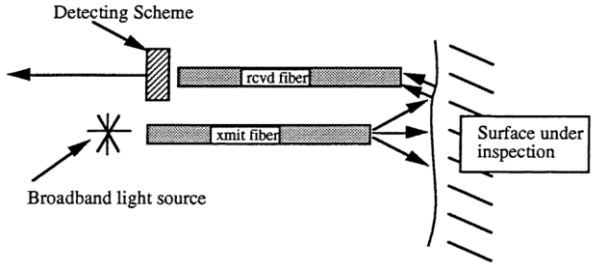

Fig. 2. Twin-fiber spectroscopic sensing [29]

signal is used to determine the presence of corrosion. The input light appears from the fiber either at its end or for certain fibers at the windowed region. Furthermore, in case the fiber is in close vicinity to the corroding metallic specimen including rebar, the light signal then illuminates the rebar which is color modulated with either absorption or re-radiation with regard to the surface color of the localized region of the rebar [29].

The above shown fig. 2 represents the spectra recorded using 100/140 μm diameter Siecor multimode optical fiber. The output from a broadband light source (quartz halogen fiber illuminator) was coupled into the transmit fiber which then illuminated a 1.25 cm diameter rebar. Spectroscopic analysis of signals is used to obtain the corroded and un-corroded spectra, returned from the windows associated with the corroded and un-corroded rebar regions.

The spectra could be recorded at 100 frames per second with the frames alternating between the windows by the usage of a computer-based spectrometer (Ocean Optics B-1000) and a relatively fast microcomputer (486/60 MHz). Because of that, it is rather possible to perform real-time corrosion analysis and monitoring of the instrumented structure. It is determined by a ratio-metric comparison of Figure 3 corroded and un-corroded spectra that there is a definite spectral.

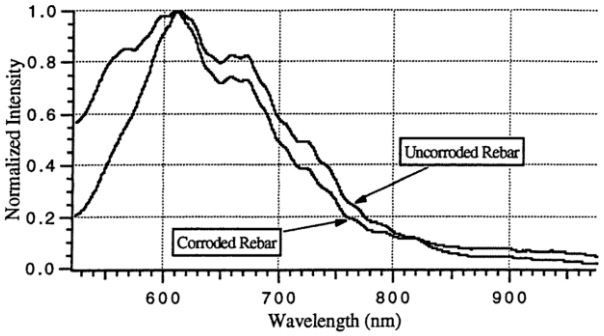

Fig. 3. Spectra recorded for corroded and uncorroded sections [29].

Sensor-aided NFTs (Dynamic NFTs – dNFTs)

Now, this section aims to introduce the proposed scheme: sensor-aided NFTs. As mentioned above, bridge management has weaknesses and that both the bridge monitoring and the inspections could easily be attempted by third parties or directly by the operator. In addition, the management of bridges is in many cases not user-friendly, especially due to the separation of the two systems. The question has arisen, how to eliminate the vulnerability and create a unified system?

Blockchain is seen as a solution in this paper, especially due to its characteristics: transparency and incorruptibility. However, blockchain itself is not the solution but the framework.

In this paper, a specific scenario is presented to illustrate the idea which can certainly be a base for future work. The goal is the optimization of bridge management in the sense of transparency, data security, and data management. In addition to that, a possible connection between SHM and inspection systems might be achieved.

A possible solution would be a smart contract that provides dynamic NFTs (dNFTs) which can be connected to sensors installed on the bridge. For this purpose, this study has provided a review of the most common sensors used in bridge management, and among them, selected one sensor to exemplify the proposed scheme: fiber optic sensor (FOS).

In the subsequent part, the integration between FOS and smart contracts is introduced, and the dNFTs` applicability on this integration is stated.

Oracle

Static NFTs are the most common tokens, and they cannot be changed after they have been minted. There is a way, however, to change NFTs or to make them perform certain actions based on preset conditions.

As previously described, NFTs are based on smart contracts, which are stored on blockchains. Both blockchains and smart contracts are decentralized, and once they have been executed and determined, they can no longer be changed. However, there is a special system, also decentralized, that plays an important role in this blockchain world: Oracle.

Blockchain oracles are entities that connect blockchains to external systems which enables smart contracts to be executed based on inputs and outputs from the real world [30]. Figure 4 illustrates such connections. This means that oracles, like Chainlink, open up the possibility for users to organize decentralized input parameters and integrate

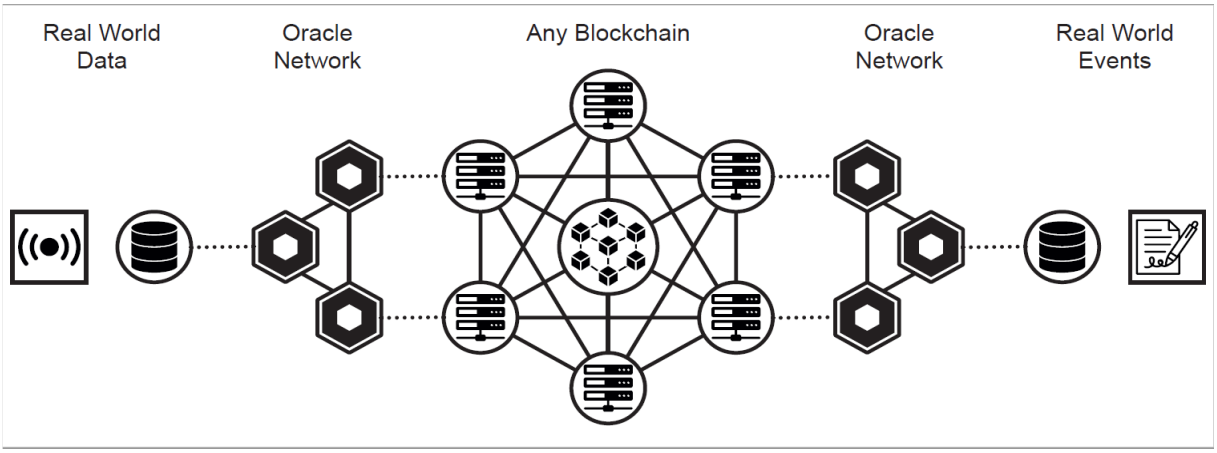

Fig. 4. Blockchain, oracle network, and real-world data and events – adapted from [30]

them into a smart contract. This allows IoT devices to be integrated into blockchains and used for numerous usage models, as for example, to generate performance-based contracts in real time that record building temperature and match it between physical object and digital twin [31].

The way fiber optic sensor (FOS) is bound to an Oracle is not covered in this paper, as this would be out of the purpose of this study once this involves specific programming design. It should be noted, however, that there are other papers that have dealt specifically with this topic. As an example of such a connection, it can be mentioned the investigation of physically connected IoT devices on smart NFTs with the help of PUFs [32].

Proposed solution

This section proposes a hypothetical scenario aiming to explain the proposed solution: bridge management using sensor-aided NFTs. For that, the interaction of a bridge, a sensor, a blockchain and a smart contract, which refers to a NFT, is explained and clarified.

Firstly, it must be clarified that for such solutions, it always needs to be considered the physical and the digital world. In the physical world, this study considers three main actors: the stakeholders, the structural asset, and the sensor. The structural asset in this case is a bridge but note that, in theory, almost any physical asset would be reasonable for such a connection. In the proposed scenario, a bridge has already been built and the sensor, the fiber optic sensor (FOS), was installed during construction. The stakeholders are, of course, those who contributed to the construction and management of the bridge, but also those who are responsible for the smart contract and the management of the digital twin.

In the digital world, the goal is a dynamic NFT that provides the current status of the structural object by displaying sensor data and serving as an inspection repository. The NFT is, thereby, a living document and reflects the health status with building interventions, like a medical record.

After explaining the main actors and in order to better explain the scheme proposed , the creation sequence must be formed backwards. To begin with, it is worthy to remember that the dNFT is based on a smart contract and both are linked at the same time. The smart contract exists on the blockchain, and in this hypothetical scenario, the Ethereum blockchain is assumed. Additionally, for this solution two Oracle protocols need to be added to the blockchain: a back-end Oracle and a front-end Oracle.

The front-end Oracle, in this case, is used to define the smart contract framework, where the standard and possible fixed values are defined. Information like project name, year of construction and company`s name would be inserted. On the other hand, the back-end Oracle acts as a dynamic and static metadata manager. The reason for this setup is that Oracle can obtain all data from a cloud based in IPFS or in another data management system. It is also important to highlight that such clouds are filled with both static and dynamic data. The static data usually comes from 3D models, such as a digital twin, while dynamic data, in this case, is meant to come

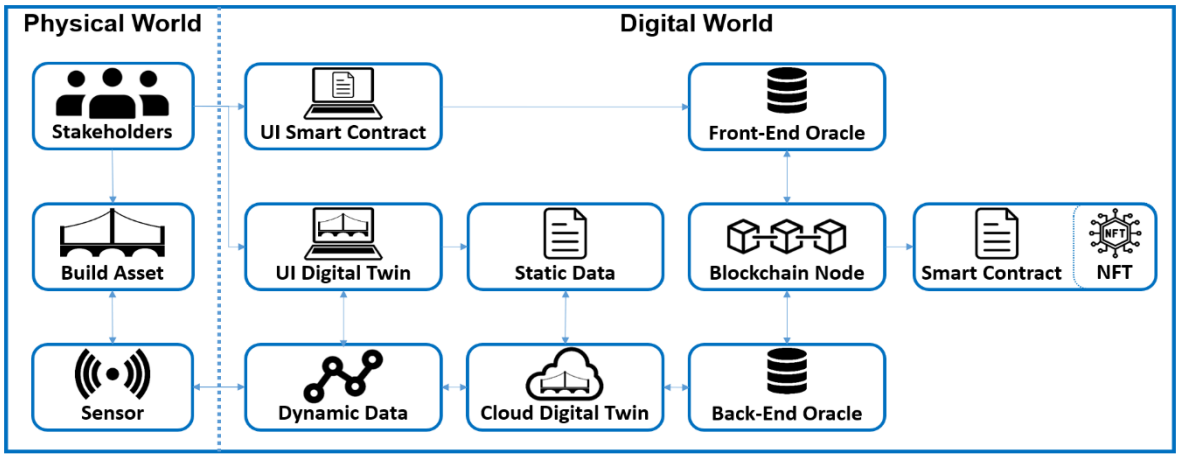

Fig. 5. Proposed scheme – adapted from [31].

directly from the sensors installed on the structures.

To summarize, by applying the proposed scheme , the data coming from the sensors is directly connected to a blockchain, which avoids intervention by third parties. In addition, the static data coming from third parties can be compared with dynamic data in order to ensure truthfulness. The Figure 5 illustrates the proposed scheme.

Based on the above-mentioned approach, it is possible to identify the differences and similarities with a regular bridge management system. In the proposed scheme, for instance, all the information captured by the sensors are transformed into a live/dynamic NFT. This fact represents a significant difference in BMS. Through this solution, no intermediates are needed, and the information received on the user‘s side cannot be tempered. The NFT output, in such a scheme, will always display the uncorrupted state-of-the-art information of the asset to all stakeholders involved in the process.

Data ownership

Despite all the potential benefits the proposed sensor-aided NFT application might be able to generate, it is easy to predict a significant number of barriers this solution would need to overcome in order to take place. In Europe, for instance, the General Data Protection Regulation (GDPR) imposes strict obligations onto any organization in the world that intends to collect data related to people who live in the EU [33]. Before applying this solution, thus, topics like data ownership, responsibilities and data security must be carefully addressed.

To illustrate, imagine the situation in which a country, such as Germany, purchases the presented scheme. In this hypothetical scenario, the German authority responsible for bridge management services across the country would be the owner of the data while a non-governmental entity would be responsible for providing the bridge management service throughout the operation of the sensor-aided NFT solution. In such an environment, the German authority would become dependent on a non-governmental third-party in certain ways, and questions like the responsibility of the information, data security, and data possession would potentially arise.

Based on this imaginary example, therefore, it is evident that for this technology to become viable and accepted, key challenges involving data ownership and its legal aspects need to be properly addressed.

4. Conclusions

Bridge management is crucial to the overall, long-term management of these assets.

Therefore, it is evident that good data management plays an important role in any bridge management task. Through the proposed method, the adapted bridge management solution aims to improve the way information is collected, transmitted, and stored. In other terms, the sensor-aided NFT concept is considered in this paper as a valuable improvement to the current bridge management systems.

In the future, the development of prototypes or suitable software would be necessary to properly test the proposed scheme. This would be extremely valuable in order to conduct a large-scale field study. Since no prototype is currently available, and this topic requires time for development and extensive testing, this paper may only make assumptions about its usability and impact. Thus, based on the importance of the topic and the high capacity of the involved technologies, it is reasonable to assume that the solution might change the industry in a positive way.

Finally, and as probably expected, there are still several open questions to be tackle in future works:

I. Which blockchain should be used? Should it be private or public?
II. Should a separate blockchain be created specifically for the construction industry?
III. Which metadata is most relevant for specific construction projects?
IV. How often should the sensor data be requested?
V. How large would data traffic be?
VI. What would be the costs to implement and manage such a system?

As a future work, surveys and interviews with experts from the industry should take place in order to validate the idea and applicability of the scheme .

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YIFAN CHENG AND KAIWEN DING

Timber Modular Assembly Robot System combined with BIM

ABSTRACT

Construction robotics has received increasing attention in recent years, with the construction industry turning its attention to sustainable, reusable construction, of which timber construction is a major aspect. With advances in automation technology, the introduction of robots into the timber assembly process has made modular timber construction more efficient. This paper first analyzes the existing advanced technologies in the field of robotics combined with gantry systems and BIM systems to compare and analyze the feasibility of using robotic systems combined with BIM in the timber frame erection process. A robotic system is proposed for use in the erection of timber load-bearing structural frames, which combines BIM and gantry systems and can greatly increase the working range of robotic arms for more complex jobs, reduce the need for specialized workers, and support individual production. At the end of this paper, concludes with a discussion of the application of robotics to construction sites, connecting factories and sites into a complete production line, innovating in synergy with architectural design, and providing an outlook on the future direction of development.

Keywords: Timber Structure, Gantry System, BIM, Human-Robot Collaboration, Assembly Robot.

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Image from Freepik

1. Introduction

1.1 Background

For decades, construction has lagged behind other industries in terms of productivity. One of the least digitalized industries in the world, the construction sector employs about 7% of the world's working-age population. Over the past 20 years, labor productivity in the sector has increased at an average rate of just 1% per year, compared to 2.8% growth in the global economy and 3.6% growth in manufacturing[1]. The productivity issue facing the construction sector is insurmountable. We need ways to reinvent construction and increase productivity. Modular construction offers an opportunity to transform the industry: moving many aspects of construction activity from traditional building sites to factories with off-site, manufacturing-style production.
The lack of adequate and affordable housing is a global issue that affects both growing and developed nations, including Australia [1]. Conventional building is a significant obstacle to solving this problem because of their cost implications. One of the most important strategies for lowering the cost of providing affordable housing is prefabrication or industrialization of buildings. To date, modular prefabricated houses have only gained a sustainable foothold in a few places. In mature markets like Japan and Austria, for example, the share of the wood-frame modular building maintains a certain level in the overall construction output. However, in many countries, including Australia, it is still in its infancy. Many factors determine the extent to which modular construction is widely used in the market, but the two biggest determinants are the real estate demand for skilled construction labor and availability (relative cost).

1.2 Motivation

To protect the environment, providing green building solutions and timber can be a key part of the solution. Timber modular building also has many problems. There are so many factors involved in prefabrication and so many variables

To increase the construction industry's productivity, help solve the housing crisis in many markets, and significantly reshape the way people build today. Creating more efficient construction methods is better to provide adequate and affordable housing for residents in dense urban centers or remote areas now. There is a shortage of labor and skilled tradespeople, and there are no skilled craftsmen on construction sites to assemble. By using digital means to focus on the problem of putting together wooden modular parts, we can reduce labor costs and improve manufacturing accuracy and productivity.

1.3 Goals

By comparing robots' systems and BIM existing solutions which is the use of digital technology to generate building engineering information models for the management of the life cycle of the built environment, this thesis tries to explore the potential of prefabricated timber modularity on site. Combining BIM and robotic structures, the solution is primarily used in the process of assembling and joining modular timber load-bearing structures. The objective of this research focuses on improving the digitization of this step, increasing accuracy and productivity in timber joining and increasing efficiency by reducing costs in future mass production.

2. Research methods

In order to explore how the robot system can be better integrated with the BIM system and applied to the assembly of wooden bars, the following research methods is used in this paper. Firstly, the literature on the integration of BIM and robotic systems in timber construction is first compared and discussed, reviewing state-of-the-art technologies and market solutions. Then the feasibility of existing technologies for digital timber structure construction is explored, a concept is proposed to combine and improve the existing solutions. Finally, the potential and challenges of the solution are discussed.

3. State of the Art

3.1 Description of timber modular construction

Modular construction refers to the assembly of standardized size building elements, where modules can be wall panels, beams, slabs, or units of "prefabricated prefinished volumetric construction (PPVC)", as shown in Fig. 1. This paper focuses on transportable modules that are fully assembled in the factory.

The frame of the modules can be made of metal, wood, concrete, or a mixture of materials, and the modular building envelope is mostly built using wood building materials due to the light weight and low energy consumption of wood [3]. Aye *et al.* [4] studied prefabricated case buildings and showed that the total mass of a modular timber structure ($0.25t/m^2$) is four times smaller than that of a modular concrete structure ($1t/m^2$), which is important if we want modular buildings to have a movable or repositionable function.

The process of building modular timber structures is divided into two main categories. The first type is to divide the prefabricated beams, panels, and other components into different units at the factory, transport them to the construction site using ships, trucks, or trains, assemble the modules at the construction site, and put the modular units together. The second type is to first assemble a whole prefabricated modular unit in the factory before transporting the whole unit to the construction site for direct wood block splicing. This paper discusses the second type of complete assembly of the wooden structure at the factory, where the production activities in the factory are not affected by bad weather and such a construction method reduces nuisance and construction interruptions at the construction site [5].

3.2 Existing BIM solution

Building Information Modelling (BIM) is an important aspect of the modular construction process and is used to create accurate virtual prototypes of prefabricated building components prior to factory fabrication. BIM contains data parameters, geometric information, spatial relationships and project information, etc. Through such virtual prototypes, it is possible to determine accurate measurements of reference frames not only in modular fabrication but also in mechanically automated construction. The position of objects can then be accurately connected to components and assemblies, avoiding the problem of reworking incorrect prefabricated components and effectively saving time and costs.

There are now many companies on the market offering modular construction solutions, such as Advenser, which provides modular solutions traditionally coordinated through BIM. With the information provided by BIM in the documentation, those involved in the different construction aspects can all collaborate more effectively during the design, construction, and operational phases of a project. [6] During the design process, Advenser creates individual design development models and CD sets of prefabricated units. Later, they are joined to

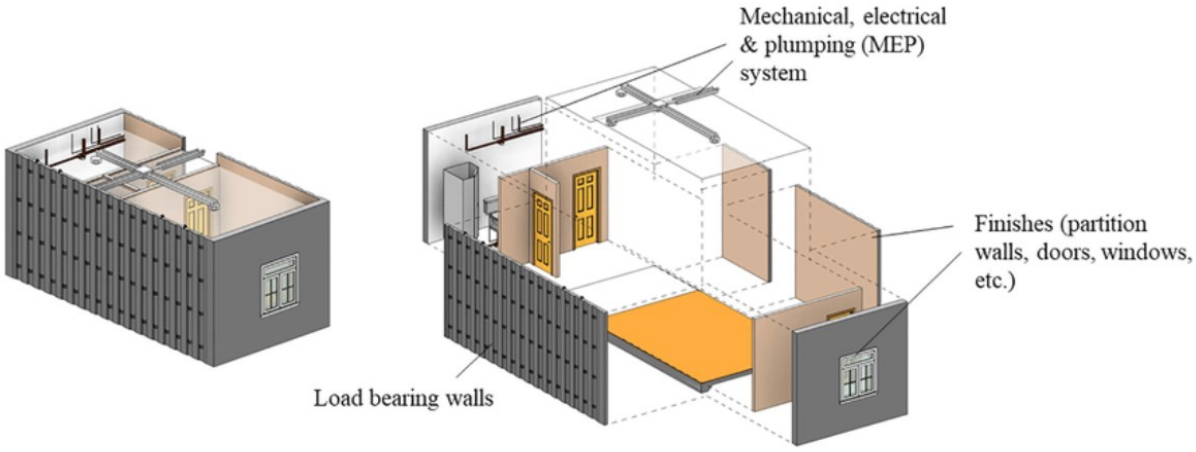

Fig. 1. Load bearing modular system for prefabricated prefinished volumetric construction [2]

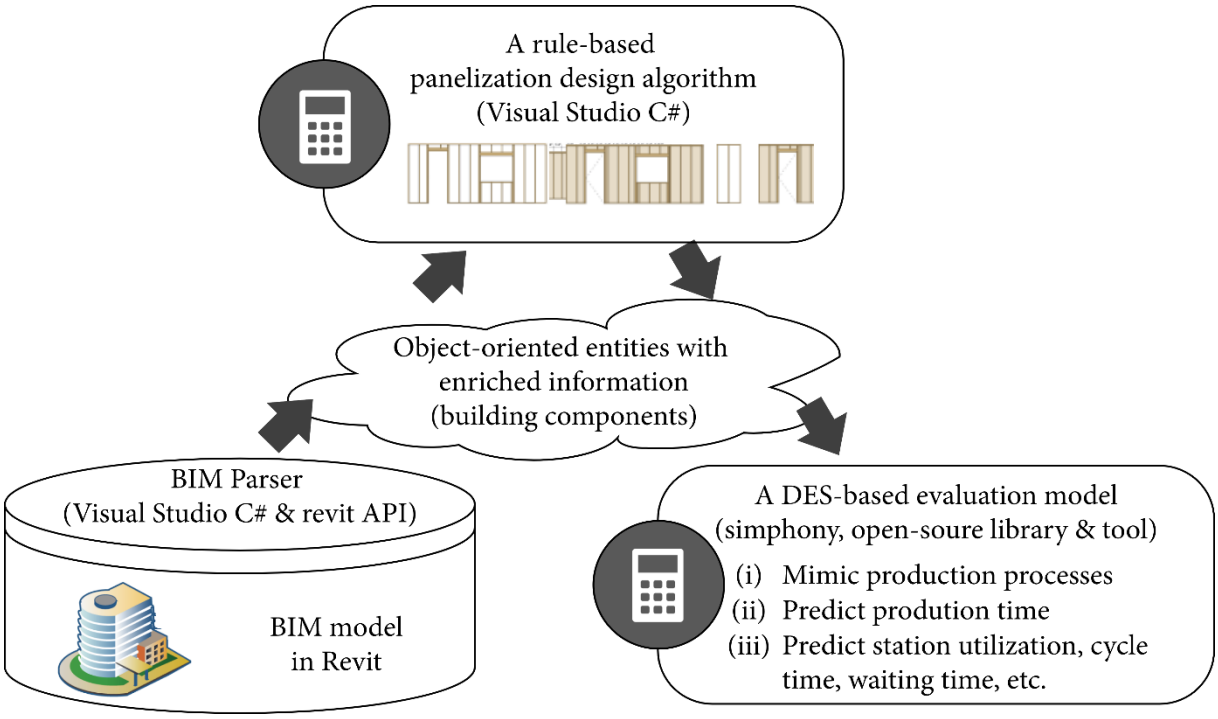

Fig. 2. A generative framework built on BIM [8]

produce an integrated BIM model of the entire project (LOD 300 Coordination Model). After a disagreement has been resolved, shop drawings for each item are created for manufacturing. Material Take-off lists that were retrieved from the BIM model aid in the procurement process. With design development modeling, construction documentation, and energy analysis modeling, they assist structural consultants and engineers. Finally, Advenser provides detailed documentation for the different participating manufacturers as well as installation drawings for the modular prefabricated elements.

There are different system platforms in the market for BIM applications in modular buildings. For example, the BIM platform Navisworks TM can be used for the coordination of MEP. [7] The BIM system created through Rogers Builders BIM completely overlaps the building model, the structure, and the MEP system, which provides the benefit of design coordination and error avoidance. In addition, Nampa, a construction company in Idaho, uses robotic arms and the Autovol process, known as 'automated volumetric modular construction, in conjunction with the MEP system to assemble prefabricated components of modular buildings on the production floor. The company is now working on affordable housing projects to make affordable housing a reality.

Through research, it is found that BIM on the market is mainly used for collaborative work in modular buildings, and there are few cases of direct integration with robotic arms. There are more advanced BIM-based generative frameworks (Fig. 2) in some research literature [8], which are more intelligent automated production systems. Through a rule-based design algorithm, the BIM model in Revit from the BIM parser is analyzed for specific data to simulate the production process based on the model and to make some predictions for automated production. Another system is a BIM-based automated construction system [9], the BIMAC system, which connects the BIM system to a robotic arm and converts the BIM model into a specific computer CNC code, which is then sent to the robot system for reading.

3.3 Existing automation solution

The frame of the wood structure module is shown in Fig. 3, made of timber I-beams attached to a timber column-beam structure,

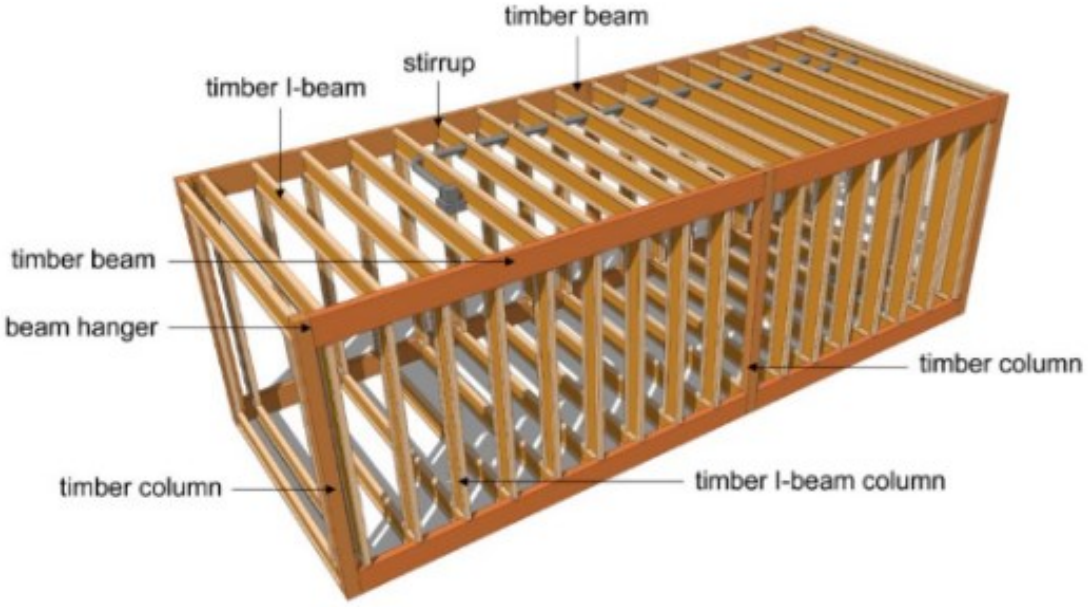

Fig. 3. Load-bearing structure of timber modules [15]

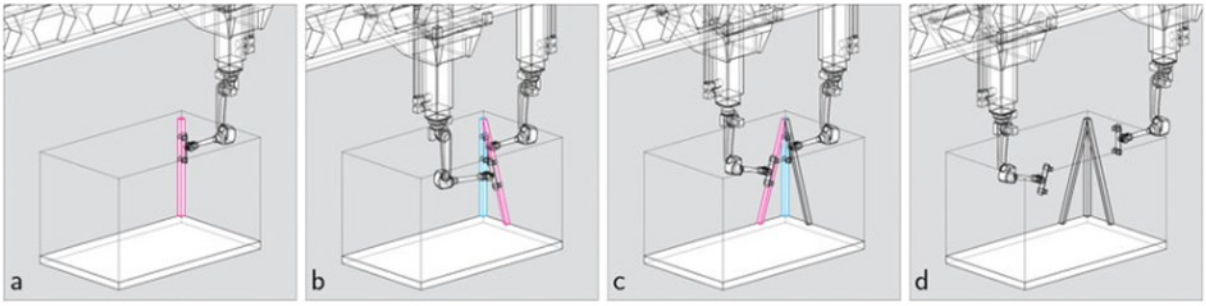

Fig. 4. Cooperative robotic spatial assembly process of the Corner technique [16]

and this paper focuses on the automation process during the assembly of the wood beam frame. Robotic assembly for wood structures has been extensively researched and applied internationally, and the invention of digital joinery machines and CNC milling machines in the 1980s [10] brought digital production to the wood construction industry, however, in practice, the assembly of components is still dominated by manual assembly by robot-assisted workers. Saidi *et al.* [11] attempted to use specific machines to perform construction specialized tasks in production. The Baxter robot proposed by Yanjiang *et al.* [12] can achieve the drilling assembly task through a step-by-step grasping strategy and a vision-guided approach. The study by Willmann *et al.* [13] proposed robotic timber construction (RTC), a new approach to non-standard timber assembly, which combines a robotic assembly system with the digital design of non-standard timber structures to achieve a spatial construction approach with layer-by-layer stacking from bottom to top. The 2016 sequential roofing project [14] developed by ETH Zurich and robotically built by ERNE AG Holzbau transforms the previous layer-based assembly approach like additive manufacturing into a spatial assembly approach that extends the digital fabrication of timber components from laboratory to architectural scale.

There are many different types of robots currently used in the assembly of wood structures, ranging from robotic arm systems that require worker assistance to robotic systems that combine vision tracking with BIM systems. The focus of this paper is on the assembly of wood frames, and a comparative analysis of three different types of robotic systems is presented below.

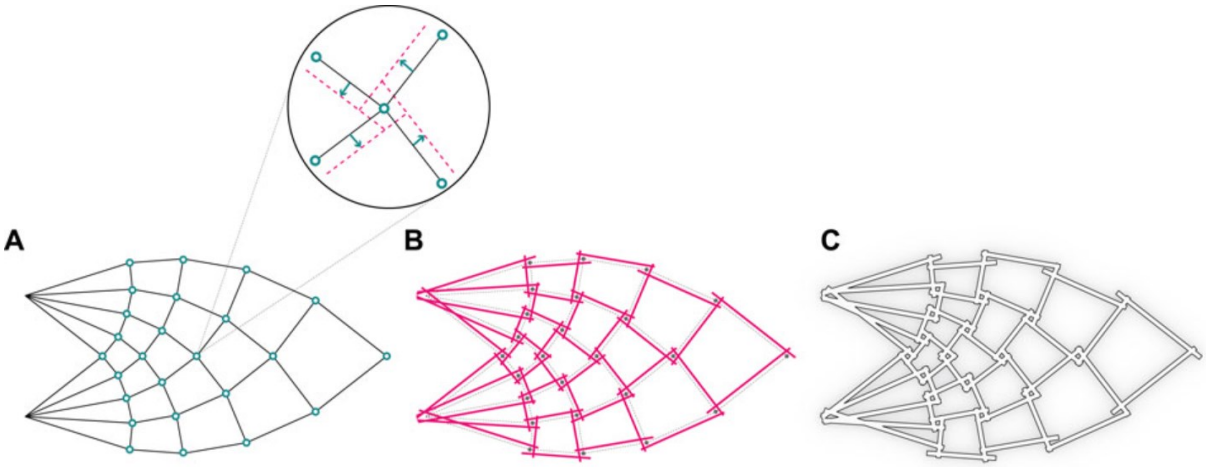

Fig.5. reciprocal connections based on interlocking cross-lap joints [17]

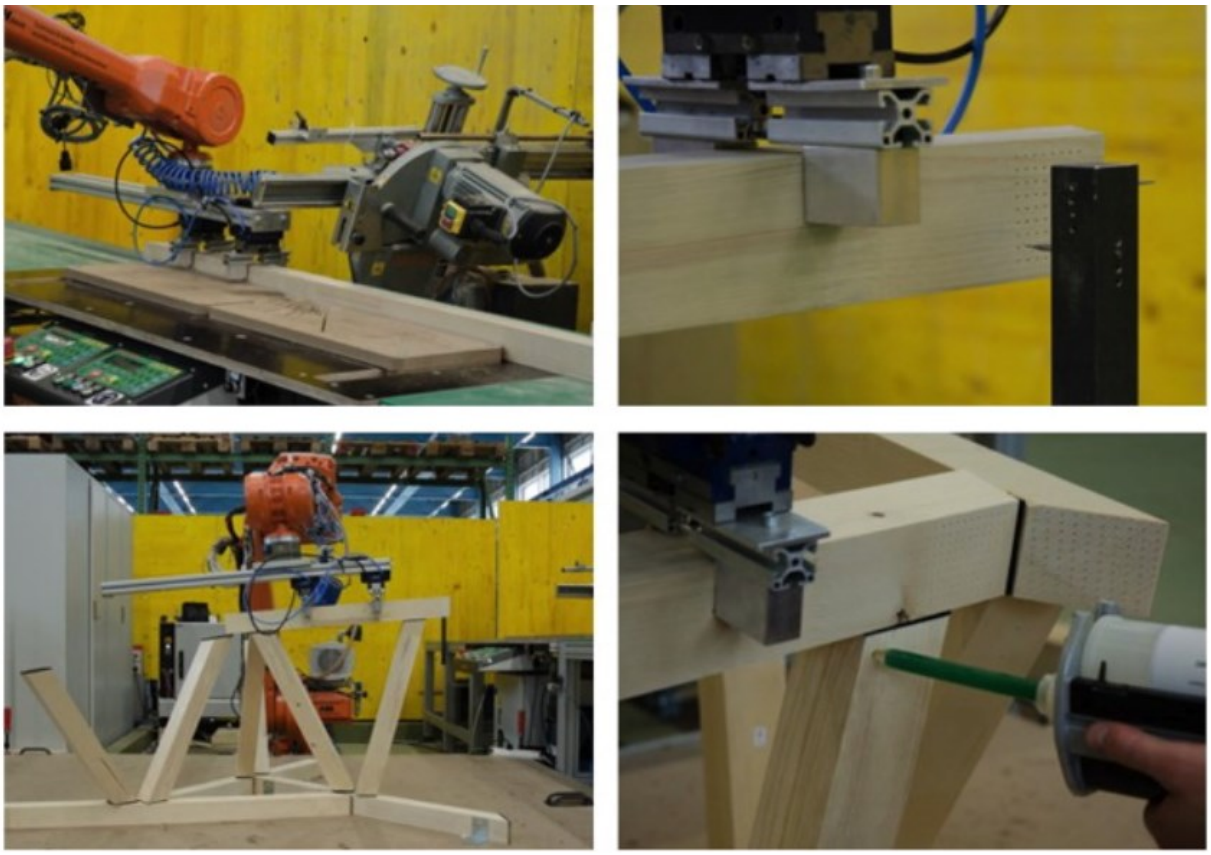

Fig. 6. Non-standard robotic fabrication system, featuring automated gripping and cutting, as well as robotic surface manipulation and spatial positioning [13]

Researchers at ETH Zurich have designed a computational method for collaborative robotic assembly of non-standard wood frame buildings [16], which advances the use of modular wood frame structures in construction sites through experiments with corner technology in the laboratory. Two robotic arms equipped with pneumatic clamps were installed in the gantry system, and one robotic arm grasped a stud and fixed it to the specified position (Fig. 4a), and the worker manually attached the stud to the base timber frame. The second robotic arm grabs the second stud and places it in the proper position, and manually connects it to the wooden frame base and the first stud using screws, etc. (Fig. 4b), and the second robotic arm releases the second stud and grabs the third stud and places it in the designated position, and the human connects the third

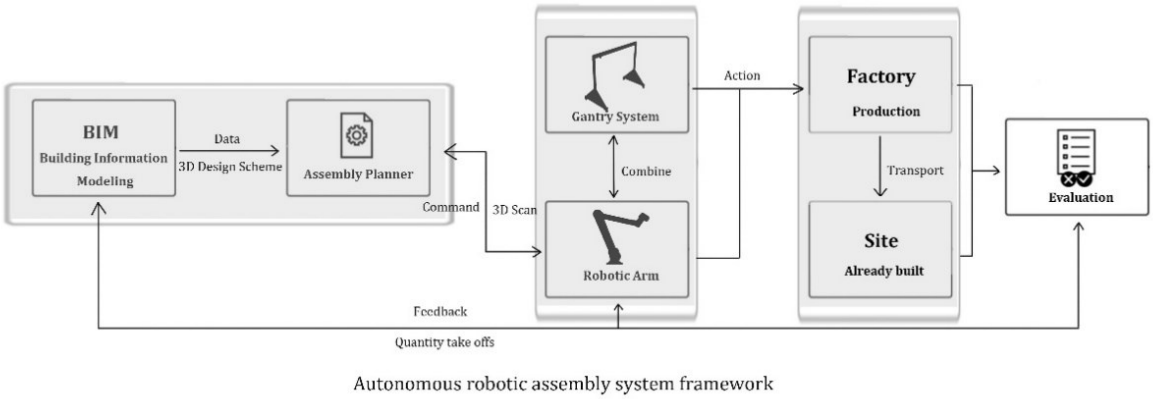

Fig. 7. Workflow of wood structure robot system combined with BIM

stud to the first stud and the base (Fig. 4c). At this point the structure at the corner is stable and the two robotic arms can release the structure (Fig. 4d).

Also combining digitization with the robot system, humans create CAD models in advance, calculate the path that the robot arm needs to grasp and place the wooden beams, transfer the data to the robot system and perform the actual operation. However, this system is not well suited for construction sites and requires specialized technicians to operate the system; the robot is completely passive and does not actually reduce labor. The use of a robot arm with a single function in the construction process is not a good solution to the problem of automation in production, so we need a robot system with a feedback function and a complete set of timber frame assembly tasks.

The second method currently used in timber frame assembly is to use a frame structure that interlocks wooden elements by using a complex lap joint connection [17] as shown in Fig. 5, eliminating the need for steel strips to hold the timber in place, which is precisely calculated and cut using a robotic system, reduces the manual requirements for workers.

However, in practical applications we usually insert steel bars into the wooden frame to enhance the stability of the modular frame. In an RTC prototype built at ETH Zurich (Fig. 6), the robot clamps a single timber member, performs cutting and drilling operations at the end, and then moves it to its final position.

4. Results

4.1 Concept overall

By comparing different robotic systems for wood structures with BIM models, this paper designs a robotic system for modular timber frame assembly in combination with a BIM system. The timber structure of the module consists of rectangular universal wood beams that can be modeled using the BIM system, and the existing proven timber frame structure is modified and directly input to the robotic system (Fig. 7). The robotic system performs cutting, drilling, moving and assembling operations on the generic timber beams to improve the accuracy of handling the beams during the actual assembly process. The design allows for the erection of complex individualized structures within a single cell, ensuring the possibility of application to industrial construction and individualized production.

Fig. 7. Workflow of wood structure robot system combined with BIM

4.2 Robot system

The robotic system consists of two six-axis robotic arms connected to a gantry system with a three-axis base that allows the arms to move and cut at all angles within the working range. The entire robotic system has a working range the size of one modular unit in a modular building. Fig. 8 shows the 3D model of the robotic arm connected to the gantry system, which is made by Rhino 7.

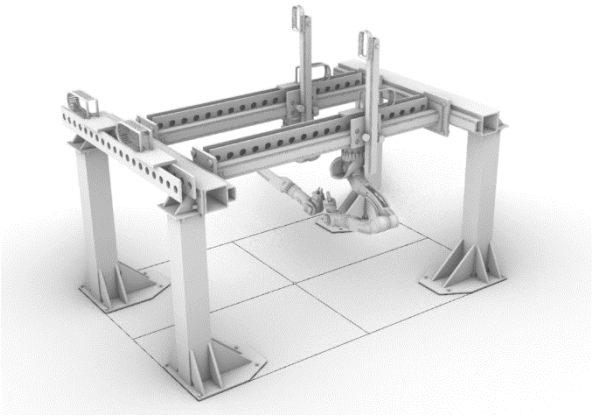

Fig. 8. Gantry robot system

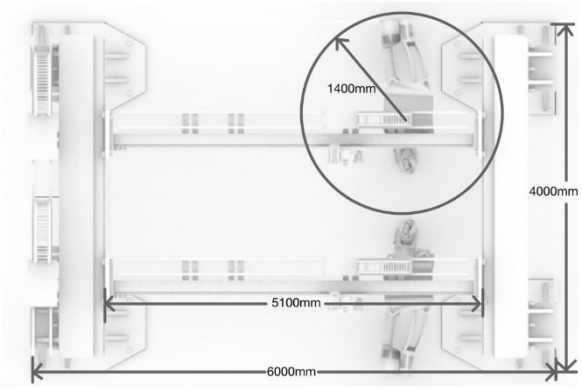

Fig. 9. Workspace of gantry robot system

The whole gantry system is fixed to the ground with a shelf height of about 3200 mm and a telescopic pole height of 2000 mm. The working range is shown in Figure 9, with a length of 6000 mm and a width of 4000 mm, the maximum reachable length of the robot arm is 1400mm. This gantry robot system can build a maximum of 24 m^3 of prefabricated timber building block.

Gantry system can move in both x and y directions. The robot arm is connected to the gantry system using a telescopic rod that allows the robots to move in the vertical direction to achieve the goal of enabling the arm to reach any corner of the work area (Fig. 10).

In order to achieve the whole process of building timber structures that using the robot system, we required the robotic arms to be able to cut, drill, and move alone, so we used to install a tool changer at the end of each robot arm with pneumatic clamps or drillers and screwdrivers, respectively (Fig. 11). Usually, one robot arm is equipped with pneumatic clamps and the other with a

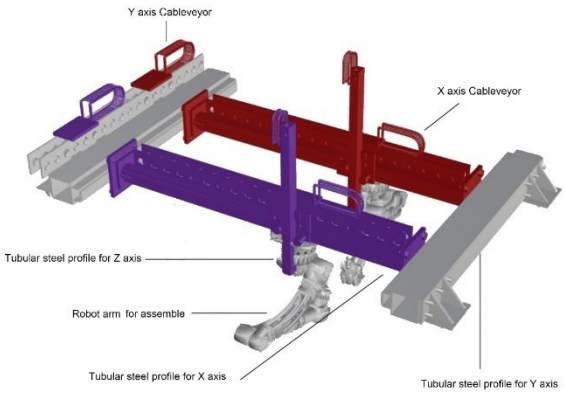

Fig. 10. Gantry robot system top part module

screwdriver and a driller. During the production process, the two robotic arms cooperate with each other to complete the assembly of wooden strips. The tool changer at the end of the robot arm allows the arm to change automatically or a person to change manually to a different tool.

4.3 BIM system

Accuracy in the manufacturing process is improved by using the parametric information provided by the BIM system to interact with the Gantry Robot system. In this project BIM is the key technology platform for integrating the robot arm working system and prefabricated part models. Similar to other automated processes, the automated installation of components for the robot arm starts with the 3D modelling of the structure to facilitate the design of the timber structure assembly task using the BIM platform modelling software Revit, which is the data source for the timber prefabricated components for the robot arm. In order to import the BIM data information into the robotic platform in the form of data, the IFC framework was used to address the issue of data interoperability. the BIM models created by Revit can be converted into the IFC data format, a data model developed by buildingSMART. By parsing the IFC file and extracting the geometric model, position information and other parameters, the scene model and the robot xyz coordinate system are mapped to obtain the coordinates of the components of the target model that can be recognised by the robot system, and then converted into path commands for robot

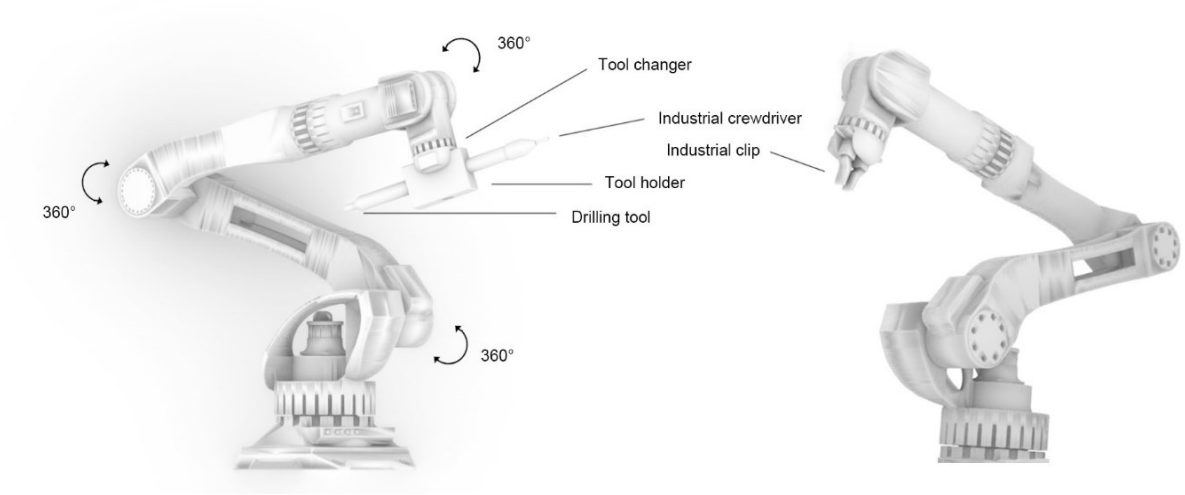

Fig. 11. Schematic diagram of the tool changer at the end of the robot arm

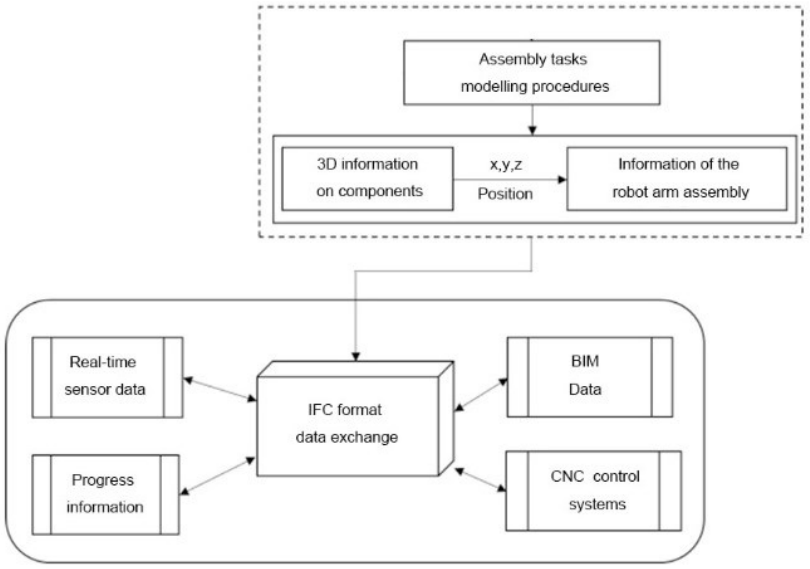

Fig. 12. Bidirectional connectivity for BIM and robotic systems

operations through the programming interface (Fig. 12). The dynamic detection can be compared with the information in the model data in BIM and can be stopped in case of discrepancies.

4.4 Potential on construction assembly product line

In the process of wooden modular building construction, after the wooden structure is erected, wall panels, doors and windows and other components still need to be installed. After assembling the whole modular unit, it is necessary to transport the modular unit to the construction site for modular assembly using ships, trains and other means of transportation.

The robotic system designed in this paper can be extended and integrated into the whole production line of wooden modular construction, and the whole automated production line can be set up in the factory, the subsequent installation of wall panels, windows and doors, and pipes can also be done with this robotic system. Since wood is easy to cut, we can cut the wood into different shaped pieces according to the architectural drawings of the desired wooden building structure. Due to this property of wood, we can customize a wide range of wooden building units with different structures or appearances according to the needs of our customers. The entire construction process of

	KUKA KR70 LP	RENE gantry robot	Corner technique robot	Concept in this paper
Axis motion	1-axis	7-axis	6-axis	6-axis
Horizontal direction	Yes	Yes	Yes	Yes
Vertical direction	No	Yes	No	Yes
Workspace	Small	Large	Medium	Large
Number of robot arm	1	1	2	2
Tool changer	No	Yes	No	Yes
Assembly method	-	Pile up in layers	Space construction	Space construction
BIM	No	Yes	No	Yes

Table 1. Comparison of robot system features

the wooden units will be done in the factory, divided into three major parts: cutting, assembling and transporting, and the entire wooden building units will be transported on a giant conveyor belt. The multifunctional robotic arm envisaged in this paper is placed in different working areas and different tools are installed for the arm according to the work to be done. Moving the entire wooden construction unit to the factory can effectively avoid the impact of bad weather on the construction site, which can affect the construction schedule.

Putting the whole timber modular building construction process into one BIM system and unifying data management makes it easy for managers, factory workers and on-site construction workers to interface and avoid waste of resources due to non-interoperability of data.

4.5 Discussion

The system can be moved in the horizontal and vertical planes by means of a manipulator mounted on the gantry system. Similar in structure to the KR70 LP laser cutting gantry from KUKA and used for the first time in the connection of wooden load-bearing structures. Compared to other gantry systems, such as the commercially available Robot Worx gantry robot system, the system developed in this thesis covers a much larger working area. In contrast to the 1-axis Gantry Robot and the 2-axis Gantry Robot, a 3-axis surface gantry has a more flexible positioning system and a larger movement area. This gantry system accompanies the movement of the robot arm in the process of joining wooden load-bearing structures. The main material is Tubular Aluminum with rack and pinion to increase the precision of the system, which is an effective combination of robotics and gantry systems. Table 1 compares several different robotic systems for wood construction with the robotic system proposed in this paper.

In the combination of robot system and BIM system, most of the current solutions on the market combine individual robotic arm with BIM, a robotic arm can only complete a single task, and the working range of a single robotic arm is small. The new wood structure assembly robot system discussed in this paper connects the BIM system with the whole gantry system equipped with a robotic arm, which has a larger working range and can move through the whole wood module, while simplifying the operation process for the user and controlling the whole wood module building production process with only one interface.

5. Conclusion

5.1 Summary

The study found that prefabricated timber modularity has great potential on site and that digital construction is an effective means of achieving higher productivity and reducing construction costs. Particularly regarding the

joining of timber structures, flexible elements in large spaces can be completed by means of robotic systems, which have advantages in terms of speed and durability.

After analyzing the existing solutions, a 3-axis Gantry Robot was designed, which is derived from the principle of the telescopic frame and effectively extends the working area of the robot arm by means of a gantry system. This Gantry Robot has been designed specifically for light load structures due to its use in the assembly process of timber module load-bearing structures, achieving greater speed and precision in its operation. If the Gantry Robot is widely used in future modular construction, the process of modular construction will be effectively accelerated, resulting in more sustainable and affordable building projects.

5.2 Outlook

Automating and digitally innovating and transforming this process can significantly drive the pace of timber construction. In the future the digital process of timber construction will also be increasingly adapted to the various environments on site, with fully automated processes from factory to site. In the future, the need for specialized workers in the construction of modular wood buildings will be greatly reduced, requiring only software to operate the robot as well as the gantry system. And with the addition of the robotic system, the accuracy of the cutting of the wood is improved, reducing the waste caused by errors that cannot be assembled. With the addition and development of BIM, connecting factory and site data in real time to improve information transparency. Meanwhile, timber construction can be transformed from modular to individual production, allowing customers to design and model quickly according to their needs, which is a great innovation for the future construction market.

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MARZIYEH SHAHSAVARAN, METE OZCAN

Surveying Techniques for Construction Robotics

ABSTRACT

Construction surveying or building surveying is to stake out reference points and markers that will guide the construction of new structures such as roads or buildings. These markers are usually staked out according to a suitable coordinate system selected for the project.
Construction surveying is mostly rely on conventional methods which includes very high human skill and experience that can be time consuming, costly and even unsafe for some conditions but there are very promising robotic and automation technologies exist in the market. We research and present these technologies in order to have better understanding and to help them to be used more by construction industry.

For this purpose we give some information about the state of art of each different technologies, make a detailed and objective comparison finally we make assessments and suggestions for these robotic surveying methods.

Keywords: Construction, Surveying, Total Station, Drone, Lidar, Photometry, Global Positioning System, Photogrammetry

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1. Introduction

1.1 Motivation

According to McKinsey research report in February 2017 construction industry has an intractable productivity problem. While sectors such as retail and manufacturing have reinvented themselves, construction seems stuck in a time warp. Global labor-productivity growth in construction has averaged only 1 percent a year over the past two decades, compared with growth of 2.8 percent for the total world economy and 3.6 percent in manufacturing. The report proposed seven ways to improve productivity and one of the ways is “Infuse digital technology, new materials, and advanced automation” and the other is “Improve on-site execution”. Therefore, if we would implement more digital technology on-site applications, we could improve the productivity as well as the quality of the work.

Construction site works begin with surveying. Construction site surveying is the science and art of making all essential measurements to determine the relative position of points or physical and cultural details above, on, or beneath the surface of the Earth, and to depict them in a usable form, or to establish the position of points or details. A good quality surveying leads the following works to be less prone to errors. On the pre-construction stage, we require land surveying of big areas, it is usually unsafe for people to walk around also it takes too much time to cover all of the land with all the detailed surveying data we require. On the construction stage of big and busy projects, project managers require regular surveying data in order to monitor and overview of the site for the right process planing and scheduling. For this time consuming, repetitive, costly work we need high automation and robotic technologies.

Although it is less frequently mentioned, land surveying is also becoming increasingly automated with the use of powerful robots. More than two decades ago, the first surveying robots were developed. They were robots outfitted with total stations and other surveying equipment that let them to find the measurements of a region with higher accuracy than a human surveyor. While many of today's robots perform the same functions, surveyors have access to more sophisticated ones. Many professional surveying firms use airborne drones to acquire a comprehensive image of a location.

Additionally, robots enable us to do 3D boundary analysis while receiving a comprehensive picture of the location we're surveying. Drones can only navigate outside structures, which may be a critical need for some surveying projects, whereas robotic total stations are available for inside surveying.

This combination of human connection and robot automation is valuable for any surveyor. The automation and intelligence of customized robotics may considerably help construction sites. The technology enables faster and more accurate surveying, as well as the management of repetitive operations at the same quality level. The ongoing usage of robotics and drones, in conjunction with the 3D knowledge afforded by BIM, will most certainly speed the construction of as-built models and increase cooperation, accuracy, and the bottom line for all key stakeholders.

1.2 Research question

In this paper we are looking for the answers of the questions like “Are robot surveying worth to use instead of conventional surveying”, “Which method is the best for which kind of surveying requirement?”, “What are the advantages and disadvantages of each technique?” and finally “What would be the evaluation of automated/robotic surveying?”

Moreover, we aim to examine different ways of robot surveying, compare their work in the surveying process, and evaluate their benefits and drawbacks.

1.3 Goal of research

However, the construction surveying process has developed significantly in recent years and now there are some robotic tools like quad-copter drones which are a reliable tool for performing exterior surveying and total stations that are more practical for surveying outsides, but they still need human interaction to control them and learn how to walk the sites before going off on their own.

The aim of this research work is to review the different specializations of surveying that derived from the conventional definition, represent the relationship between different brains of surveying, and to assess number of modern survey technologies available today. We consider the standard DIN 18710 “Engineering Surveying” to evaluate the fitness of robotic surveying technologies. DIN 18170-1 defines the general requirements of surveying including the accuracy requirement and role of surveyor. DIN 18710-2 contains the requirements of site surveying.

In the final part of the research, we will offer solutions for improvement and an easier operating robotics surveying process.

2. Research Methods

In this paper, the methodology carried out to mainly based on;

- Academic papers and articles. Especially for comparison section we researched for academic articles for the sake of objectivity and clear data. Because commercial sources might not be as objective as we wish.
- Articles written by surveying companies and surveying experts
- Video conferences and online training videos of surveying experts

These sources in this research to have a better understand the state of art and process flows.

- Technical data-sheets of robotic surveying systems manufacturer companies such as total stations, LIDAR, drones; This data sheets has helped us to understand the detailed features of the robotic systems and surveying tools.
- DigitalBau exhibition helped us to meet with robotic surveying companies make face to face interviews with them. In order to plan the interviews first we created a list of surveying companies that took part in the exhibition. Then we created a list of questions that we will ask. The questions were about the cost, efficiency and key features of robotic surveying solutions. After visiting the companies, these interviews are documented by taking notes and photos.

2.1 Criteria for evaluation

Each robotic surveying method has different characteristic comes from the characteristics of the sensor technology, data collection methods, and data process methods. Therefore, each of them has some certain advantages and disadvantages. First of all, it is very important to evaluate them objectively. Thus, we try to ensure to have the same site conditions, we compare and evaluate in terms of comparable features which refers the same feature and has the same units such as time, cost, accuracy, level of detail. We use compassion tables in order to have a clear overview related criteria for evaluation.

3. Results

This section includes the results of this research project.

3.1 History and Development of Surveying

Purposes of surveying:

The aim of surveying is to prepare a map to show the relative positions of the objects on the surface of the earth.

Some of the purposes of surveying is:

-To collect field data.

-To prepare plan or map of the area surveyed.

-To analyze and calculate the field parameters for setting out operation of actual engineering works.

-To set out the field parameters at the site for further engineering works. [1]

History and development of robotic surveying:

The investigation, construction and documentation of buildings and their constructive details is intrinsically tied to the development of geodetic and photogrammetric surveying methods. From ancient times to the 18th century elementary methods based on mechanical distance measurement and simple angle measurement have been used for building construction surveys. 150 years ago the German civil engineer Albrecht Meydenbauer developed photogrammetric measurement techniques

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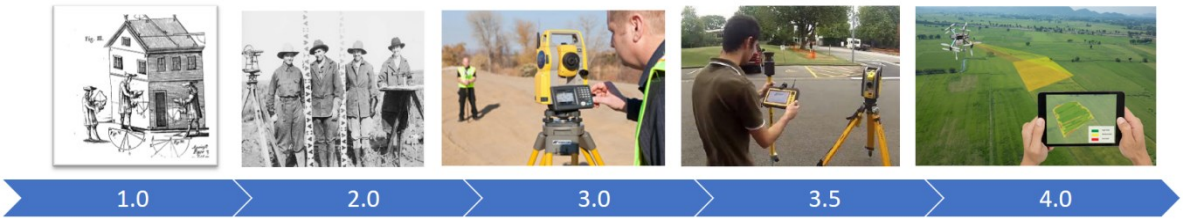

Fig. 1. Shows an evolution of surveying over the years [18]

as an alternative method to the traditional manual measurement. The ideas and methods Meydenbauer developed are effective to this day. More than 100 years ago, photogrammetry asserted oneself as the most effective method for building measurement. In the second half of the 20th century, electronic surveying instruments such as electro-optical tacheometers, electronic level instruments, digital cameras, global positioning systems and laser scanning revolutionized surveying technologies.

Such as the classification of industrial revolutions from 1.0 to 4.0 we can make an analogy to present digital and robotic evaluations of surveying history.

1.0 Mechanical tools: It was a period of time that we only had surveying tools such as measure tapes and angle meter.

2.0 Optical angle measurement: It was the revolution of theodolites which is a surveying instrument with a rotating telescope for measuring horizontal and vertical angles to make precise measurements of areas and triangulate the position of objects in a specific area.

3.0 Electronic distance measurement: The revolution of electronic tools such as laser meters and the most effective one is total stations which is actually a theodolite that uses laser beam and electronics to calculate angles and distances and contains an on-board computer to collect data and perform triangulation calculations.

3.5 Robotic electronic distance measurement: This revolution from manual total station to robotic total stations which can locate and follow the target itself.

4.0. Robotic surveying: This is the recent revolution of surveying and still has been developing. This covers a robot which can navigate itself (on air or on ground) and the robot carries a surveying tool (such as LIDAR). Therefore the site operation process of surveying which is usually time consuming, not cost efficient and unsafe for human operations can be implemented by robot.

3.2 State of Art

In this section first we introduce robotic surveying processes and then each technology with its definition, characteristic and some process workflows.

Processing workflow for robotic surveying

Robotics is revolutionizing countless industries, and land surveying is no exception. A growing number of robots are being

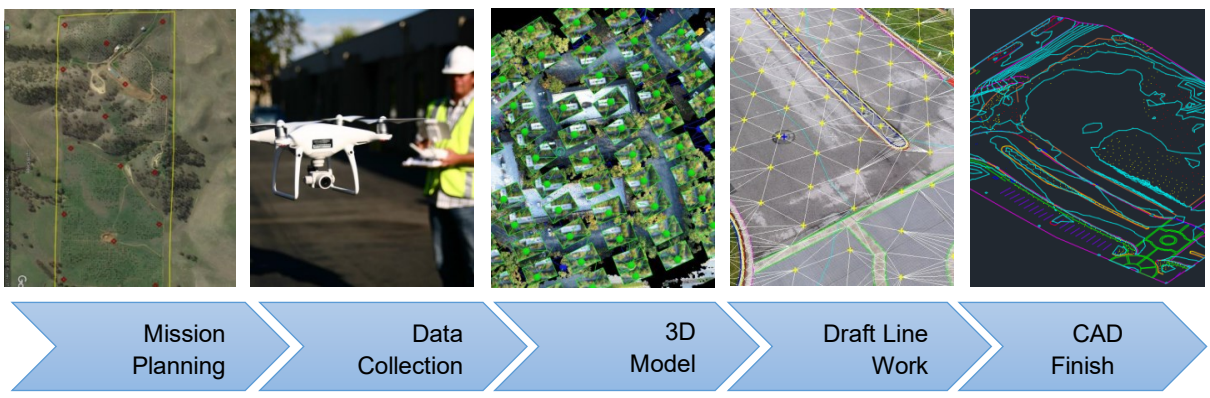

Fig. 2 shows the Processing Workflow for robotic land surveying [19]

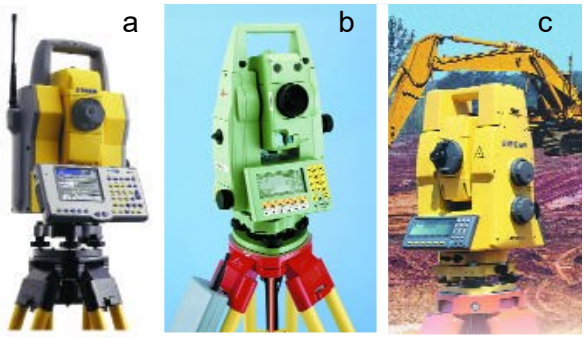

Fig. 3. Robotic total stations are manufactured by three companies: (3a) Leica Geosystems, (3b) Trimble, (3c) Topcon. [20]

implemented due to their high return on investment, efficiency and versatility. Surveying robots offer a slew of incredible benefits for site planning, mapping and risk assessment, among other projects. Nowadays, robotic total stations and drones are most popular in surveying process. Although the process pictures that refers to steps of workflow is from land surveying, engineering surveying follows a similar process workflow if LIDAR or photogrammetry sensors are used. Only if total stations are instead of having the steps "3D model processing" and "draft line work" there would be "layout work" before the final "CAD finish"

Robotic Total stations

A Robotic Total Station (RTS) is the advancement to the conventional Total Station, which requires only a single person to operate and determine the location of the points surveyed. With the Robotic Total Station, the operator holds the reflector and controls the total station from the observed point with the help of a Remote Positioning Unit. Depending whether the target is static or in dynamic motion, RTS can be categorized as a passive RTS or active RTS. [2]

By the 1970s, however, the electronic theodolite began to replace the transit since it could measure angles more accurately on both the horizontal and vertical axes. In the early 1980s, "total stations," which measure distances very accurately by using electronic distance meters (EDMs), became the instrument of choice. Then in late 1990, Geodimeter, Dandryd Sweden introduced the first "robotic total station," adding automatic tracking and radio communication to a radio and data collector at the "target" or pole. Thus, for the first time, no person was required at the instrument—only at the target, reducing the size of a survey crew. Today three companies manufacture robotic total stations, Trimble,

Every system uses a target, which has a prism to reflect light back to the instrument for measurement, and an electronic data collector, which communicates with the instrument through radio communication also known as telemetry.

By using servomotors, prisms, and infrared technology, robotic total stations search for, and then lock onto, the target, automatically following it as the layout person moves it around a job-site. At the same time, the data collector built into the target is being updated with information radioed from the instrument.

All manufacturers provide computer software to download and upload coordinate information. This information can come from computer aided drafting (CAD) files downloaded from office computers, PCMCIA

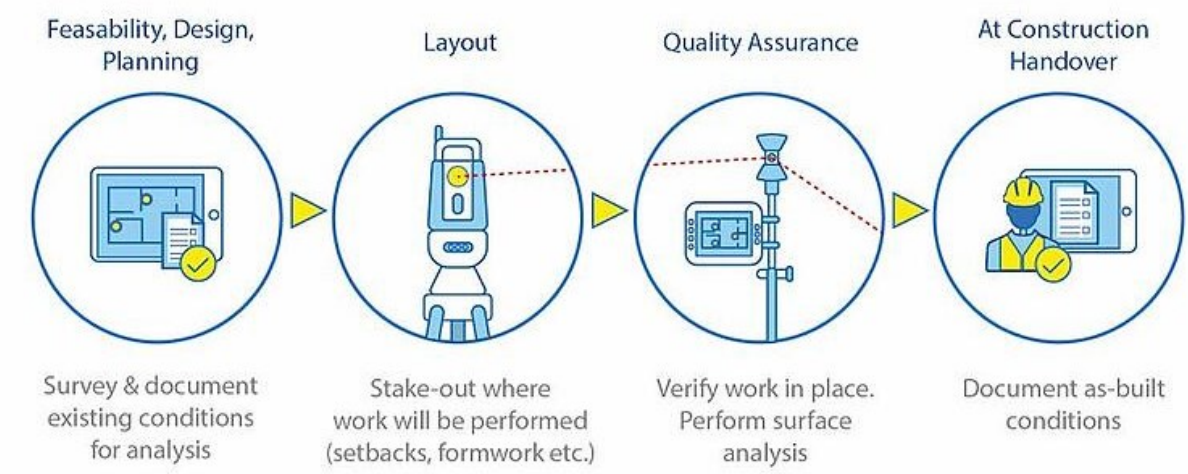

Fig. 4. shows use of RTS in construction [21]

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cards (flash cards similar to those used for digital cameras), ASCII files, or coordinate points manually entered into the instrument.

Working with RTS on a Job-site:

Robotic total stations offer the maximum flexibility on a job-site. While increasing productivity and accuracy, they reduce labor cost and eliminate error." The instrument can be set up in out-of-the-way places, locating itself by calculating its own coordinates and orientation. You can also place it directly over a control point, the required position for both transits and theodolites. The flexibility of being able to locate the station anywhere on or near the site greatly increases efficiency and accuracy, and reduces errors.

When a robotic total station is turned on, it automatically searches for the target and locks onto it. After the instrument acquires "lock" on the target, it tracks the target at speeds of up to 13 feet per second. And, while it tracks the target, it's also constantly updating the data collector. "Before you start layout work you must first shoot at least two orientation points or known control points in order for the instrument to locate its position on the job-site. These two control points are usually land survey points. Other control points can be established and used after a project is started. You are now ready to do layout work. The instrument directs you to each point for staking out. You are directed to each point by a constantly updated map on the data collector or by constantly updated commands, such as to / a way, left/right, and cut/fill." [4]. Applications of RTS in building construction:

Construction managers can use BIM and the Robotics Total Station technologies for accurate building practices. Site survey points generated in the Building Information Model can be uploaded to the RTS. Based on the points generated from the model, the field staff then can lay out all of the points. For instance, the accurate positioning of the hangers would ease the coordination of the MEP contractors. Furthermore, field staff can survey the components of the building with robotic total station to ensure that they are built according to the design and within acceptable tolerance range. This proactive quality control approach would prevent any subsequent conflicts.

Overall, robotic total station uses the information from BIM/CAD to survey both for construction and quality control purposes. Commercially construction contractors use Robotic Total Station for building layout works to check elevations, locate column and walls, layout anchor bolts and layout utilities for each floor of the building. Some of the commercial software packages offer support to transfer the building coordinates from the model to the total station. The automatic target locking feature of the RTS can be made use of to locate the points faster with spot on accuracy. Moreover, there will be certain points in the construction site that cannot be physically reached to hold the reflecting prism. In those cases reflectorless distance measuring option that comes with the Robotic Total Stations can be used to get the coordinates remotely.

Unmanned Air Vehicles (UAV) or Drones

Drone surveying may be defined as an aerial survey performed utilizing drones and unique cameras to prepare aerial data having downward-facing sensors. It is majorly utilized by surveyors and engineers in the field of construction for terrain assessments and mapping. Drone surveying can be done 90% quicker than we used to do normal surveying methods. It is used in making highly exact maps and survey points. The firms utilize drone mapping to recognize job-site errors, track work progress, predict schedule delays, etc.

During a drone survey, the ground is photographed many times from various angles, and each clicked image is tagged with some coordinates. The collected data are processed utilizing drone mapping software to make construction assets like 3D models, 2D maps, and digital elevation models, from which highly precise measurements and volumetric computation are performed. The drone collects highly accurate data fastly, without the requirement for surveying staff to walk over dangerous terrain or height to gather the data.

The uses of drone surveying are as follows:

Land management and development, Precise measurements, Stockpile volumetric measurements, Slope monitoring, Urban planning.

For very accurate drone surveying, it is essential to accurately point the position of a



Fig. 5. The two common types of drone mapping methods are: (5a) Photogrammetry (5b) LiDAR [22]

drone in flight. This can be performed either by utilizing Ground Control Points (GSPs), Real-Time Kinematic Survey (RTK), or Post Processing Kinematic (PPK) survey. GCPs are known points available in the ground whose coordinates are known. GCPs allow the drone to give precise data about its location and the distance it moved between the two locations.

As putting GCPs on the ground is time-consuming and needs labor, vehicles, equipment, and lots of paperwork, techniques like PPK and RTK have been introduced. RTK is a GPS correction technology in which the places data of the drone is given real-time corrections during the drone surveying and image clicking process. PPK surveying is a GPS correction technology that rectifies the location data of the drone only after the finishing survey data is gathered and kept. It is done post the site work.

Depending on the surveying software and data sensors, a drone can achieve several types of deliverables:

- 2D Orthomosaic Maps
- 3D Orthomosaic Maps
- 3D Models
- Thermal Maps
- LiDAR Point Cloud
- Multispectral Map

Surveying Techniques

LIDAR

LIDAR or 3D laser scanning was developed in the early 1960s for submarine detection from an aircraft, and early models were used successfully in the early 1970's. Nowadays, the environmental research is hard to imagine without the use of remote-sensing techniques like Light Detection and Ranging (LIDAR). High spatial and progressive resolution of the measurements, the possibility of observing the atmosphere at ambient conditions, and the potential of covering the height range from the ground to more than 100 km altitude make up the attractiveness of LIDAR instruments.

The working principle of Light Detection and Ranging system is really quite simple. A LIDAR sensor mounted on an aircraft or helicopter. It generates Laser pulse train, which sent to the surface/target to measure the time and it takes to return to its source. The actual calculation for measuring how far a returning light photon has traveled to and from an object is calculated by: **Distance = (Speed of Light x Time of Flight) / 2**

Accurate distances are then calculated to the points on the ground and elevations can be determined along with the ground surface buildings, roads, and vegetation can be recorded. These elevations are combined with digital aerial photography to produce a digital elevation model of the earth.

The laser instrument fires rapid pulses of laser light at a surface, some at up to 150,000 pulses per second. A sensor on the instrument measures the amount of time takes for each pulse to reflect back. Light moves at a constant and known speed so the LIDAR instrument can calculate the distance between itself and the target with high accuracy. By repeating this in quick progression the instrument builds up a complex 'map' of the surface it is measuring.

With airborne Light Detection and Ranging, other data must be collected to ensure accuracy. As the sensor is moving height, location and orientation of the instrument must be included to determine the position of the laser pulse at the time of sending and the time

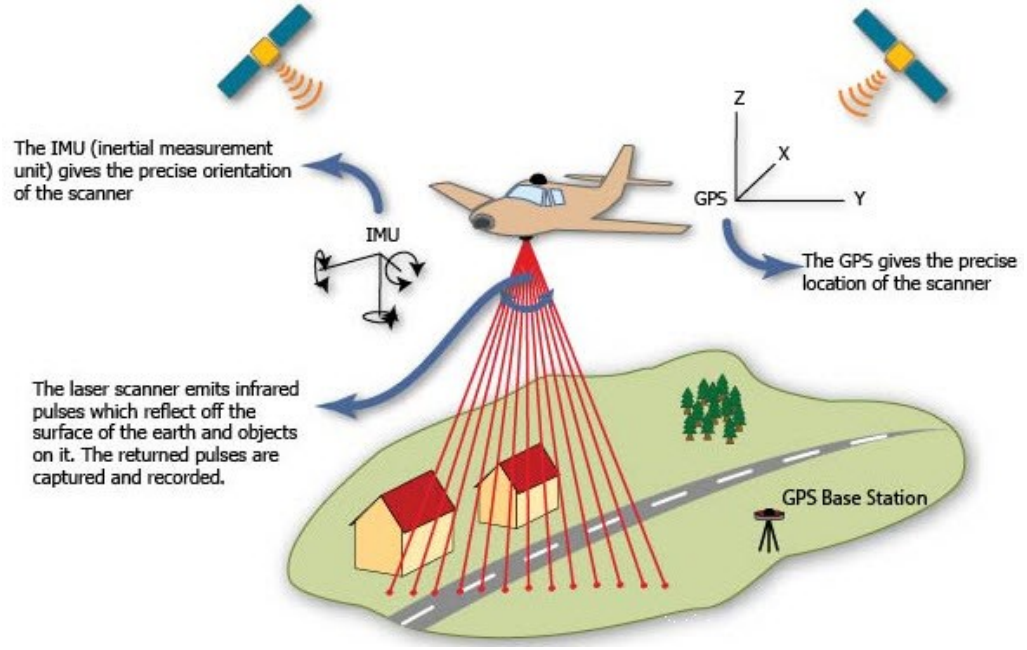

Fig. 6. Light Detection and Ranging System [23]

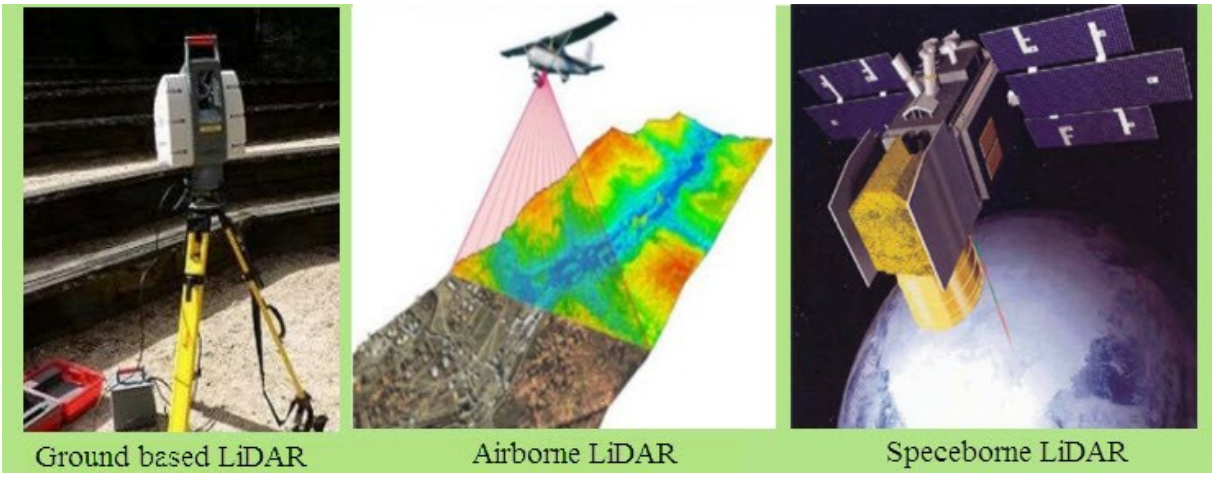

Fig. 7. LiDAR Systems Based On Platform [23]

of return. This extra information is crucial to the data's integrity. With ground-based Light Detection and Ranging a single GPS location can be added at each location where the instrument is set up. [5]

LIDAR System Types Based on the Platform:

Ground-based LIDAR

Airborne LIDAR

Spaceborne LIDAR

If you're surveying land with dense vegetation where light pulses can still penetrate between branches and leaves, Lidar yields high vertical accuracy. [6]

Main Components of LIDAR Systems:

Most Light Detection and Ranging systems use four main components: Lasers, Scanners and Optics, Photodetector and Receiver Electronics, Navigation and Positioning Systems/GPS

Photogrammetry

Photogrammetry is defined as the science, art and technology to obtain information on landmarks Industrial and physical nature of a region by used photographic or non-photographic Image of the region. It can be defined also science that helps to get the 3 dimensions of images from 2-dimensional. The Photogrammetry differs from the ground area in that the ground area deals with nature while Photogrammetry is obtained from the

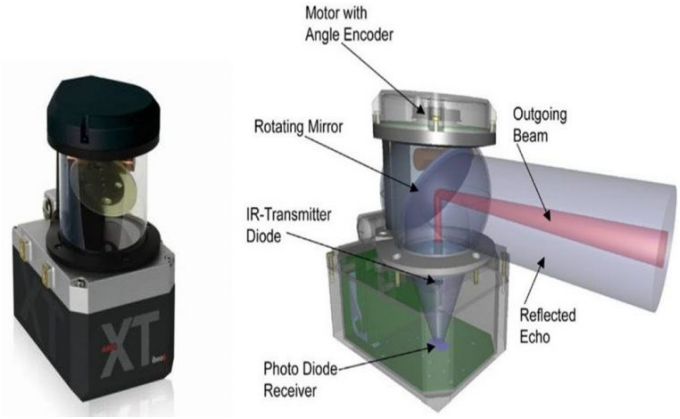

Fig. 8. Light Detection and Ranging Systems Components [23]



Fig. 9a. The ballistic camera **Fig. 9b.** Dual Camera **Fig. 9c.** Theodolites [24]

images Without dealing directly with nature in most of the work. [7]

The Photogrammetry is divided according to the camera position during taking pictures:
- Terrestrial Photogrammetry: Ground images are taken by cameras mounted on the ground where the place and direction of the photo is known and used for this camera with Theodolites mounted on a Triangular base.

- Aerial Photogrammetry: This is the branch of photogrammetry where the photographs are taken from air station.

• Photographs taken from a Aerial camera mounted on a aerial vehicle (aeroplane for the purpose of photography)

• Aerial photographs Used for various purpose, mainly information extraction on the ground surface

• Photographs are taken from camera station in the air with the axis of camera vertical or nearly vertical.

• Aerial Photogrammetry is the best mapping procedure yet developed for large objects and are useful for military intelligence.

• For this, aerial camera is used which are fixed on flying aircraft.

• One of the most important specialties of this science is to determine the appropriate scale for taking images, so that the purpose for which the images are taken is achieved at the lowest cost.

This is a significant advantage over photogrammetry, as photogrammetric surveying will only produce high vertical accuracy when there is sparse vegetation on site. While lidar does have similar limitations, it can penetrate areas with up to 90% vegetation under good conditions. (Photogrammetry sits closer to the 60% mark.) The aerial imagery obtained via UAV photogrammetry can be used to produce a variety of different data products such as: DEM / DTM / DSM (surface models), Orthophotos (geospatially corrected aerial images), Georeferenced Maps & Models, Meshes & Point Clouds, 3D Building Models,



Fig. 10. Aerial photogrammetry [24]

Contour Maps, NDVI Model/3D Vegetation Modelling, Volumetric Surveys [6]

4. Discussion

This section includes evaluation of robotic surveying technologies according to DIN 18710 “Engineering Survey” in term of the role of the surveyor and required accuracy definitions following comparisons of different robotic surveying technologies and methods with each other and purposes to assist in order to choose the optimum surveying method according to work conditions.

4.1 Requirements of Surveying According to DIN 18710

Since robotic technologies undertakes some processes from human surveyors, first of all we should consider the role and responsibility of the surveyor according to standard. DIN 18710-1, Section 4.8 “Implementation” includes a paragraph to define the role of surveyor:

“The surveying project manager must have the appropriate specialist knowledge with regard to the task. The qualifications of the executors must be documented. The project

Object points	Accuracy class	Standard deviations α_L	Remark
Points in open terrain	L1	50 mm < α_L	Very low accuracy
Topographic points	L2	15 mm < $\alpha_L \leq$ 50 mm	Low Accuracy
Clearly identifiable points (e.g. mandatory points for the route)	L3	5 mm < $\alpha_L \leq$ 15 mm	Medium Accuracy
Track points, points of paved flat surfaces	L4	1 mm < $\alpha_L \leq$ 5 mm	High accuracy
Points of Industry and machine measurement	L5	$\alpha_L \leq$ 1 mm	Very high accuracy

Table 1. Accuracy classes for object points in positional recording (18710-2 Table-2) [17]

Object points	Accuracy class	Standard deviations α_H	Remark
Points in open terrain	H1	20 mm < α_H	Very low accuracy
Topographic points	H2	5 mm < $\alpha_H \leq$ 20 mm	Low Accuracy
Clearly identifiable points (e.g. mandatory points for the route)	H3	2 mm < $\alpha_H \leq$ 5 mm	Medium Accuracy
Track points, points of paved flat surfaces	H4	0.5 mm < $\alpha_H \leq$ 2 mm	High accuracy
Points of Industry and machine measurement	H5	$\alpha_H \leq$ 0.5 mm	Very high accuracy

Table 2. Accuracy classes for object points when recording heights (18710-2 Table-3) [17]

manager must ensure that the survey work is carried out correctly." [16]

Thus we see that even if robotic technologies take a role on site in surveying works, the responsibility to ensure a proper surveying is conducted still belongs a surveying specialist. We can use robots for difficult and time consuming works instead of a human, however a surveyor must approve the work and deliver the documentation.

The standard has a accuracy classification depending on the purpose for the requirement of accuracy;

It is seen that land surveying accuracy between 15 mm and 50 mm which is defined as very low and low accuracy and we can obtain it with LIDAR and photogrammetry by using UAV. But in construction surveying, we need 1 mm accuracy which is defined as high and very high accuracy and we can only obtain it by using robotic total stations. Besides it is obvious that accuracy requirement of height dimensions is higher than positional (plan) dimensions. This is important to stake out points in height at structures of construction site which we do not include in land surveying. In conclusion, we can use drones for land surveying but we can not use them in construction surveying.

	Conventional (Manual TS)	Robotic Total Station
Number of workers	2	1
Points per day	300	600
Hours worked per day	8	8
Hourly rate	36 Euro	36 Euro
Total cost per point	1,92 Euro	0.48 Euro

Table 3. Operating cost comparison of RTS with conventional total station

4.1 Comparing Conventional Surveying with Robotic Total Station Surveying

First of all, we compare conventional surveying (manual total station) with robotic total station which is a little development in terms of automation and find out how much benefit the robotic total stations offer. [8]

Therefore, we can list four important differences between conventional (manual) and robotic total station as follows,

- Conventional total stations require manual operation

Each of the functions of a mechanical total station still has to be manually operated, and any manual effort takes more time and introduces the potential for more mistakes.

How a robotic total station is different: A robotic total station is an automated tool that can execute workflows faster and more accurately. The station continuously follows the prism and measures on its own without human intervention. The gains you can make in speed and precision far exceed what's possible with a mechanical layout tool.

- Conventional total stations require a team of two

Although a mechanical total station can offer big improvements over doing things the old-fashioned way, it still has to be operated by a team of two: one person to move the instrument and another person to move the prism.

How a robotic total station is different: By pairing with a tablet, a robotic total station requires just one qualified technician. Layout can easily be performed twice as fast, saving significant labor costs.

- Conventional total stations limit your ability to catch mistakes

A mechanical total station requires one operator to stay behind the instrument and another to move the prism. Because the team is so focused on manual tasks, they're less likely to notice mistakes or question things that seem off. Undiscovered errors made at the layout stage often lead to rework and requests for information (RFIs) during construction.

How a robotic total station is different: With a robotic total station, the single operator can move freely around the space while the station does the work. Freed up from manual tasks, the operator gains a better view of the site and is able to quality check the layout. This makes it easier to catch and resolve any issues upfront that could impact construction, decreasing the likelihood of costly problems down the road.

- Mechanical total stations produce limited gains in productivity

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A mechanical total station is a step up from traditional layout tools and methods, but you're literally leaving money on the table by continuing to rely on largely manual processes when there's an automated solution available.

How a robotic total station is different: You can lay out an average of 600 points per day and in some cases over 1,000 points per day using a robotic instrument and one person, as opposed to around 150 points per day with a mechanical instrument and two people. With a robotic total station, you can conservatively achieve a 90% cost-per-point savings over a conventional total station. [9]

The below comparison showcases the significant productivity gains (2 times more productive) and cost gains (four times lower cost), moving from a manual total station to a robotic one. Although points per day data is not a constant value and changes according to construction site and layout that is required to mark, the data shown on the table is obtained by researching several different sources and selected as average values for both techniques. Hourly rate value is obtained by "https://www.salaryexpert.com/salary/job/quantity-surveyor-construction/germany/frankfurt-am-main" which is the average of surveyor construction.

	Leica FlexLine TS07 (Manual Total Station)	Leica TS16 (Robotic Total Station)
Angular accuracy	1", 2", 3," 5", 7"	1", 2", 3", 5"
Prism range	0.9 m to 3'500 m > 10'000 m (Long Range mode)	0.9 m to 3'500 m > 10'000 m (Long Range mode)
Distance measurement accuracy on prism	1.0 mm + 1.5 ppm	1.0 mm + 1.5 ppm
PinPoint EDM: Reflectorless range1	R500: > 500 m R1000: > 1'000 m	R500: > 500 m R1000: > 1'000 m
Distance measurement accuracy reflectorless	0 m - 500 m: 2 mm + 2 ppm > 500 m: 4 mm + 2 ppm	0 m - 500 m: 2 mm + 2 ppm > 500 m: 4 mm + 2 ppm

Table 4. Technical Specifications of Manual and Robotic Total Stations.

This table gives a idea about operation productivity and costs of RTS. However it does not answer the question clearly that if a company should buy and use RTS what will be the benefits. In order to answer these questions we present a case study to demonstrate the effect of RTS.

Case Study: Precast Parking Deck with Robotic Total Station

A major construction company in Hawaii opted to pilot a Robotic Total Station when it was contracted to perform precast for a large parking deck structure. Each precasting component had a dowel grouted into a sleeve that allowed prefabricated panels to be plugged in on-site. The firm originally built-in some contingency for a percentage of the 875,000 required dowels to be outside of specs.

The team's accuracy using RTS far outpaced that original expectation. Not one of the 875,000 dowels had to be reworked. Additionally, there was zero delay onsite. All panels were assembled on time, as soon as they arrived on site. The end result was that the project completed two weeks ahead of schedule. Not only did the contractor not incur the cost of reworking the dowels, but they saved cost on rental of equipment, including the crane that was hoisting the panels. Including the cost of the RTS rental, software, and training, the project manager reported an over 10x return on investment on the pilot project. [10]

We will consider this project data as a base data and calculate return of investment cost of robotic total station. However, there are tens of different total station manufacturer brands

in the market and each of them have several models. We chose one manual and one

robotic total station models of the same manufacturer for the sake of fair comparison for this part of the paper. The models have intentionally same or similar specifications in

terms of accuracy and range in order to compare only robotic features.

In the table you can see the detailed specifications of the chosen total stations.

It is obviously seen that robotic features comes with a trade off operating time (battery life) because of the additional sensors and the hardware required of automation calculations. However, if we consider a full work day is 8 hours one battery will cover a full working day.

Cost of the total stations are as follows;

https://www.capitalsurveyingsupplies.com/leica-flexline-ts07-manual-total-station/

Leica FlexLine TS07 (Manual Total Station) - 10.000 Euro

https://www.sccssurvey.co.uk/leica-viva-ts16-total-station-1.html

Leica TS16 (Robotic Total Station) - 32.000 Euro

(The price includes 5" angular accuracy total station and all other stuff which are necessary to operate a surveying such as tripod, prism, battery, charger etc.)

For the same features in term of surveying the cost of robotic device is about three times more than manual device. We need to find out whether this initial cost is worth to operate for a construction company.

Therefore, we will calculate the return of investment cost of robotic total station. We assume that a working day is 8 hours, we need 2 workers for manual total station and hourly rate is 36 euro, then the operating cost for one day is as follows;

2 [workers] x [8 hours] x 36 [EUh] = 576 EU/day

For RTS we need 1 worker, therefore the operating cost is 288 EU/day

We will use the case study data of 875.000 point in total and use the productivity data from table 3. The days necessary to complete the work for one total station and 2 workers

Conventional TS ; 875000 / 300 = 2916 days

RTS 875000 / 600 = 1458 days

Therefore the operating cost for manual total station;

2916 [days] x 576 [EU/day] = 1 679 616 EU

On the other hand, the cost for RTS;

1458[days] x 288 [EU/day] = 419 904 EU

Considering the investment cost difference of two tools which is 22 000 EU, it is obvious that the return of investment which is about 1 million euro is much higher than the cost.

On the other hand we can calculate how many points are required for full return of investment;

32000 [EU] + X points * 0,48 [EU/ point] = 10 000 [EU] + X points * 1,92 [EU/ point]

The result is 15 277 points which is only about 2 % of the total amount of the case study project.

Our opinion using RTS instead of conventional total stations has a potential of increasing productivity and efficiency. The initial cost difference is not much comparing with productivity increase thus time save. For single point stake out especially indoor construction sites, it is still the best robotic method exists in the market. In addition, better BIM integration will help project managers and different sub-contractors to organize and co-operate much better.

4.2 Comparing Total Stations with Robotic Drone Surveying in Land Surveying

In this section we will cover a comparison between surveying with total stations and using robotic drones (multi copter) with sensors (Photogrammetry and LIDAR). Total stations can be used in both engineering surveying and land surveying while drone surveying can only be used in land surveying due to accuracy requirements of DIN 18710 standard and safety problems of flying a drone inside of the construction site.

First of all there are some obvious differences and expected advantages of using flying drones instead of workers with total stations on the site.

Speed – A huge selling point of drone surveying is that accurate and actionable data can be collected much faster than traditional methods. Drones can scan up to 2.8 km^2 a day (per team) and data can be ready for final delivery within two weeks.

Safety – The drone can be piloted from a safe location while the drone itself is high above the ground, which significantly reduces the potential risks for on-site teams.

Access to remote locations – Whether you need to scan rocky terrain, overgrown swamp and marsh, or access high altitudes, a drone can reach areas with ease.

Cost effective – Drones can collect the data much quicker and with significantly fewer man hours, reducing the overall cost.

Accuracy – High quality sensors offer specifications with incredibly high accuracy, usually around 2 cm. [11]

These are the main advantages that are expected from robotic drone surveying .Therefore, we will research and analyse how much benefit it has. We will use the data of academic paper that makes an experiment about it and illustrate their work. The study is implemented by C. Arango and C. A. Morales from Universidad de los Andes.They used two methods of data acquisition, the first one with a total station (Leica Ts-02) , and the second with a multicopter drone DJI Phantom 2 vision plus. [12]

Volume Estimation ; The first comparison is calculation of the volume of the site. Therefore the point clouds are obtained by using two different methods and the output of the results are as followed;

In the output data, it is clearly seen one of the main differences between TST and drone surveying; drone surveying output with photogrammerty provides much detailed overview of the land with real objects while on TST output data only marked points are visible. Real image data provides full overview and assists designers and investors make better decisions.

Actual data were collected from engineers recycling plant were the stockpile was, even though this information is approximate, for this case is assumed as the real volume. Based on the information provided in table 4, there was a 2.88% difference between the volume calculated with the TST data and the actual volume, and −0.67% difference between the volume calculated with the drone data and the actual volume, a positive value indicates that the estimated volume is higher than the actual

Time taken for	Total Station	Drone
Setup equipment	5 min	5 min
Obtain data	3 h	30 min
Initial Cost	13 000 EU*1	10 000 EU*2

Table 5. Volume calculation comparison with total station and drone surveying.

	Volume (m^3)	Difference Volume (m^3)	Percentage	Percentage Difference
Actual	11500	-	-	-
Total Station	11831.2	331.2	102.88 %	2.88 %
Drone	11423.58	-76.42	99.34 %	-0.67 %

Table 6. Time comparison between both methods

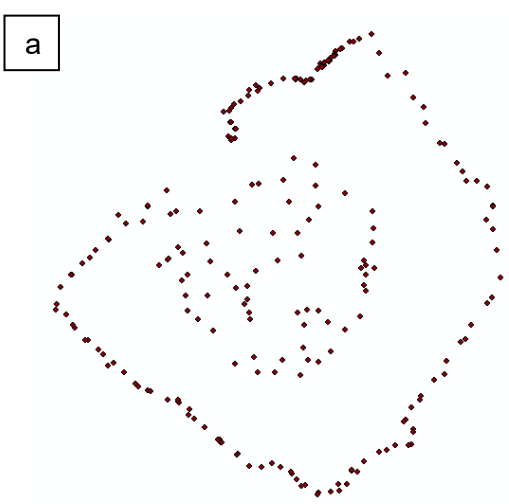



Fig. 11a. Point Cloud from TST data top view **Fig. 11b.** Drone Point cloud drawing top view [25]

volume and vice versa. The percentage difference shows that the volume obtained with drone data is more accurate than the volume obtained with TST data. Therefore in the same conditions robotic drone surveying provides better volume estimation that actually means it has better contour measurement and surface level measurement.

*1 https://www.capitalsurveyingsupplies.com/leica-flexline-ts07-manual-total-station/

Leica FlexLine TS07 (Manual Total Station) 1" angular accuracy. This is the updated corresponding tool of what is used in the research paper "Leica TS-02 1" angular accuracy."

*2 https://store.dji.com/de/product/phantom-4-rtk-se-and-dji-care-plus?vid=116451

DJI Phantom 4 RTK with GNSS receiver. This is the updated and corresponding model of what is used in the research paper "DJI Phantom 2 vision plus"

It is obviously seen that surveying the same area with total stations takes 6 times more time and land surveying drone has lower initial cost. However, total stations are still have the main advantage of single point stake out accuracy of 1-2 mm while drone surveying offers about 2 cm. Also drones can not work indoor areas such as buildings at construction stage. In general, the cost comparison is depends on the size of area, desired accuracy (because more accuracy means longer flying times and much longer data processing time) but there are some average values we can present to give an idea.

A photogrammetry system can cost between $2,000-$40,000 depending on the type of aircraft, camera, and level of accuracy. Most firms are achieving a return on investment (ROI) of 2-3 projects. We created a real-world example scenario to have a better idea;

A company is contracted to provide 30 cm contours on a 40500 m^2 site. Traditional methods would take a field crew of 3-4 employees 3-4 days to complete. The average expense for a field crew is roughly $1,000 per day, costing the firm $3,000-$4,000. A drone system priced at $4,000, along with drone mapping software to process the data at $5,000, provides an ROI within 2-3 projects. A LiDAR system can cost between $90,000-$280,000, depending on the level of accuracy needed to achieve. The time in the field to achieve the same level of data in more challenging areas would be increased at least 10-20 times. Given the above scenario, this would cost $30,000-$40,000 to collect the data, providing the same ROI of 2-3 projects for the entry level LiDAR system. There is also a huge shortage of manpower in surveying,

and this technology helps companies increase their efficiencies with the same amount of employees. [13]

Our opinion is drone surveying offers a great solution for land surveying. Instead of collecting data from only some chosen part of the land we have a full set of data points which covers the whole land and this is very important for further planning processes because otherwise you would have to visit the

Time expenditure and level of detail of the results	Topographical method	Mobile laser scanning
Measurement time (field works)	2h	30 min
Processing of the measurements. Generation of the points cloud	12 min	3 h 30 min
Total time	2h 12 min	4 h
Measurement processing. Generation of the points (cameral works)	468	59 .7 millions
Average of point quantity, in 1 m^2	<1 (1 point/59 m2)	>2550
Averages of altitudes differences on the soft surface, in cm	Grass cover 2	Soil 0.7
Averages of altitudes differences on the hard surface, in cm	Asphalt cover 0.4	Concrete 0.5

Table 7. Comparison of methods according to the time expenditure and level of detail of the results

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site again to collect new data which would be waste of time and money. Instead of having only some simplified and approximated drawings, you have many options with drone surveying such as DEM, DSM and DTM which are really helpful in order to see all the details clearly and that will assist to create the optimum design options. Finally, land surveying works which requires more than 1 day work on site with conventional total station method you can save time and money by upgrading to a drone surveying method besides the output of the surveying includes all the terrestrial details which will prevent any missing point on site that may be lead to visit the site again.

4.3 Comparing Total Stations with Robotic Ground Surveying

In this part, we compare conventional surveying (total stations) with ground robotic surveying with LIDAR sensors. Especially in recent years a robotic dog named Spot by Boston Dynamics which has made several partnerships with surveying companies, has become popular. The most suitable comparison that was implemented in a academic research paper is prepared by a group of scientist in Lithuania.

They surveyed the same cross-road structure by using a total station (Leica TCRP1205) and a LIDAR sensor system (Street Mapper 360) which was mounted on a truck vehicle.

The results of the experiment can be listed as follows:

1. In the same territory within a rather short time period (~30 min), significantly more detailed (>1000 points per 1 m^2) and informative data is derived with the laser scanning method than when measuring by total station method. Mapping large and multi-component objects, it is more appropriate to use the laser scanning, because with increasing size of the object, the difference between the methods in terms of the time expenditure decreases.

2. Regarding the more informative data, the system of laser scanning could be applied for the multiple practical uses. The areas of application include geodetic surveys of the linear engineering structures, compilation of the detailed models of the surfaces; identification of defects of coatings and coverings; implementation of archaeological, cultural, architectural investigations; engineering and inspection works; water reservoirs lines; investigations of slope stability, etc. Such systems are able to completely substitute the traditional measurements by the total stations.

3. The main differences of the analyzed methods when compiling the topographic image in diverse areas is the informativeness of the measurements and data, the speed of data processing, the level of detail of the results and various possibilities of their application. Both methods are effectively employed when solving miscellaneous engineering, geodetic and other assignments.

Our opinion is; no matter using LIDAR or photogrammerty as a measuring method and no matter whether using the self navigated robotic vehicle on the ground or on the air, robotic surveying for land or road surveying always results better than total stations in term of time spending on the site, having a much more detailed (especially with LIDAR) and easy to read (especially with photogrammetry) output data. This high level land survey data helps designers, investors contractors and subcontractors to have a much better overview of the site without missing any detail thus all project progresses become less prone to errors.

4.4 Comparing LIDAR and Photogrammetry as a Robotic Surveying Method

In this section we compare two different sensor systems of data collection used in robotic surveying. Both of them has some advantages and disadvantages comes from inherent of the sensor.

Advantages of LIDAR;

The most cited positive of using LiDAR for mapping is the technology's accuracy. But as a standalone statement that doesn't give us much to work with. LiDAR is the way to go for absolute accuracy and is typically the best choice when the aim is a realistic bare earth model. That's because it's the best method for accounting for elevation, vegetation, and the conditions at hand.

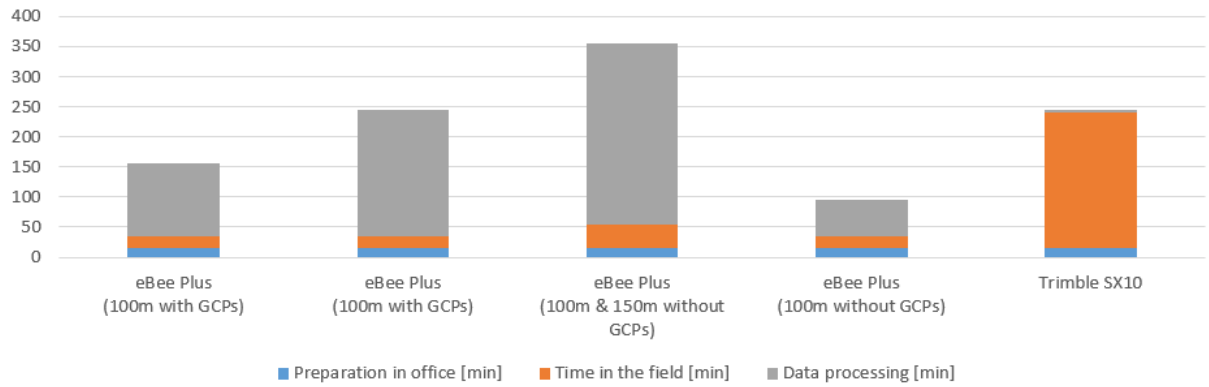

Fig. 12. Time needed to collect the data [25]

LiDAR's integration with GNSS data and the fact that it's a direct measurement - firing out thousands of laser pulses from above - ensure the final digital terrain map has extreme vertical accuracy.

Topographical complications don't only come in the form of terrain undulations. Vegetation can also block photo-based surveying methods from getting granular ground-level data.

LiDAR's light pulses penetrate the gaps between leaves and branches, reaching the ground below and improving the accuracy of measurements.

LiDAR is also preferable if the light conditions of your worksite are inconsistent. If you want to carry out night-time surveys or low visibility missions, LiDAR can handle the task without needing an external source of light.

Lastly, LiDAR allows you to capture details that are small in diameter. A great example of this is power cables. Thanks to high-density point sampling and the direct measurement approach, you can use LiDAR to accurately map cable catenary.

Disadvantages of LIDAR;

The most obvious challenge that comes with working with LiDAR is its cost. Because of the greater operational complexity (and the need for more sophisticated components and sensors), you can easily spend hundreds of thousands of dollars on a complete survey solution.

This complexity also widens your room for error and increases the dependence on an experienced professional. With multiple sensors and information that's not readily accessible without a fair amount of processing, extracting the data you need isn't straightforward.

It's also important to bear in mind that traditionally LiDAR sensors have been bulkier than simple cameras. With drones becoming increasingly popular for aerial surveying, the need for a bigger drone to handle a heavier payload can add to an already significant expense.[14]

Advantages of Photogrammetry;

The main benefit of working with photogrammetry is its accessibility. The rise of drone technology and mapping software has simplified workflows and brought accurate maps and 3D models within reach of any organization with a decent camera drone.

Aside from camera calibration, basic flight planning, and plotting your ground control points, carrying out a mapping mission and turning that data into something useful is relatively straightforward. There are countless scenarios in which this process produces tangible results, in industries as varied as construction, conservation, mining, and agriculture.

Importantly the results are accessible, too. Maps and models with recognizable features and colors are instantly intuitive, making them a great collaborative tool and something stakeholders can work from without spending too much time manipulating the data.

Another big part of Photogrammetry's appeal is how affordable it is. As we've touched upon, getting started means investing a few thousand dollars on a professional camera drone and much less than that on the software you'll need to process your data.

Finally, Photogrammetry offers a more flexible approach. Depending on the task at hand, you can have more control over the

	Laser scanner (LIDAR)	UAV flight at 100 m flight height	UAV flight at 150 m flight height
Number of Points	24,416,594	1,246,951	645,695
Points per m^2	741	37	19
CloudCompare – std.dev [cm]	reference value	5.2	5.9
Total collection time (in–field & processing) [min]	225	20	20
Approximate cost (EUR)	80,000 EUR	30000 EUR	

Table 8. Summary of key comparison findings.

trade-off between mission speed, altitude, and accuracy.

Disadvantages of Photogrammetry;

The first is that the accuracy of your maps and models is highly dependent on the quality of your drone's camera and the drone itself.

Sensor size, aperture, resolution, and focal length all impact your ground sample distance (GSD) alongside the altitude you are flying at. On top of that, you'll struggle to produce results with absolute accuracy without several using ground control points or an RTK or PPK enabled drone.

The second challenge facing your Photogrammetry ambitions is the weather. Or, to be more specific, the light conditions. Darkness, cloud cover, dust, and more can all negatively impact the quality of your surveying results. [14]

When it comes to data processing, you can only measure what you can see clearly. This means that flights with limited visibility - whether due to vegetation, shadows, or the time of day - will produce fewer ground points and less accurate maps and models.

In order to make a more detailed and numerical comparison we present the data of a research paper by Armin WEBER and Thomas LERCH Lerch Weber from AG, Switzerland. Acc. They used a photogramety tool of senseFly's eBee Plus RTK/PPK photogrammetry UAV and Trimble's SX10

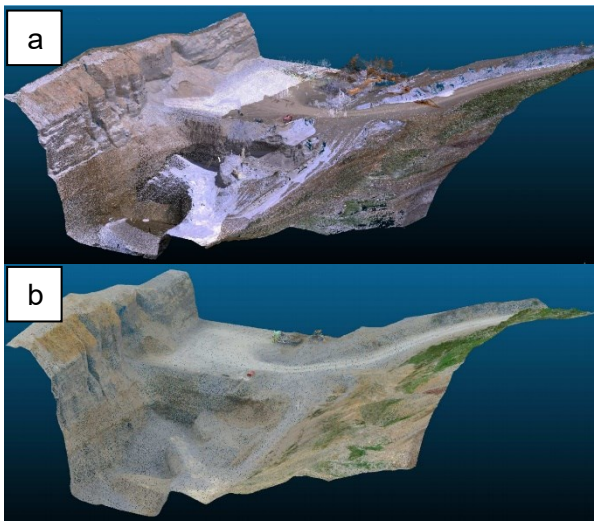

Fig. 13a. Screenshots of the TLS' point cloud [25]
Fig. 13b. Screenshots of the 100 m / no GCP UAV point cloud [25]

scanning total station which is a LIDAR sensor placed on a total station. Even though total station is not robotic as UAV this section is to compare sensor data of LIDAR and photogrammetry.

A 40 000 m^2 gravel pit is chosen to do the experiment and comparision Five individual point clouds were generated in total: four UAV point clouds (derived from two UAV flights, flown at different heights above ground level), and one merged laser scanner point cloud from five station set–ups.

The result data tables are as follows;

The results of the experiment can be listed as follows:

1.The process of collecting point data in the field with the RTK–enabled photogrammetry, without the need for GPCs, was more than twice as efficient as using LIDAR (Tabl

2.When combining these in–field and processing timings, comparing each technology's total data collection time (Table 8) shows that that the overall efficiency of the Photogrammetry is higher than that of the LIDAR for a gravel pit survey such as this. For this surveying experiment and most of land surveying positional accuracy is similar.

3.Point density is very high in the case of the LIDAR point cloud, however the comparisons above show that the photogrammetry less dense point clouds achieve similar results.

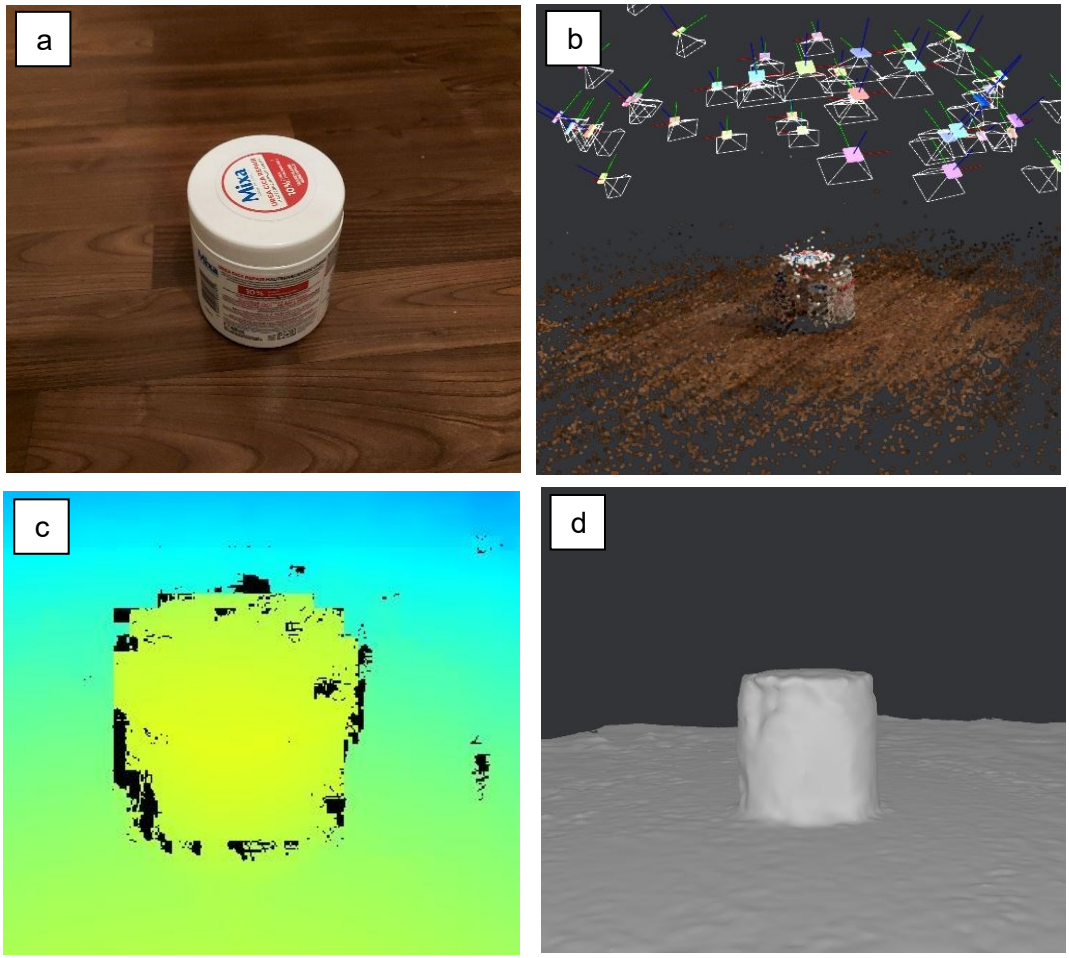

Fig. 14. Our experiment by Meshroom and converting 2D images to 3D Model, (14a) the image taken by camera, (14b) the 3d model is created by Messhroon Software, (14c) the result of the 3d model in Meshmixer, (14d) the 3d model without material.

We can conclude therefore that, while the photogrammetry point clouds provide less detail than a LIDAR point cloud (set to medium density), there is still enough detail provided for most typical survey applications. But for surveying projects where the very highest level of detail is essential, such as digital preservation projects on small sites for example, a laser scanning methodology is undoubtedly optimal.

Our opinion is; For land surveying operations if there is no need of very high detail surface scan for the small object detection and if there is no vegetation photogrammerty provides good quality of land surveying data. It is much easier to operate with integration of drones RTK (real-time kinematics) and photogrammerty softwares and they all can be much more accessible for the users. Besides there is a significant initial cost between photogrammerty and LIDAR sensors.

Photogrammety is so accesseble that we found a free software on https://alicevision.org/ which is called as “Meshroom”. Meshroom is a free, open-source 3D Reconstruction Software based on the AliceVision framework. We installed it and by using our smartphone cameras we took 60 different images of an object. We opened a new project inside of the sofware and created a 3D scan model by using 2D images that we took.

Although we are not professional surveyors and although our camera is not a professional camera we got pretty good results in terms of level of detail. This scanned model data can be used in CAD and BIM softwares. With this experiment we saw that photogrammetry is so accessible for non-professional and there are really advantages computer algorithms that can convert a 3D object by using many of 2D images even without geo-data or any kind of tracking system.

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5. Conclusion

In this research paper we defined problems in conventional construction surveying which is related to the lack of automation. Afterwards, we implemented a market research in order to present what robotic surveying solutions exist in the market and what the state of art is for all different kinds of methods.

We prepared a detailed comparison of the different methods in terms of time, accuracy, safety, level of detail as output, efficiency and cost in order to have an overview and chose the right method for the right job. Our opinion is for the final decision of which technique is the best, first we need to separate the surveying work into three sub categories:

1. Construction site surveying (indoor or outdoor single point stake out): This surveying is usually what we need during construction period. We need single point accuracy with a high level (1 or 2 mm) deviation. For instance, when we need to layout anchors a steel column on the foundation we only need to stake out particular anchor points. We do need to survey more points.

For this kind of surveying the only option is total stations since they are the only that can reach 1-2 mm accuracy and they are used for single point stake out. Do we need robotic total stations? When we have to stake out not only several point but hundreds of points each project, robotic total stations have benefit with productivity also requires only one person instead a team of two.

2. Land surveying: This surveying is implemented for obtaining the boundaries and topographic properties of the land. Since the land areas are usually extremely large and out of urban regions, surveying with total stations usually takes more than 1 day site visit. This leads waste of time, and high labor cost in comparison with UAV-LIDAR or UAV-photogramery techniques. UAV technique can survey a 40000 m^2 land in 20 minutes of data collection at site and a few hours data processing in office while it requires about 6000 minutes (100 hours) of site works with one total station team. Instead of only stake out selected points on the site with total stations LIDAR or photogrametry scans all the land with very high point density in comparasion with total stations. Point density of total stations usually less than 1 point/m^2, with LIDAR can provide up to 1000 points/m^2 and photogrammerty provides up to 40 points/m^2. This high resolution output also leads to catch every detail on the land and makes possible for each calculation (area, volume) to be more accurate. In conclusion, although single point stake out of total stations has high accuracy, staking out many number of points in a short time is much more important in land surveying than milliliter level accuracy thus robotic surveying should be considered. What sensor is the best for land surveyors? For most of the land surveying works, photogramerty offers better solutions with its lower cost, easier implementation and photo visual output. For some certain situations such as removing vegetation and grass, working with low light conditions, need to catch very small details, although it is three times more expensive using LIDAR is the only option.

3. Construction site surveying for monitoring purposes: It is a popular process especially in recent years with a developments on LIDAR and robotic dog technologies. LIDAR sensors can be carried on hand by personals which is not a fully robotic surveying only the sensor is automated, or the LIDAR is connected to a robot and the robot can navigate itself on a predefined route to complete the LIDAR scan work. With this kind of surveying project managers and designers has the opportunity of monitoring the progress of the site. LIDAR output file can be integrated and superposed with BIM models thus progress of construction can be reported visually. Schedule delays or mistakes can LIDAR demonstrates can be detected easily.

Our opinion is although this new kind of robotic becomes popular in construction sites, it is not efficient to use this expensive technology (about 100.000 EU according to our interviews in DigitalBau 2022 Köln) only for monitoring purposes. We should use its self navigation, tracking, and tool carrying ability features more efficiently. We offer a better surveying solution by using this robotic technology in this paper.

The summary of our conclusions are;

- Total stations are still the only option when it is required millimeter level of accuracy (for instance; anchor points at the construction site.

- Robotic total stations make a great difference in terms of speed, precision and cost especially for big projects.
- Drone surveying is very promising for land surveying (including road constructions) and construction site monitoring with their high-detail and realistic output with photogrammetry.
- Although LIDAR sensors are relatively expensive they can be very useful for some certain scenarios;
  - They can be used on any ground or aerial vehicle (drones).
  - They are the only option if it is required to have DEM or DSM where there is vegetation.
  - They can work in low light conditions.
  - Their output data has more detail than photogrammetry.

5.1 Suggestions and Our Approach for Improved Robotic Surveying

In this section we offer some solutions for better robotic and automated surveying. First of all we wish to mention about a different technology for land surveying that uses satellites.

Even in the present, there are some companies which provides satellite monitoring services, for instance one of them is named UP42 founded in Berlin [15]. They use satellites with very high resolution and high quality cameras and they provide 50 cm accuracy images and daily updated. With some image recognition and segregation to identify objects and borders of lands also they provide Digital Surface and Digital Terrain Models. It is not enough for detailed topographical properties of the land now but in the future when the accuracy increased and update rates as well, it can be the best solution for land surveying and monitoring instead of using drones.

Lastly, we wish to add our solution for construction site (indoor or outdoor) surveying. We mentioned that total stations are necessary for millimeter accuracy single point stake out and robotic total stations can find and follow its target automatically and thus only one surveyor is needed to carry and setup the total station onto a tripod, to load the layout projects into robotic total station, to schedule the work-plan and to carry the prism (target) when it is used in the prism mode. After the site work finished, surveyor should publish the output documents and reports. Although robotic total stations are really advanced in term of finding targets, tracking its position and location and measuring angle and distance itself, it still relies on human skills to setup each time in the right location on tripod, start the survey and after survey finished for one section, surveyor must unpack everything and carry the tool to the next section for the new task.

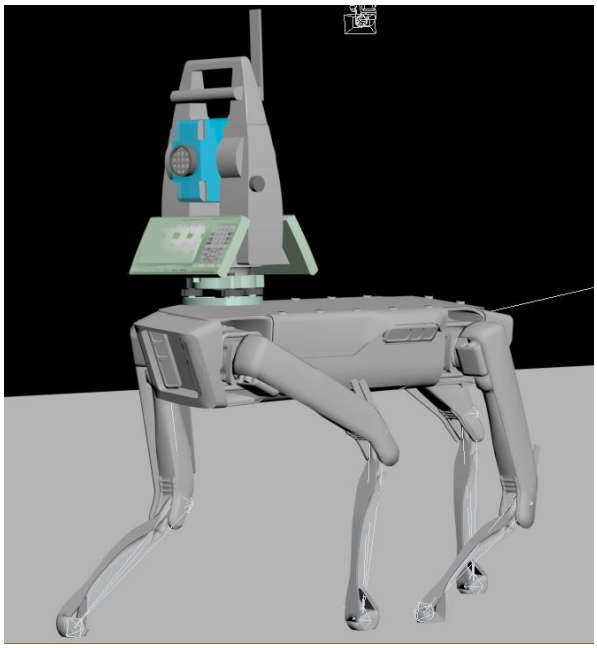

Fig. 15. Combination of Robot Dog and Robot Total Station by 3D MAX

We also mentioned a new technology robotic dogs which can walk around all construction site are used with LIDAR for monitoring purposes. The cost of robotic dog is about 50000 EUR (according to our interview in Digitalbau 2021 in Köln) and we think it should be used not only with LIDAR but also with robotic total stations.

Robotic total station has two different modes of staking out points, one mode is called prism mode and a person should carry the prism, which is tracked by RTS in terms of linear and angular position, and when prism is on the right point the person can see it from the display of a small tablet PC and mark the point for further treatment. Second mode is called laser mode. With this mode, RTS does not need a prism and its laser beam directly shows the stake out points one by one to the person, all the thing the person needs to do it is to mark the point that RTS shows and click the button for the next point that RTS will show.

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Fig. 16. Using this robot in construction site

Our approach is putting a RTS on to a robot dog. Therefore we will not need a tripod setup we will not need someone to carry the RTS and tripod between the sections always. The robot dog with robotic total station with the help of ground control points will always know and track their location and according the surveyor's schedule that she/he can create and monitor it from her/his office, this combined surveying robot can navigate itself, setup itself and start to stake out points that are needed for construction processes itself. When the task is finished for one section it can quickly move to another section of the building and start a new surveying task. According to legal regulations a surveyor under supervision of the authority of the federal state must exists to be sure for accuracy and confirmation of surveying output. Surveyor should have this responsibility but just like getting important help of UAV with LIDAR or photogrametry, surveyor lets the repetitive, unsafe and time consuming site work to robotic tools and focus of planing, and output data analysis. Automation and robotic technologies help people to do repetitive, time consuming and unsafe works in all industries including construction industry. In our opinion, instead of doing more physical works surveyor of the present and future should know more about computer algorithms, should be a part of Digital BIM based construction industry by doing more data analyse and process development. This is our opinion and suggestion. In order to decide whether it is a valuable method there are some points that need to be discussed;

- How efficient this method would be in term of human-robot collaboration, process time, cost, accuracy and precision?
- What would be the compatibility of different devices with an implemented software?
- What would be the return of investment considering the investment cost and productivity?
- Is robot dog the best solution to move around a RTS autonomously or is there a better alternative device such as a robot car with wheels or tracked laying?

All these questions should be tested and observed with repeatable and reliable experiments. After the results are obtained, we can discuss how valuable this method is.

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TIMUR KUZU, DOMINIK LEITNER, ZIYU ZHAO

The drilling and blasting tunnelling documentation process – best practice and an integrated digital management approach

ABSTRACT

This paper gives an insight into the state-of-the-art tunnelling method of drilling and blasting. In detail the focus lays on the in-depth investigation of the documentation procedures during the main project phases: planning, construction and operation and maintenance. Due to the lack of digitalisation these documentation procedures are currently inefficient and prone to error.

In the following chapter, Building Information Modeling (BIM) as possible digital planning method and Industry Foundation Classes (IFC) as an open standard exchange format are introduced as a possible solution approach to modernise tunnel documentation procedures. The market and company structure here in Germany favours Open BIM as the most promising approach. To resolve the current state of non-standardised data transfer between stakeholders/software the implementation of IFC must be further pursued. Efforts are currently made by the buildingSMART organisation. To support their work for the IFC-Tunnel project this paper develops an extended digital documentation framework based on a Common Data Environment (CDE) and evaluates additional IFC requirements/properties for the different project phases.

An improved method for the geotechnical information quality and availability is proposed for the planning phase. Additional IFC-properties are offered for creating a digital tunnelling report supporting the construction phase. Lastly, to improve the quality and accuracy for the visual tunnel inspection during the operation and maintenance phase, new IFC-properties are introduced.

The analysis shows that even though great efforts are already made by the buildingSMART organisation with the publication of a Requirements Analysis Report, still the offered solutions cover only a small fraction of tunnelling projects, focusing largely on the design aspects. Reasons for this include the high individuality of tunnelling sites and their unique requirements for different construction phases. Thus, lacking implementation of digital planning methods leave a basis for future research efforts in the direction of drilling and blasting especially.

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Keywords: tunnelling, drilling and blasting, documentation processes, BIM, IFC, digital planning method, open standard exchange format.

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1. Introduction

Today approximately 4.5 out of the 7.9 billion people worldwide live in urban areas. By 2030 this number, according to the United Nations, increases by an additional 700 million people. By then, 60% or 5.2 billion people will live in towns or cities [1].

As a consequence, cities will have to cope with the development of an increasing need for housing as well as for the transportation of people, also here in Europe. At the same time, the fast-pace living in the cities outruns the efforts for sustainability and environmental-friendliness in many places. This state led the political decision makers in the city of Paris to take actions and initiate the largest infrastructure project in Europe. The “Grand Paris Express” is a unique project to boost public transportation to absorb these challenges. Four new fully automated subway lines with 68 stations and a track total of ~200km are planned until 2030 [2]. The increasing urban population asks for a modern public transportation system to allow for comfortable commuting during the rush hour and to simultaneously decrease private car ownership for an improved environmental footprint.

Tunnels are the key structures for the success of these projects. Their effective and efficient planning, construction and later operation and maintenance are crucial factors, to be able to comply with the tight project schedule. Here, the data collection, the processing and the exchange of information between the different involved stakeholders present a major challenge today.

This paper gives an insight into the state of the art of the drilling and blasting tunnelling method, records the documentation procedures during the different project phases and highlights its current challenges. The second part introduces BIM and IFC as a possible digital planning method with open standards for tunnelling and gives an insight into the current state of implementation. Based upon the findings in the Requirements Analysis Report by the buildingSMART organisation additional IFC properties are developed and evaluated to further improve the current implementation efforts for IFC in tunnelling.

2. Research methods

The research process of this paper revolved around a first keyword search in the RWTH available databases online. The keyword search focused on the tunnelling method of “drilling and balsting” as well as around the terms “BIM” and “IFC” as basis for a potential digital planning approach. From there the research was further specified to receive a more detailed insight into the topic.

3. Results and discussion

3.1 Drilling and blasting – State of the Art

Drilling and blasting tunnelling is, together with the tunnel boring machine (TBM) approach, considered to be the main tunnel construction method for ultra-long and ultra-deep rock tunnels. In comparison between both however, the drilling and blasting method is usually cheaper and more flexible, while the TBM method offers faster excavation speed and higher degrees of mechanisation and automation [3].

Construction process description

Drilling and blasting tunneling is usually used in rock environments with medium to high strengths and can be categorized as a

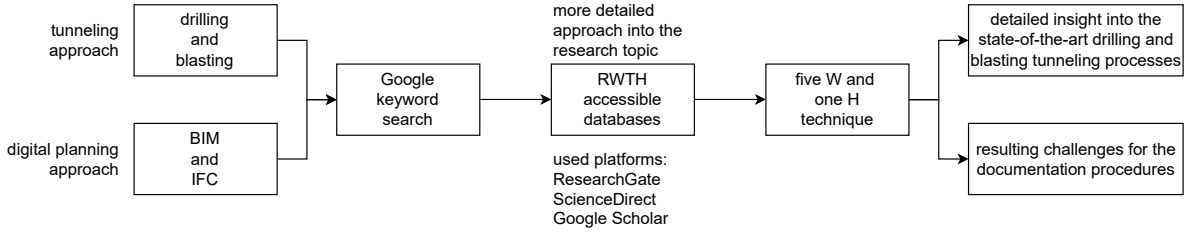

Fig. 1. Overview research procedure

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cyclic or discontinous construction method (subsequental execution of work processes).

First, drill holes for the explosives are drilled, cleaned from excess material and checked for their respective dimension and location. After that, the holes are filled with explosives that are connected to the detonation mechanism, allowing for a precise detonation order from the inside to the outside. Before blasting the gaps between the explosives and rocks are filled to increase the detonation pressure as well as to reduce the overall explosive consumption. In order to minimise the amount of dust after blasting, the tunnel is thoroughly ventilated and shotcrete is used to secure the excavated wall areas to prevent any additional soil from falling. Lastly, the blasted material is loaded and removed from the blasting area before the drilling and blasting cycle is repeated from the beginning [4].

Information chain

Tunneling projects involve a number of different stakeholders who rely on a regular information exchange throughout the different phases of planning, construction and operation and maintenance of the tunnel. Therefore, the ability to efficiently and effectively acquire and transfer data is crucial to track the progress and developments of a project.

Documentation

One important aspect during the construction phase of a drilling and blasting tunneling project is the documentation of processes. It serves as the information basis to evaluate the tunnelling progress with target-actual comparisons. Furthermore, having verifiable information is useful in case of construction disturbances to support statements and detect causes for construction delays or errors. Apart from that, the construction documentation serves as the basis for payments, thus required to offer a realistic and holistic representation of the construction procedures and progress.

There are different types of documentation material collected during any kind of construction project like the daily construction report, delivery lists, meeting transcripts, photo and video files or notices of delay. For tunnelling projects there are additional tunnel-specific documentation resources such as the tunnelling report, support element reports or hour reports. The daily construction report and the tunnelling report are conducted on a daily basis by the construction management team and serve as the main source for data collection. For this reason they are observed in more detail in the following.

The daily construction report is an essential piece of documentation, it contains information on the actual construction workflow with respect to the contractual agreements and states influences and disturbances during the actual construction progress. Furthermore, it is signed by both the contractor and the client, thus being a useful source of evidence to proof delays and justify additional costs. The daily construction report generally includes the date, construction site and project, external conditions like the weather, used resources in terms of employees, machines and sub-contractors, working hours and shifts, downtime and their

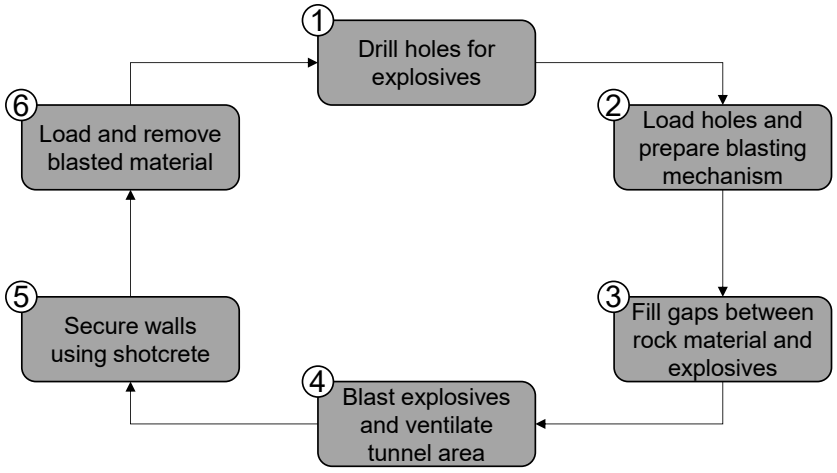

Fig. 2. Drilling and blasting – tunnel construction processes

causes as well as essential activities and completion dates for specific work segments.

The tunneling report in comparison, focuses on specific tunnel-related processes and states the activities and operations in a shift-based report, including employee count, material consumption and machine data. There is no standardised format, for the necessary information content included in the tunneling report, however the cycle diagram is the core part and displays the construction activities on site chronologically over a 24-hour time period. Fig. 3 shows an example cycle diagram, listing the single tunneling activities vertically and their required time horizontally [5].

Apart from the data itself, the documentation procedure is important for the comprehensive understanding of the information chain. The processes are based on an Austrian tunnelling project, however similar techniques apply for most other drilling and blasting sites as well. For the tunneling reports, the foreman of a construction team takes handwritten notes on the ongoing construction activities and uses the breaks between operations to fill out paper templates in the site container. After his shift, the foreman delivers the template to his supervisor who signs the report and transfers the information into separate Excel-sheets for the team hours and support structures. These are then printed out and handed forward as

the hour and support element reports. The construction manager is responsible for checking and filing the tunnelling report, based on which he fills an Excel-sheet to create a daily internal notice stating the overall progress.

The total documentation effort per employee depends largely on the position they hold within the project. For the workers on-site, the foremen spend around one out of eight hours per day on documentation, whereas their supervisors spend two out of ten hours per day for these tasks. The construction managers are required to dedicate around 50 % of their work time to documentation (five out of ten hours per day). Additional effort in offices is required to digitize the tunneling reports, occupying an intern for approximately 50 hours per month [6].

Software

There are several software platforms available for the documentation of a tunneling project. During the Austrian example project, iTWO was used for accounting purposes as well as to manage sub-contractors, to create quantity reports and for an overall project coordination with target-actual comparisons. Besides that, Tunnel:manager was used to digitize the tunnelling reports as the software is able to perform information analyses and to provide estimations on the expected resource consumption. Additional software solutions are used to digitize geological reports, manage personnel data and qualifications and to create project schedules [7].

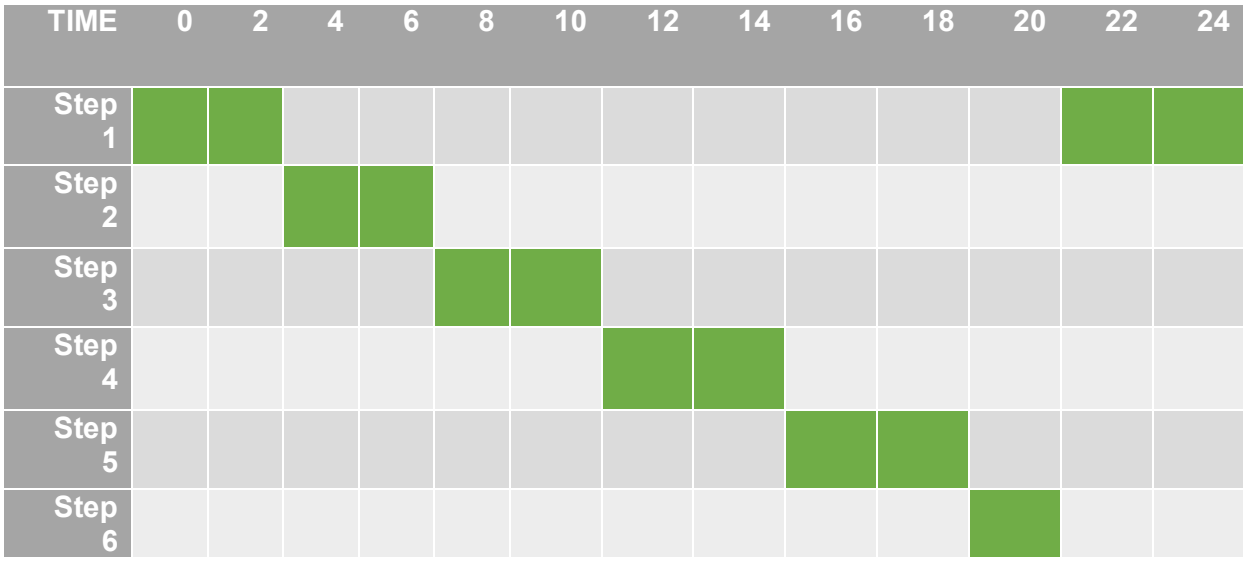

Fig. 3. Tunneling report – Cycle diagram

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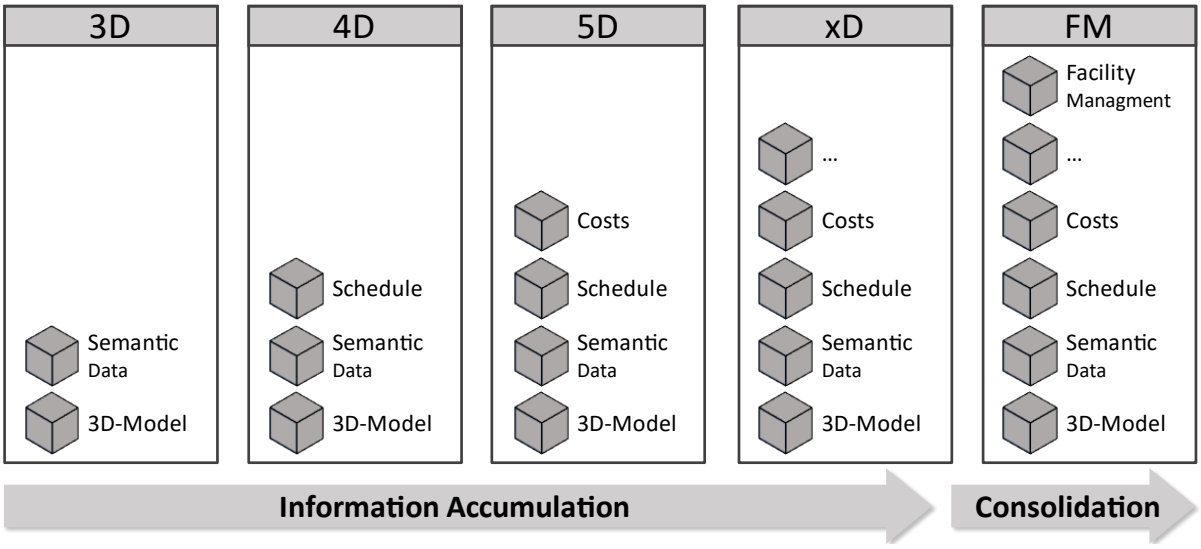

Fig. 4. increasing information depth with multi-dimensional design

Challenges in information processing

Considering the aforementioned chapters, different challenges emerge during the information chain of tunneling projects. These can be assigned to the different project phases of planning, construction and operation and maintenance of the tunnel. These challenges serve as the basis for the proposed solutions developed in the later chapter of this paper.

Planning phase

During the planning phase, numerical simulations of tunneling processes are used to minimize risks and to mitigate hazards. However, the required information is usually only available in a heterogeneous and dispersed form, preventing the application of complex numerical models [8].

Apart from that, the software solutions used for geotechnical finite-element analyses are mostly proprietary and their results are usually not interchangeable between each other. This is due to the use of different file formats (→proprietary software), which makes efficient collaboration increasingly more difficult.

Construction phase

For the documentation during the construction phase, handwritten information is manually transferred into several Excel-sheets multiple times before being digitized in a higher-level system, resulting in a large amount of additional work. These Excel-sheets are prevalent due to their flexibility and ease of use, however they require a manual input and are not part of an integrated higer-level system. Furthermore, the manual data transfer is prone to input errors, illegibility and the loss of handwritten notes places an additional risk.

Operation and maintenance

Eventhough it being a subjective evaluation method, the vast majority of tunnel inspection processes are performed manually. The purpose of inspections, to evaluate the condition of the tunnel, can be conducted using different approaches. Visual inspections are considered as non-destructive methods and the most important ones, as they provide valuable information to a well-trained eye and give preliminary indiciations on the condition of the structure. To document the condition of the tunnel, photo and video documentation is often used during this phase [9].

Regarding future developments however, smart and automated solutions are becoming increasingly important as they influence the lifecycle of the tunnel, allow for an early failure detection and the reaction to unexpected circumstances [10]. Thus, the development of a framework to organize that data and meet the demands of automated solutions is required.

3.2 Building Information Modeling – digital planning method

The aforementioned challenges in the information value chain leave potential for an overall improved tunnel construction planning. Today the best practice is dominated by predominantly analogue information exchange processes between the different stakeholders involved along the value chain. The aim of successful project planning is the intention to fulfil the contractual agreements, to prevent a project cost overrun as well as to meet the agreed-on date of completion. The prerequisite to comply with these demands is that requirements and constraints are successfully formulated in a clear, transparent and comprehensive way in every project phase and for all project parties [11]. This calls for a standardised digital planning approach supporting the whole life cycle of a tunnel construction project. The highest potential for a successful implementation shows the BIM planning approach which is already rather widespread in the building industry but did not breakthrough in tunnelling yet.

Technology description

Against popular public misconception Building Information Modeling is not just the 3D modelling of building geometries but a digital planning method managing and coordinating project information of all stakeholders in the different phases during the whole life cycle of a construction project. The interconnection of three-dimensional geometric data with additional non-geometric data (e.g.: type information, technical properties, costs, etc.) describes the object/building in greater detail (→multi-dimensional design).

The intended goal is to create a holistic and consistent building information model which is accessed and maintained by all project stakeholders to facilitate collaboration and increase the project insight/transparency during all HOAI service phases from design and construction over operation and maintenance to the dismantling of the tunnel.

An overall process optimisation can be achieved because key decisions can be made already during the early planning phases due to the availability of the virtual model and the ability to perform computer-aided testing and simulations [12].

Another characteristic denoting a virtual model compliant to the BIM approach is the automatic modification of the model properties in all dimensions if changed in one dimension [13].

Little/Big BIM and Closed/Open BIM

Characteristics and fluid transitions, as well as current use-cases and the prevalence of digital planning methods, make a more precise classification into different subcategories necessary in order to define Building Information Modeling more comprehensive and precise.

Little/Big BIM – describe the consistency of the BIM application

Little BIM only allows for subject-specific work and for a BIM application only in individual segments during the project execution. The used software solely supports one party, a planning office or a discipline and limits collaboration and exchange (”island solution”).

Big BIM in contrast enables the software application along a continuous and interdisciplinary value chain. All stakeholders involved during the whole life cycle are integrated [14].

Closed/Open BIM - describe the openness/interoperability of the used software

Closed BIM can be described as the proprietary solution. The software environment of only one developer is in use. The interoperability and compatibility to external solutions is limited.

Open BIM allows for a continuous application of different software solutions along the process chain as well as the exchange of data via open interfaces [15].

Model granularity (LoX) – information depth

The project requirements and project progress as well as the stakeholders or specific modelling tasks have an influence on the information depth of the BIM model. Different terms became established

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describing the individual information levels. The nuanced variations available are specified in the following to create a better understanding (the following definitions are according to the DAUB-Working Group):

LoG:Level of Geometry

The LoG describes the geometric detail of a building. DAUB expanded and defined the already existing building level of geometry for the tunnel specific geometrical representation. This categorisation includes four degrees of detail from LoG 100 to LoG 400 visualising tunnel specific activities such as:

- Excavation
- Excavation support (support layer and further support measures)
- Waterproofing
- Inner lining
- Fitting out

LoI: Level of Information

Additional semantic information describes a specific construction element presented in the 3D model in further detail (→information content of an object). These attributes can be calculation formulas or simple geometrical information.

For conventional tunnelling e.g.: structure number, materials, tunnel metre, etc.

LoD:Level of Detail

The Level of Detail is composed of the Level of Geometry and the Level of Information.

LOD: Level of Development

Dependent on the geometry and the object information content as well as the individual planning phase and discipline. With the resulting degree of maturity of the model one is capable to make statements about e.g., collisions with existing buildings and infrastructure or the most economical tunnel alignment.

Big BIM - the desired method of the public sector

The government appears as the most important client/contract authority for the planning and construction of infrastructure projects here in Germany [16]. Therefore, for reasons of market neutrality and competition, it has an increased responsibility for different parties to ensure a fair participation. This calls for the implementation of open platforms and company-neutral interfaces where only the Open BIM approach fully satisfies all these demanded requirements.

The Open BIM standard propagates the two guiding principles of “Data only Once” and “Digital by Default” which must be followed and implemented consistently to successfully modernise tunnel construction processes [17].

Data only Once

Open BIM functions as the basis of a “single source of truth” to build an open and collaborative platform for all stakeholders involved in the value creation chain. Intended is the continuous use of a common digital model during the complete life cycle of a tunnelling project from the beginning.

Digital by Default

This principle asks for the critical evaluation of the currently analogue/paper-based (documentation) processes to ensure a fracture- and loss-free digital supported tunnel construction along the whole life cycle.

Long-term storage/archiving

In the following potential advantages of Open BIM especially in the context of the public sector’s needs as contract authority are further elaborated.

Especially infrastructure projects often require a long planning and construction time. With an aspired service life of the tunnel structure of around 90 to 130 years the access, usability as well as the editing of data must be ensured [18]. Only an open project planning approach can guarantee for these requirements. A proprietary file exchange often breaks compatibility and therefore loses its usability after a short amount of time already.

Monopolies and lock-in effect

The specification of proprietary software during the tendering would lead to a monopoly position of a selected few companies in the long term. Not only to secure an open market and a fair competition but also to facilitate the

market entry for new stakeholders (e.g.: innovative start-ups) an open standard must be pursued. The dependency on only a small number of software companies distorts the market but also leads to a "lock-in" effect (customer dependency on a specific product).

The heterogeneity of the German construction market consisting of predominantly small and medium sized companies as well as the complex and changing requirements for software during every service phase even further underlines the need of open standards and company neutral interfaces along the whole life cycle of a tunnelling project [19].

Industry Foundation Classes (IFC) - open standard exchange format

A tunnel construction project involves a number of different stakeholders using various different software applications during the planning processes and HOAI service phases leading to the need of data transfer in between the stakeholders/software at some point (→interoperability). Two possible paradigms for the data transfer exist:

1.) Exchange by means of proprietary/native format

2.) Exchange by means of an open/neutral format

For the successful implementation of Open BIM the exchange by means of a manufacturer-independent format is an important prerequisite. During recent years Industry Foundation Classes (IFC) internationally emerged as the most popular exchange format for BIM data, due to following reasons:

- Standardised
- Vendor-neutral/manufacturer-independent
- Free-of-charge

IFC can be defined as the schema or specification framework providing general definitions for the exchange of all building information over the entire life cycle of a building project [20]. Since the 1990s the buildingSMART organisation updates and publishes the IFC standard. Part of the organisation are representatives of companies, private persons, academia and politics.

The IFC implementation and standardisation procedure

The IFC standard must keep up with a changing construction industry. The different stakeholders or changing project requirements are the initiator for new definitions and extensions to the standard. The integration in the valid IFC standard follows an internal procedure at buildingSMART first, before being published by different (inter-) national standardisation organisations.

buildingSMART – internal procedure

1. IFC extension project proposal
2. Decision to accept proposal by buildingSMART
3. Development of the IFC extension project:
   - Defining possible application scenarios
   - Implementation proposal of the new data definitions into the overall IFC schema
4. Final integration of IFC extension project by the buildingSMART Model Integration Group (MSG)

→ release with the next IFC version [21]

IFC integration at (inter-)national level

ISO – International Organization for Standardisation

- publishes the work results of the buildingSMART organisation

CEN – Comité Européen de Normalisation

- implements in close cooperation with the ISO the new standards on the European level

DIN – Deutsches Institut für Normung

- represents the German interests at the CEN

VDI – Verein Deutscher Ingenieure

- implements technical regulations at the level of the architectural and engineering offices

These organisations are in close contact with each other to ensure a seamless integration of new standards and to avoid differences and overlaps. The hierarchical organisation starts at the international level of the ISO and ends with the regional implementation at the level of the VDI [22].

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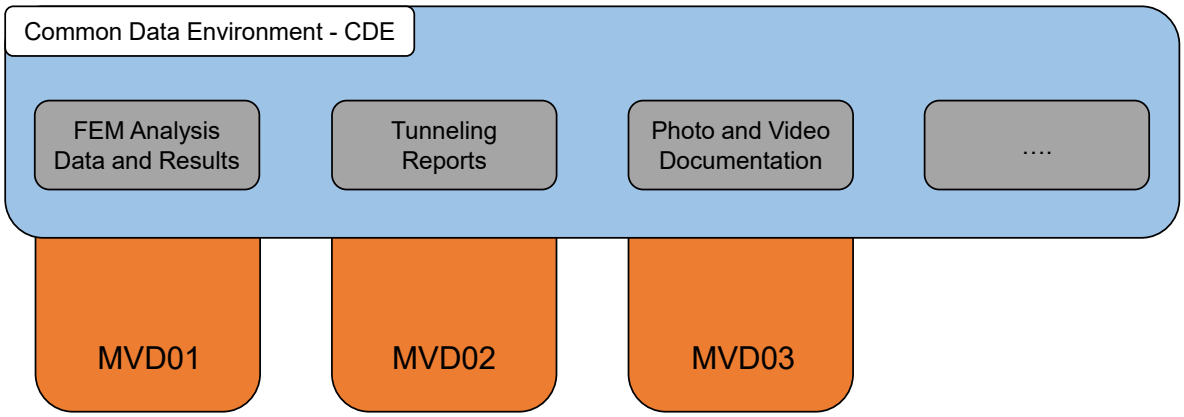

Fig. 5. Common Data Environment (CDE) framework

In addition, a property-set mechanism within the IFC standard defines a procedure for the individual expansion for specific use-cases which cannot be represented by the published standard yet. These subject-specific use-cases get pushed here in Germany especially by a consortium of experts for infrastructure projects proposing extensions for IFC-Bridge, IFC-Road and IFC-Tunnel [23].

IFC file format structure

The IFC exchange format is especially suited to contain and represent four different types of information/data [24]:

- geometry
- representation of relationships between objects and their connection/dependencies
- attributes of an object such as material properties, performance indices or context information
- metadata describing (individual) constraints and documents changes

The following definitions are according to Borrmann Et al. - Building Information Modeling Technology Foundations and Industry Practice [25] and buildingSMART organization [26]:

Class (entity)

Classes define the standard attributes and dependencies of an object. An additional “type definition” can be added to describe objects in further detail.

Property sets

Property Sets contain the attributes for an individual building class component. IfcPropertySet is a container class with grouped properties (IfcProperty). Each attribute has its own name assigned (IfcProperty.Name). It is possible to integrate individual attributes with own Property-Sets.

Model View Definition (MVD)

The Model View Definition (MVD) is a preset to filter the data of a model included when exported with IFC. Different use-cases favour different Model View Definitions. With IFC 4 the MVD “Model Reference View” and “Design Transfer View” were introduced.

The Model Reference View includes only the most important information as the basis for project coordination and quantity estimations, whereas the Design Transfer View is mainly used for editing.

Common Data Environment (CDE)

The Common Data Environment is an essential software tool for the central data and model management. It allows for the storage of project-relevant information of all stakeholders in a common environment (→single source of truth). Individual rights are defined to only allow for the role-based access to information of the different project parties involved [27].

IFC-Tunnel Project – Requirements Analysis Report

For tunnelling, such an IFC-extension project was initiated by a selection of different domain experts in June 2019. The outcome of this project was the publication of a Requirements

Analysis Report (RAR) in November 2020. This first phase lays the basis to define the IFC-Tunnel extension, followed by a detailed description in phase 2. The Requirements Analysis Report defines the general scope of the IFC-Tunnel project, summarises the considered use-cases and provides first descriptions of the semantic and geometric requirements for the structure and elements of tunnels.

At a later stage, the second phase required for the IFC-extension then refines the specification already published in phase 1. Also, the proposed elements and their relationships get described in the Unified Model Language (UML). It serves as the basis for the implementation of a conceptual data model for the technical extension in IFC [28]. The phase 2 was expected to be completed in the end of the year 2021, however until now there was no document published presenting the results (July 2022).

3.3 Additional IFC-schema properties

To yield the most value out of the data that is created throughout the different phases of the project, we propose the use of a common data environment (CDE) as a database to organize the different project data including for example simulation results, construction reports or photo and video documentation. Depending on the specific use-case, this allows to apply data-filters in form of model view definitions (MVDs) to select only the relevant information out of the complete database. Within the IFC-Tunnel Requirements Analysis Report, there is currently only a superficial description of four different MVDs for tunneling based on the main MVDs for IFC4, however a detailed definition of these MVDs is currently missing [29].

For our framework we suggest to add more MVDs, as the currently proposed ones seem to be more general and not specific to single criteria or different phases of the project. Another reason for increasing the number of MVDs is the large amount of overall data, thus being able to reduce the displayed content helps to provide manageable and concise models. Fig. 5 shows the concept of the framework using a common data environment as the database and accessing the specific data using the predefined MVDs.

Planning phase

The introduction of the CDE drastically reduces the problem of dispersed information, as all the relevant data is then included in one database. This allows for a common availability of information between all stakeholders whilst reducing the chances of errors by ensuring that the content is up to date. Thus, different planners have access to the same common data resulting in more

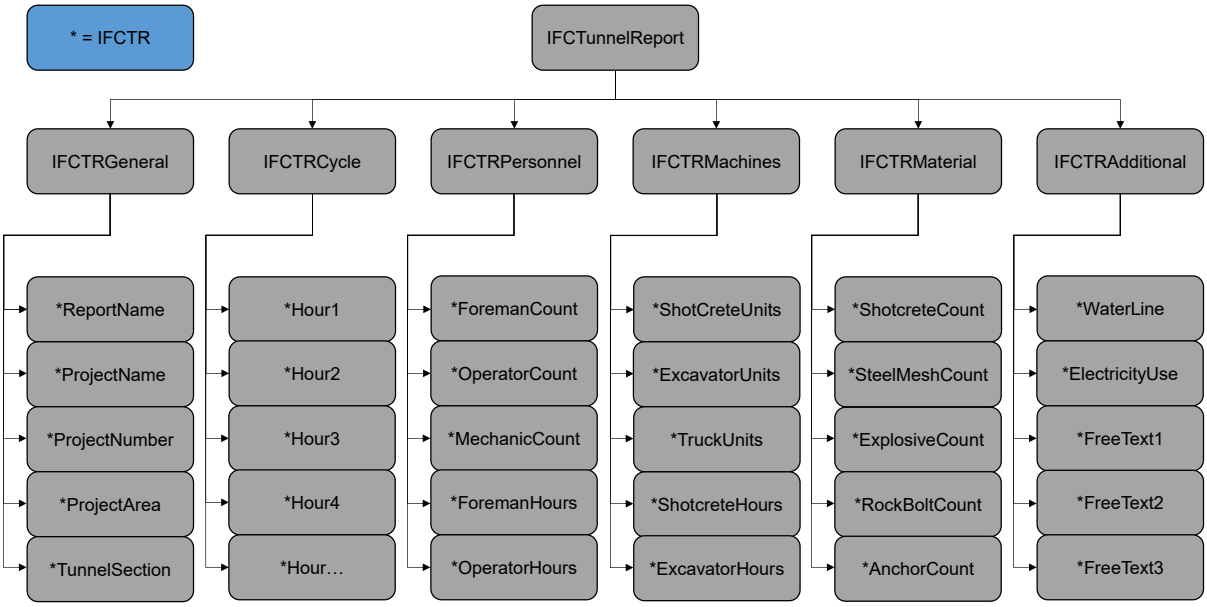

Fig. 6. Common Data Environment (CDE) framework

comparable and accurate simulation results. The most important aspects during planning include the soil conditions and properties, thus adding IFC properties for those can be helpful to improve cooperation during planning.

To share the simulation results via IFC, dedicated property sets are required within the IFC-Tunnel schema. However, these are not available at the moment, which might be another reason why the market leading geotechnical simulation applications like Plaxis3D currently do not offer file exports to the IFC format. As simulation results can include large amounts of data, we suggest to focus on the evaluation of the data results in the beginning, thus stating e.g. if the given soil conditions support the excavation process or if there is a likelihood of failure.

Construction phase

To overcome the challenges of documentation during the construction phase, one important aspect is to reduce the amount of manual data entries and to follow the approach of digital by default. Thus, the tunneling report, as the most important piece of documentation during construction, should be digitized as soon as possible. As there is currently no template for the tunneling report in the IFC schema, we propose to add the properties for the IFC-Tunnel schema. The attributes of the IFCTunnelReport then follow the structure of the general tunneling report, meaning they are categorized into general information, the cycle diagram, personnel ata, machine data, material data and additional information. The naming of the attributes begins with IFC follwed by TR (Tunneling Report), to know that they are associated with the tunneling report. The categories are then further sub-divided to include the required information content for each section. Fig. 6 shows the proposed structure of the IFCTunnelReport property including the different categories.

maintenance approach. Thus, the CDE can be applied to collect the information from the inspections and to transfer the data into IFC models using the MVDs. This concept allows for the creation of inspection models, representing the different parts of the tunnel and their respctive inspection status.

4. Analysis and discussion

Regarding the current developments towards a unified IFC-Tunnel schema, most publications focus on the definition of physical tunnel properties and geometrical information, rather than on the documentation structure. Thus, the documentation aspect is also only slightly considered within the current version of the IFC-Tunnel Requirement Analysis Report (RAR) by buildingSMART. The model view definitions (MVDs) described in the RAR also offer little information about which of the proposed MVDs is suitable for documentation purposes as precise definitions of them are expected in phase 2 of the IFC-Tunnel project.

For the planning phase, the introduction of IFC still demands active development from the software companies to include the IFC properties and support the import and export of IFC files into their software. This could also allow the exchange of information between different software platforms, which due to mostly proprietary software and the use of own file formats is rarely possible at the moment. Without the active support of software companies however, the establishment of IFC can be substantially disturbed and would result in the ongoing use of proprietary file formats with little possibilities to exchange data between software solutions.

There are different aspects that must be considered when trying to digitize on-site documentation material into IFC. For the tunneling report for example, there is no standardised form because the requirements differ between tunneling sites. This makes it difficult to evaluate the most important aspects and develop a unified template for the IFC-Tunnel schema. Further construction sites and their documentation processes need to be observed to evaluate recurring information of high importance and the ways on how that data is captured. Apart from that, the cycle diagram within the tunneling report should offer a graphical representation of the construction processes during the day. As the IFC-schema itself is solely text based however, the value of having a visual representation of the processes is lost if there is no possibility to interpret the information within the software that is used to open the IFC file. Here it is again important that the software companies develop integrations to

display the reports in a graphical representation. Furthermore, especially because the drilling and blasting tunneling is rather traditional and less automated, there is still the aspect on how the documentation can be performed completely automatically to further decrease the risk of error and time consumption.

For the operation and maintenance, current developments are pushing towards more automated solutions. Thus, additional digital data is produced and must be evaluated for the IFC-Tunnel schema. This however results in potential changes for the proposed IFC properties, as digital inspection methods offer different kind of data compared to the traditional and manual inspections. Apart from that, interaction with IFC models on-site can be improved with technological advancements, increasing the usability and being able to change IFC properties on-site.

5. Conclusion

5.1 Summary

Because of the current state of analogue data acquisition and information exchange procedures, the drilling and blasting tunnelling method leaves big potential for improvement during its different phases. For these reasons, susceptibility to errors, inefficiency and an excessive demand for personnel deployment are still prevailing problems, today. With the government being the biggest contractor for infrastructure projects in Germany, the implementation of Open BIM and IFC as an open exchange standard should be pursued, aiming to modernise the drilling and blasting tunnelling method and to improve the collaboration of stakeholders and the interoperability of applied software. Especially the buildingSMART organisation makes great effort to accelerate this development. With the publication of the Requirements Analysis Report (RAR) they laid the foundation for the implementation of an IFC-Tunnel standard.

Based on a Common Data Environment (CDE) to organize the different project data, this paper proposed different requirements for the IFC-Tunnel schema to provide the stakeholders with manageable and concise models during the planning, construction and operation and maintenance phase of a tunnel project. However due to the individuality of tunnelling sites and special requirements, as well as missing standardisations for documentation processes and material, like the tunnelling report, defining relevant properties for the IFC-Tunnel schema is a complex undertaking. Furthermore, new developments regarding the automated inspection of tunnel elements cause changes in the documentation procedure and require new digital frameworks to evaluate the additional information.

5.2 Outlook

Apart from the development of IFC properties and Model View Definitions (MVD) to display the specific information content in a condensed way, the additional need to improve the data acquisition and processing on-site became apparent. For that, solutions to automatically create reports could be further researched, especially from the point of view of an increasing machine autonomy.

For the report content however, standardised formats are important to offer effective and efficient solutions for any tunnelling site. Thus, further tunnelling projects should be investigated and researched to elaborate the most important aspects to include in the standardised forms like the tunnelling or the inspection reports.

As the buildingSMART organisation is currently developing the basic framework for the IFC-Tunnel schema focusing on the geometric representations, in-depth requirements for the documentation structure are still to come. Therefore, the proposal for the additional properties is a potential subject to change depending on the developments of the overall IFC-Tunnel schema.

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