Construction & Robotics

RESEARCH DRIVEN PROJECT VOL. 4

Research Paper / WS 2022

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Funded by BLE Seed Fund of Faculty 2 - Grant of RWTH Aachen University

The content of the book was created for teaching purposes as part of the Research Driven Projects course.

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First published 2024

Available via the institutional repository of RWTH Aachen University:
DOI: 10.18154/RWTH-2023-08854

Preface

The following book shows the results of the Research Driven Project of the C&R master students of the winter term 2022. The results are based on research, market analysis and own developments that were realized during the semester.

A special feature this year was the visit to BAUMA 2022 (see Fig 1.). During this excursion, the students were able to see developments in automation and digitalization of various construction machines first hand. We would like to thank all the companies that welcomed the students, showed them their developments and answered all their questions.

The results of the semester show the impact of that experience. Students have explored a wide range of topics and have researched about how the future of construction might look like. Topics range from methods of comprehensive information exchange to the potential analysis of water leak detection, analysis of 3D concrete printing processes, and the automation energy potential of smart home devices. To this end, the students have developed prototypes and demonstrators for testing and analysing their concepts. The following articles summarise their work in order to share their experiences and results with future students.

Fig 1.: Group photo at the BAUMA 2022

We would like to thank all the students who took part in the Research Driven Project in the winter term of 2022 and contributed their results to the fourth book of the Research Driven Project.

Aachen, 09. April 2024

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Contents

Research Paper

Jaime Romero and Miguel Gutiérrez

Analysis of information exchange between structural design and Revit using IFC

Abstract

The construction industry faces difficulties in transferring information between different software. Engineers and architects use specialized software, but sharing their progress is challenging due to exchange file format issues. BIM (Building Information Modeling) relies on the Industry Foundation Classes (IFC) as the primary format for information transfer, but it suffers from information loss during exchange.

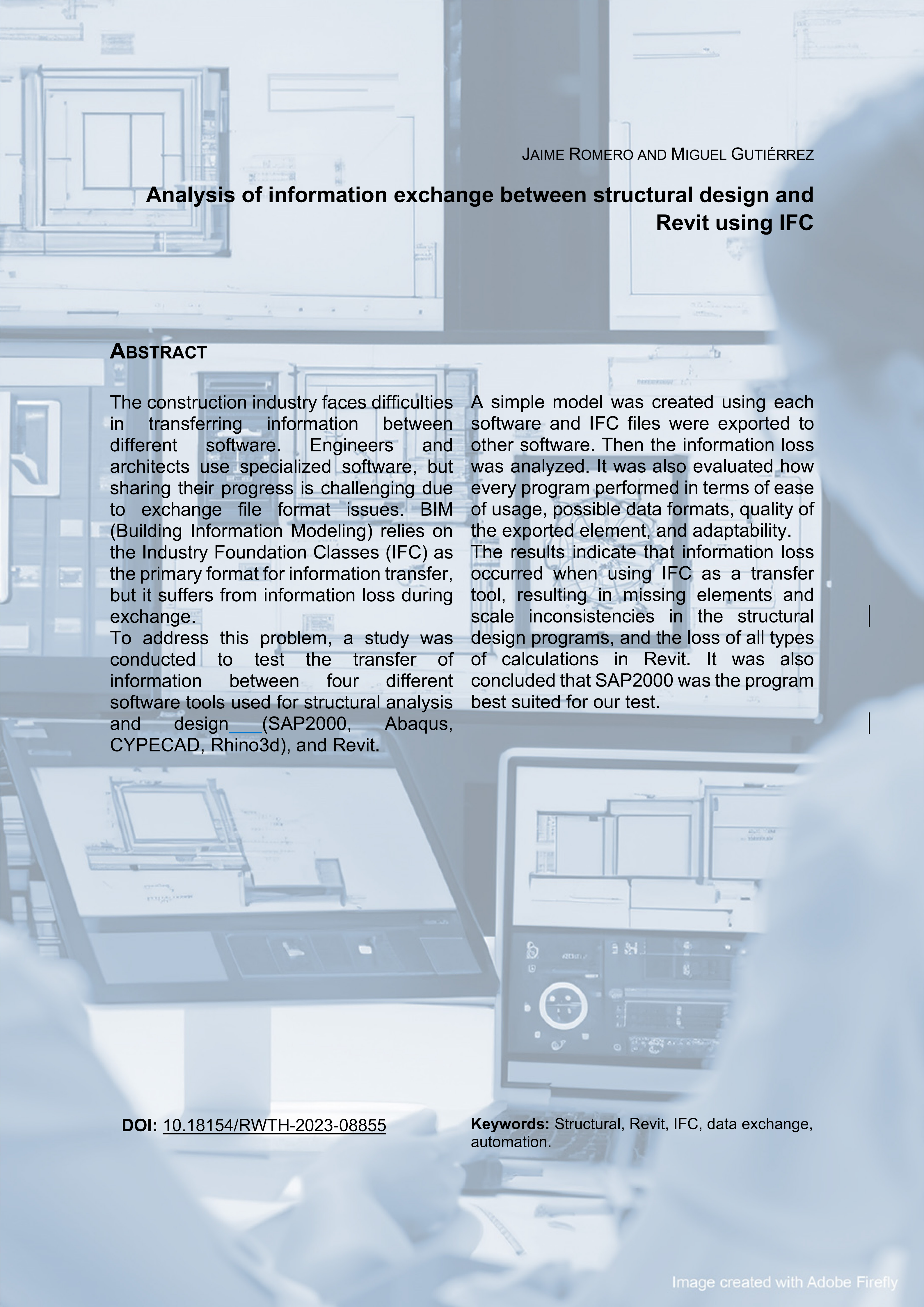
To address this problem, a study was conducted to test the transfer of information between four different software tools used for structural analysis and design (SAP2000, Abaqus, CYPECAD, Rhino3d), and Revit.

A simple model was created using each software and IFC files were exported to other software. Then the information loss was analyzed. It was also evaluated how every program performed in terms of ease of usage, possible data formats, quality of the exported element, and adaptability.

The results indicate that information loss occurred when using IFC as a transfer tool, resulting in missing elements and scale inconsistencies in the structural design programs, and the loss of all types of calculations in Revit. It was also concluded that SAP2000 was the program best suited for our test.

DOI: 10.18154/RWTH-2023-08855

Keywords: Structural, Revit, IFC, data exchange, automation.



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1 Introduction

Professionals and researchers in the construction industry recognized that one of the primary challenges facing this field is the automation of processes. A construction project typically comprises distinct phases, including planning, manufacturing, assembly, and operation. In this particular paper, we will concentrate our efforts on the planning and design phase. This phase involves various disciplines, such as architectural and structural design, and our research paper primarily focuses on the exchange of information between these two fields.

Architects and structural engineers, both use a variety of software to make their designs and calculations. There are several software manufacturers that offer their own products, and each one of these products brings its own specifications. Usually, this implies that every software uses its own file format. At the moment, at which this research paper is being written, the standard information exchange format file is IFC. Industry foundation classes (IFC) is the main file format used in the construction industry in particular in Building information modeling (BIM) programs such as Revit [1]. An IFC file will contain information related to the building model, such as spatial elements, materials, and shapes [2][3]. This format has the advantage that it is a neutral platform, it can be opened in any BIM software [4].

Within the overarching goal of streamlining the information exchange processes between structural design and architectural software within a BIM framework [5], architectural software solutions have evolved to incorporate modules for assigning crucial structural characteristics, such as loads and boundary conditions. This holds the potential to significantly expedite the design process if data exchange can be relied upon. In an ideal scenario, an IFC file could serve as a comprehensive starting point for structural design, with just a designer's validation needed. Likewise, achieving seamless and dependable geometry exchange between

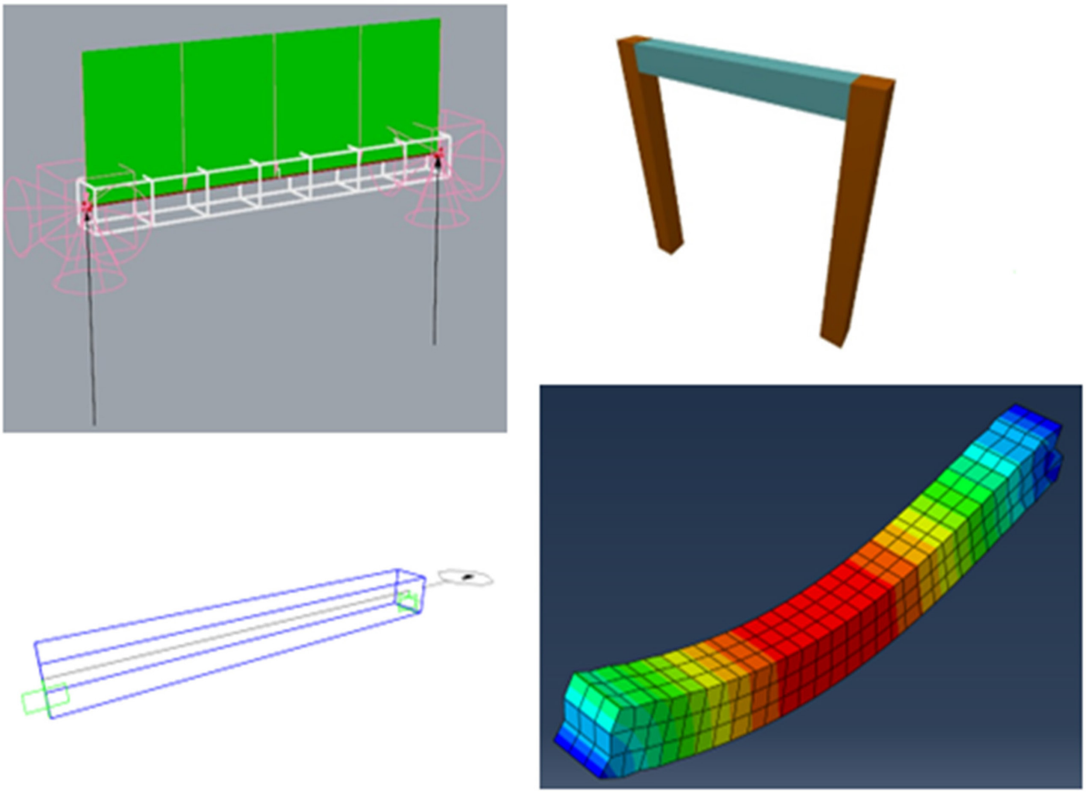

Fig. 1. Sample 3D models (from left to right Rhino3d, CYPECAD, SAP2000, Abaqus).

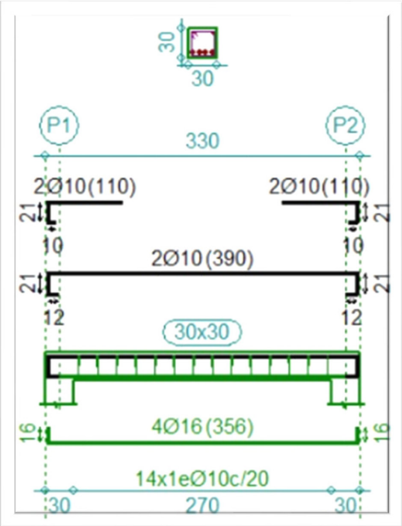

Fig. 2. Reinforcements on CYPECAD.

software like Revit and structural design tools is paramount for facilitating efficient design adjustments and reiterations. This synergy not only accelerates workflows but also ensures a higher level of accuracy and consistency, ultimately contributing to the creation of safe and efficient structures in the realm of modern construction.

1.1 Existing solutions

Robot Structural Analysis Professional is structural load analysis software that can be integrated with Revit, allowing data exchange between both programs [6]. The data transfer is made using the Autodesk desktop app and the common file format between both programs is SMXX. This format type is specific to Autodesk products and especially to Revit. With robot structural IFC file format could be avoided. This could mean that information between Revit and the structural design program is not lost, but we will not test this in this paper.

Another important trend solution is the utilization of IFCopenshell, an open-source software library designed for the manipulation of IFC files according to the specific requirements of structural software [7] . This approach involves the development of code to configure the IFC file, ensuring that the resulting exchange file is perfectly legible and compatible with both architectural and structural software. IFCopenshell presents a promising pathway toward achieving reliable data exchange, streamlining the collaborative design process, and fostering a more efficient and error-free construction industry.

2 Methodology

We conducted interviews with two professionals in the construction industry. One of the interviewees was a civil engineer who utilizes structural design software, while the other was an expert in charge of drafting plans using Revit. Both professionals shared their feedback, stating that when they receive an IFC file from another program, there is

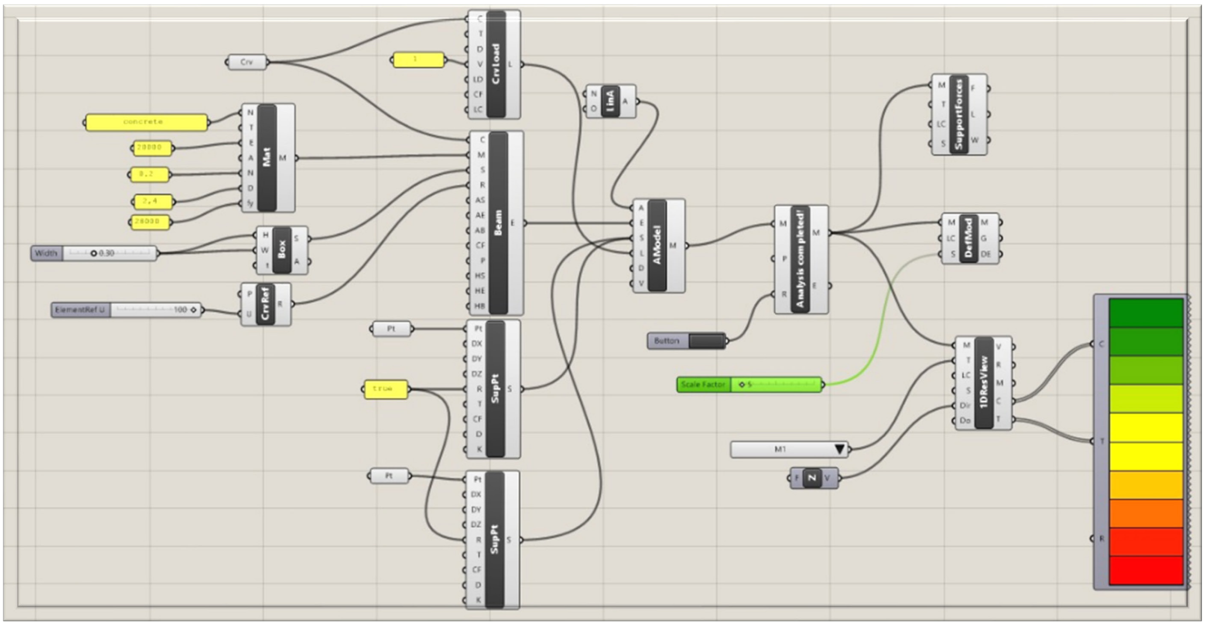

Fig. 3. Grasshopper script.

often a loss of information, and it is more efficient to recreate the design from scratch. As a result, we decided to create a sample model on four different structural design programs (CYPECAD, Abaqus, SAP2000, and Rhino3D) and on Revit, and then export each model using the IFC file format. Next, we tested the ability to open the models created on a structural design program in Revit and vice versa. The interviews also allow us to have an idea to what the obtained results will look like. This will allow us to see if the loss of information is made by the exchange or by a misuse of the software.

2.1 Sample

We decided to create a uniform sample model in each program, taking into consideration any limitations each program might have. Our goal was to make each model as similar as possible. The agreed-upon sample model consisted of a 3-meter-long beam embedded at both ends, with a cross-section of 30 by 30 cm and a uniform load of 1 kN/m distributed along its length. If feasible, we aimed to add reinforcement of four 16 mm bars and 10mm stirrups spaced 20mm apart.

2.2 CYPECAD

CYPECAD is a structural design software widely used in the construction industry, particularly in Spain and Latin America [8]. For the purpose of our theoretical analysis, CYPECAD presented some limitations. The program requires the creation of at least two floors and must adhere to the laws and regulations of a specific country. In our case, we added two columns and placed the 30 by 30 cm beam between them, ensuring that the model adhered to Spanish regulations.
Once the model is completed, CYPECAD calculates the reinforcements needed. We changed them so they are closer to how we defined the model. We then exported the model into IFC format to be opened in Revit. Exporting in CYPECAD can be done easily and it even asks for the IFC version.

2.3 Rhino3D

Rhino3d is a 3D modeling software and grasshopper is visual programing tool that allows us to interact with the 3D model. Usually is not used for structural design, although it is commonly used for parametric design [9][10][11]. We can use plugins in grasshopper to add this functionality. For our test we used a plugin called kiwi3D for the structural calculations. Using Rhino3D, we decided to not add any reinforcements as this will overcomplicate the code. Once the script was done, we used another plugin called “BIM GEOMGYM IFC”, which allows to import and export IFC files.

2.4 SAP2000

SAP2000 is a comprehensive structural analysis and design software developed by Computers and Structures, Inc. (CSI). It is widely used in the construction industry, particularly in the United States, where it is recognized as one of the leading tools for building design. The software is well suited for the building industry because it makes it easy to model structures and perform various types of analysis.
One of the key features of SAP2000 is its user-friendly interface, which makes it accessible to engineers and designers with varying levels of experience. To use the software, you first define the materials and cross sections for your structure. Then you can create a grid and draw elements, such as beams and columns, that make up your structure. The next step is to set boundary conditions and loads, such as wind, earthquake, and gravity loads, that will act on your structure. Finally, you can perform the calculation to determine the response of your structure to the applied loads.

2.5 Abaqus

Abaqus is a finite analysis program used for composite elements and 3D printing elements. This program is rarely use in the construction industry and is the only one without any type of IFC support. For the modeling process in Abaqus is necessary to follow different steps because this software works through a special flow in which you have to define multiples environments for

Property	Rhino/ Grasshopper	ABAQUS	SAP2000	CYPECAD	Revit
Geometry	✓	Partial	✓	✓	✓
Material	x	x	x	x	x
Load	x	x	x	x	x
Boundary conditions	x	x	x	x	x
Reinforcement	x	x	x	x	x

Table 1. Quality of exported element per software.

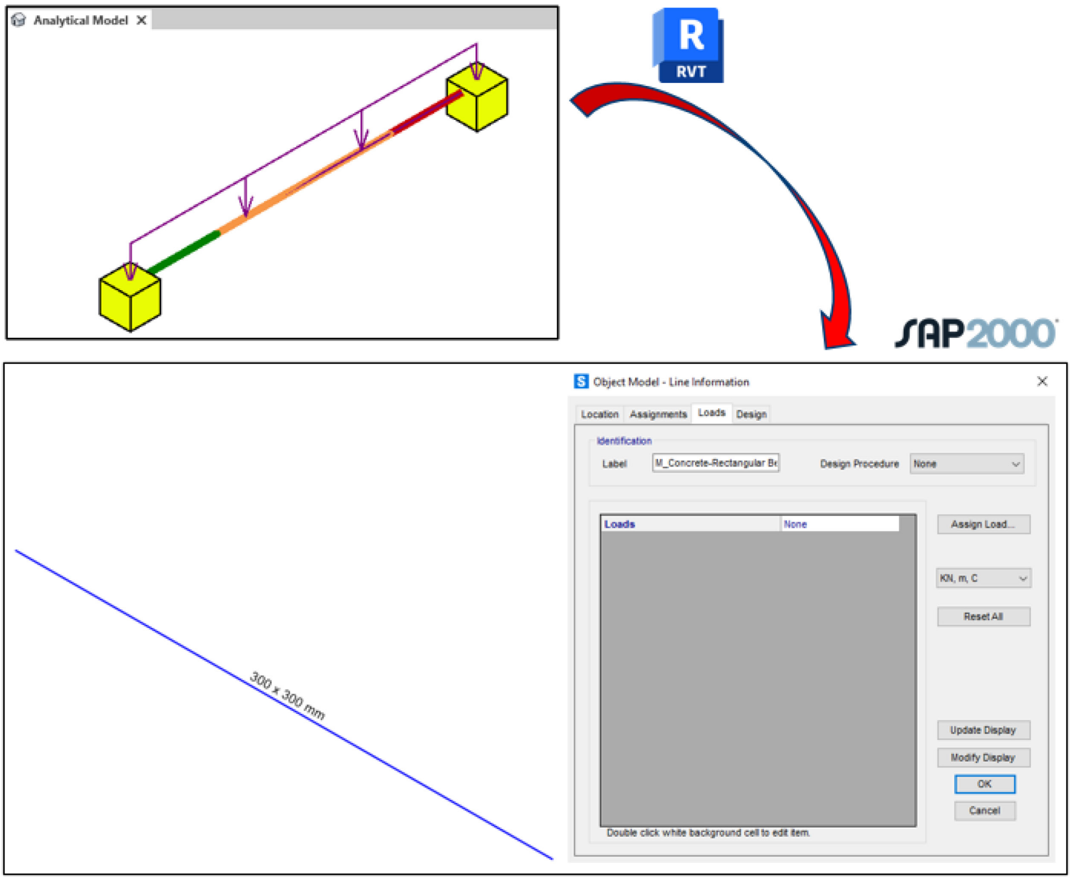

Fig. 4. Exported element from Revit to SAP2000.

each necessary components of the model. The model made in Abaqus follows the sample conditions. Abaqus does not support IFC file format, either for import or export. In order to enable exportation to Revit, the Abaqus file was accessed through Autodesk Fusion360, and underwent a conversion process to a format compatible with Revit.

2.6 Revit

Revit is Building Information Modelling (BIM) program used in the construction industry all around the world. One of the main advantages of Revit is the use of elements parametric families, which allows to make changes and updates on the project with efficiency. Once we use IFC to import and export from Revit, we will check two things: do the elements obtained in Revit belong to a parametric family? do the resulting model in the software have the characteristics defined in Revit?

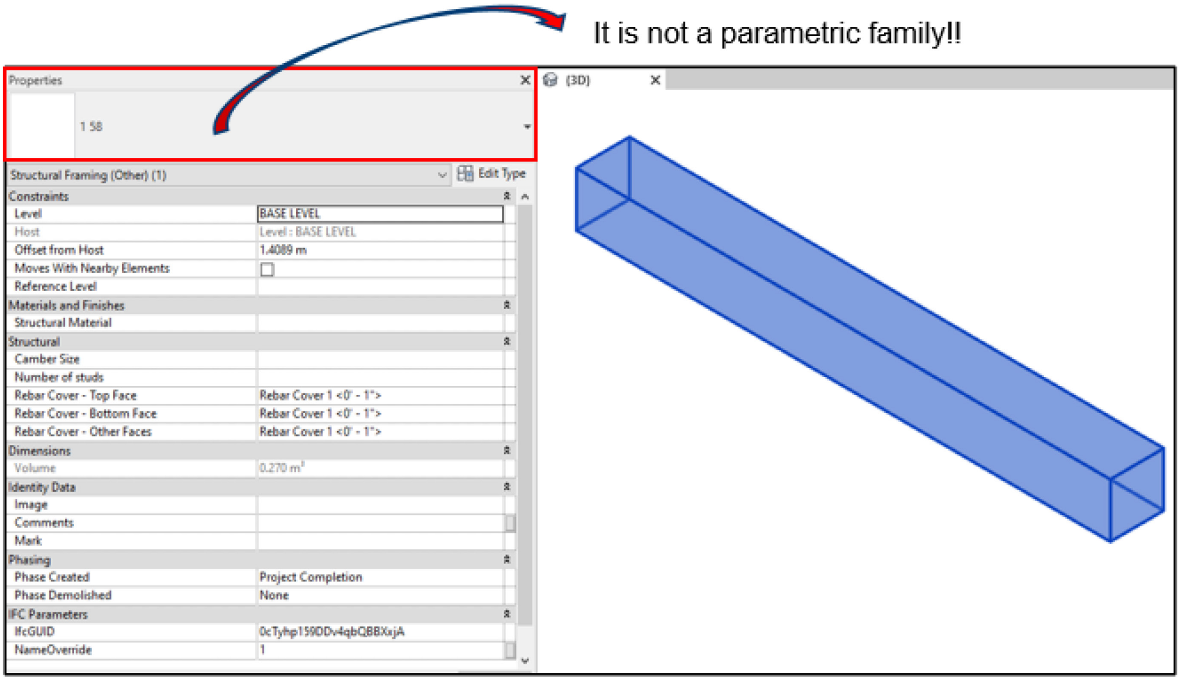

Fig. 5. Exported element from CYPECAD to Revit.

3 Results

From the previously described methodology, different qualitative and quantitative results were obtained. To analyze these results a valuation matrix was created, to allow a more objective evaluation of the findings. Four evaluation criteria were defined: usage (complexity of the exchange process), possible data formats (handling IFC format or another common format), quality of the exported element (accuracy of the process), and adaptability (plugins offer or another tool that allows the exchange). Each item received a different importance percentage according to its relevance for the overall exchange process.

3.1 Matrix components

The quality of the exported element was defined as the most important criterion for the evaluation matrix, analyzing the properties of the element that was obtained at the end of the import process in both Revit and design programs. The properties analyzed were: geometry, material, load, boundary conditions, and reinforcement.
Analyzing the elements obtained in Revit, it was possible to establish that there is an important loss of information. Of the parameters defined in table 1, the only one that managed to be efficiently transported was the geometry. In this case, the length of the beam and its cross-section were correctly identified and assigned by Revit. In all other cases, the defined properties were lost.
Figure 4 shows the result of exporting the element defined in Revit to the structural design software SAP2000 using the IFC exchange format. It can be seen in the software image that the element has the correct geometry but has no load assigned. Also, the boundary conditions, the reinforcement, and the material defined in Revit are lost during the process.

Figure 5 displays the subsequent workflow: a structural component made in CYPECAD and conveyed as an IFC file to Revit. The outcome produced in Revit is an element where solely the geometry matches the CYPECAD definition. Furthermore, Revit automatically designates a family referred to as "1 58", resulting in a reduction in the worth of the imported object [12].
The default family assigned by Revit is hard to parameterize, which decreases the value of the sample and the overall exchange procedure. In summary, one of Revit's advantages as a tool for constructing models and blueprints is the utilization of parameterizable families, which gets

compromised during the exchange process. The export and import capability using various file types was the second most important criterion established. In this aspect, besides the number of formats, their validity and relatively common use within the construction industry were taken into account. For instance, the Rhino/Grasshopper software enables users to work with a significantly large number of file types. However, it should be noted these programs are utilized in a wide range of applications, so not all of these options are pertinent to the present investigation.
Finally, two more standards were defined for the matrix, the usage and the adaptability of the programs. The first is purely subjective and was evaluated based on our experience as users during the investigation. Table 3 shows the resulting matrix, where it is evident that the only program with an outstanding rating on this topic was SAP2000, due to its practicality when importing. For the other applications, considerably more search time was spent in completing the task. It is important to measure this software management procedure since automation and reproducibility of processes within the world of construction and design are very essential.
Adaptability tries to measure the trend of manufacturers to connect its product with the BIM technology, Revit in this case. Along with the development of the research were found different tools that evidence or not that tendency. For Rhino were found several plugins which accomplish the task, also for SAP2000 a special complement for Revit came into the picture. CYPECAD has a tool that allows checking updates in the model you are working on but not something for the exchange process. In the last position, Abaqus got the worst value here because it was not identified anything for the software. he results show parity between the qualification obtained for Rhino, CYPECAD, and SAP2000, the latter being the one that achieved the best percentage. Contrary to the above, it is established that ABAQUS obtained the worst rating, being isolated from the others.
Considering the criteria employed to evaluate the programs, it was determined that the usage, availability of formats, and quality of exported elements showed consistent results. Out of these attributes, three software

Software	Export	Import
Rhino/Grasshopper	3DM, 3DS, 3MF, SAT, AI, AMF, DWG, DXF, DAE, CD, X, EMF, GF, PM, KMZ, GTS, IGS, IWO, UDO, FBX, OBJ, CSV, X_T, PDF, PLY, TXT, POV, RAW, RIB, SVG, SKP, SLC, STP, STEP, STL, VDA, WRL, VRML, GDF, WMF, X3DV, XAML, XGL, ZPR, IFC(PLUGIN).	3DM, RWS, 3DS, 3MF, AI, AMF, DWG, DXF, X, E57, DST, EXP, EPS, OFF, GF, GFT, GH, GHX, GTS, IFC, IFCZIP, IGS, IGES, IWO, GGN, FBX, SCN, OBJ, IV, PDF.PLY.ASC.CSV.TXT.XYZ.CGO_ASCII, CGO, ASCI, PTS, RAW, M, SVG, SKP, SLC, SLDPRT, SLDASM, STP, STEP, STL, VDA, WRL, VRML, GDF, ZPR.
ABAQUS	SAT, IGS, STP, WRL, WRZ, 3DXML, OBJ.	SAT, IGS, IGES, STEP, STP, DXF, SLDPRT, SLDASM.
SAP2000	XML, STEP, IFC, IGS, DAT, EXR, MDB, S2K, F2K, DXF, FWP, SSI.	XML, STEP, IFC, IGS, DAT, EXR, MDB, S2K, DXF, FWP.
CYPECAD	4, IFC2X3, C3E, DXF, DWG.	XML, STEP, IFC, IGS, DAT, EXR, MDB, S2K, DXF, FWP.
REVIT	DWG, DXF, DGN, SAT, STL, PDF, FBX, GBXML, IFC.	IFC, IFCXML, IFCZIP.

Table 2. Possible data formats per software.

Criteria	Rhino/ Grasshopper	ABAQUS	SAP2000	CYPECAD
Usage (15%)	2	2	4	2
Possible data formats (25%)	4.5	3	4	4
Quality of the exported element (50%)	3	1	3	3
Adaptability (20%)	5	2	4	3
Result	3.43	1.75	3.50	3.10

Table 3. Evaluation matrix.

received the same or pretty similar score, with only one deviation in each case. On the other hand, the adaptability component showed the highest level of variation, with each program receiving a unique rating. This can be seen in the accompanying graph.

4 Discussion

The research question was properly answered: although today IFC is the most common format to exchange models between the structural and the architectural disciplines it is clear exists inefficiency in the process. In this chapter, we are going to discuss the reasons for this response.

4.1 Improvement opportunities

Improving the workflow between structural design software and Revit (BIM) presents a significant opportunity. Our research highlights that the current process results in a significant loss of information, indicating its inefficiency. This loss is particularly concerning given that only the geometry is transferred, and the parametric family properties that add value in Revit are missing. These findings prompt an important question: is it worthwhile to engage in this exchange process when most of the information will be lost? To shed light on this, we conducted interviews with professionals, including the structural engineer and the BIM modeler. Our interviews revealed that the current process using IFC is limited to geometry, consistent with our research. Additionally, the methodology is highly inefficient, and the process is primarily used to import information from other disciplines for interference checking and reference. This highlights a clear lack of automation, as the information acquired through this process cannot be used as a starting point for modeling.

In this same sense, the possibilities of automation that are seen by us, as well as by our interviewees, are great. The advantages offered an efficient flow of information between the parties would have is attractive, we must not lose sight of the fact that depending on the size of the project, the information flows in both directions can be overwhelming. A small change, the need for alternatives, and unforeseen conditions are some of the reasons why an appropriate flow of data would mean considerable savings in work that translates into time and money.

It is important to emphasize that it is not about eliminating necessary processes, nor about a single professional being in charge of managing all the software ignoring all the knowledge that is required to make use of this type of specialized tools. It is clear that engineers and architects specialized in their disciplines are needed to use wisely the programs, however, the professionals consulted, as well as ourselves as engineers who have made use of these tools, identified the need to work on the efficient exchange of information that allows optimizing workflow. As mentioned in the results obtained for the adaptability criterion, it can be interpreted as a sign that companies are seeking to automate the flow of data between disciplines with the development of plugins. Although some of these add-ons were tested, there are limitations, such as the need for additional payments to have them. In this same sense, versions, and configurations must be consistent in order to make correct use of

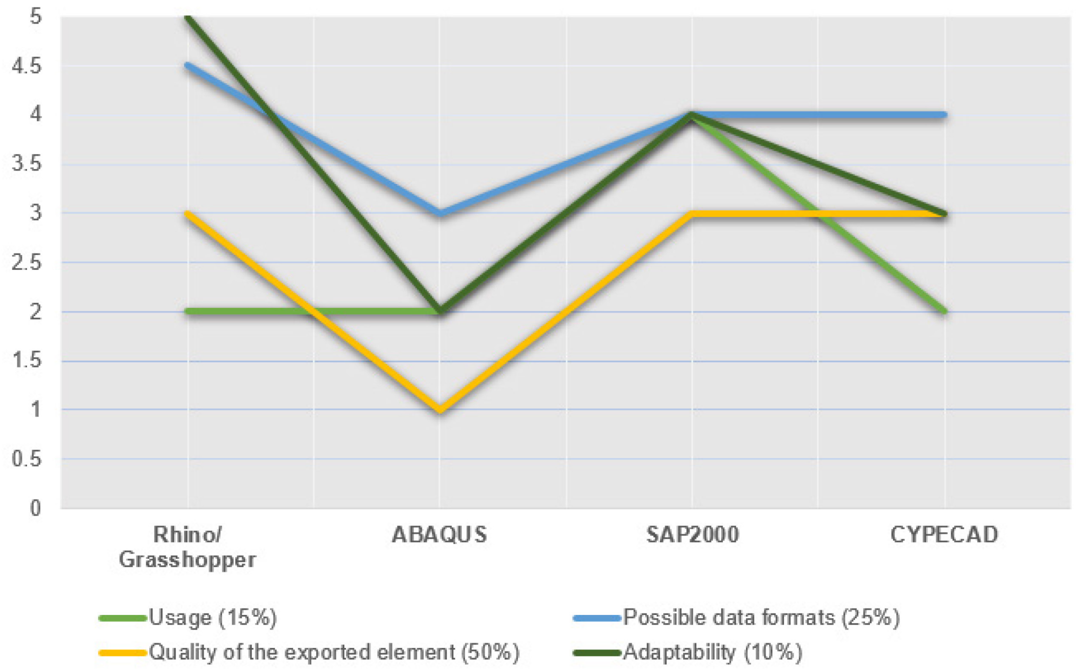

Fig. 6. Variability of indicators per software.

these specific exchange formats. The results suggest a wide scope for improvement in the field, and the companies are currently pursuing this path. As it was commented at the beginning of the document, the potential for improvement in the design flow between software from the same vendor, such as Robot Structural and Revit, suggests that similar investigations could be conducted to explore the exchange format used there. This concept could be expanded to solve the issues found with the IFC format.

4.2 Software results

ABAQUS obtained the worst rating according to the parameters established in this research, which means that in terms of examining the ease and tendency of the analyzed software to interact with Revit, it was not efficient. This may rely on the basis that it is software for Finite Element Method analysis, and its use is not for specific building design and construction purposes but more for investigation and detailed estimation of particular elements.
Consistent with the results obtained for Abaqus, it can be said in general terms that SAP2000 and CYPECAD performed well, being programs specialized in the structural design of buildings, where the exchange of models with the architectural branch is done regularly.
Finally, rhino/grasshopper presented a surprising performance. It is well known that these powerful tools have gained acceptance as software to automate processes within engineering, due to the ease of visual programming and adaptability to different fields. Thus, our results direct us in that sense, since despite not being a software specialized in structural design, it performed at the same level as the others.

5 Conclusion

After conducting extensive tests with specialized structural design software such as CYPECAD and SAP2000, alongside the utilization of the 3D modeling software Rhino3D, our findings underscore a significant challenge in the current state of information exchange within the construction industry. Despite our best efforts, our experiments demonstrated that we could only successfully transfer the geometric aspects of structures between these software platforms. Particularly, when attempting to transfer data from ABAQUS, a less common yet specialized analysis program in the construction field, to Revit, the limitations of the existing exchange processes became all the more evident.

The predominant use of the Industry Foundation Classes (IFC) file format for information sharing revealed its inherent constraint - it primarily handles geometry data, leaving critical structural and design information underutilized. This realization shows us the pressing need for substantial improvements in the data exchange process within the construction industry.
Enhancements in the IFC file format or the creation of more robust and standardized data sharing methodologies are essential to ensure that all pertinent information, beyond mere geometry, can be effectively and reliably communicated between software platforms. Addressing these challenges head-on promises to streamline construction projects, leading to increased efficiency and productivity in an industry where precision and collaboration are paramount.

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Camilo Bedoya Cadavid and Rodrigo Javier Magán Valencia

Analysis of water leak detection techniques and feasibility to implement in Latin American countries

Abstract

Water scarcity as well as the difficult access to drinking water has become a worldwide problem, even in the countries with the largest reserves of this resource, such as Latin America. Not only because water sources are declining, but also because of the poor management and waste due to poor infrastructure less and less people are having access to drinking water. This paper focuses on the research and analysis of the techniques used in more advanced countries for the water leakage detection and to what extend could these be applied in Latin American countries. First, current technologies and techniques were investigated, then these were divided into two categories according to their technological degree: Low-Tech- and High-Tech-Techniques. Subsequently, two case studies were presented and used to evaluate the possible application of these Techniques in two different scenarios. On the one hand a rural environment and on the other an urban environment. With the help of a decision matrix and seven carefully chosen criteria, the proposed techniques were rated and scored, being Ground Penetrating Radar – GPR the solution which best suited to both situations while fiber optic sensors and pressure monitoring systems being the least suitable for the urban as well as the rural environment respectively. It was concluded that there is no absolute perfect solution for the water leakage detection, hence this matter could be approached from several perspectives and different solutions could be used at a time.

DOI: 10.18154/RWTH-2023-08856

Keywords: Water Leakage, low-income Techniques, high-income Techniques, Latin America, Detection.

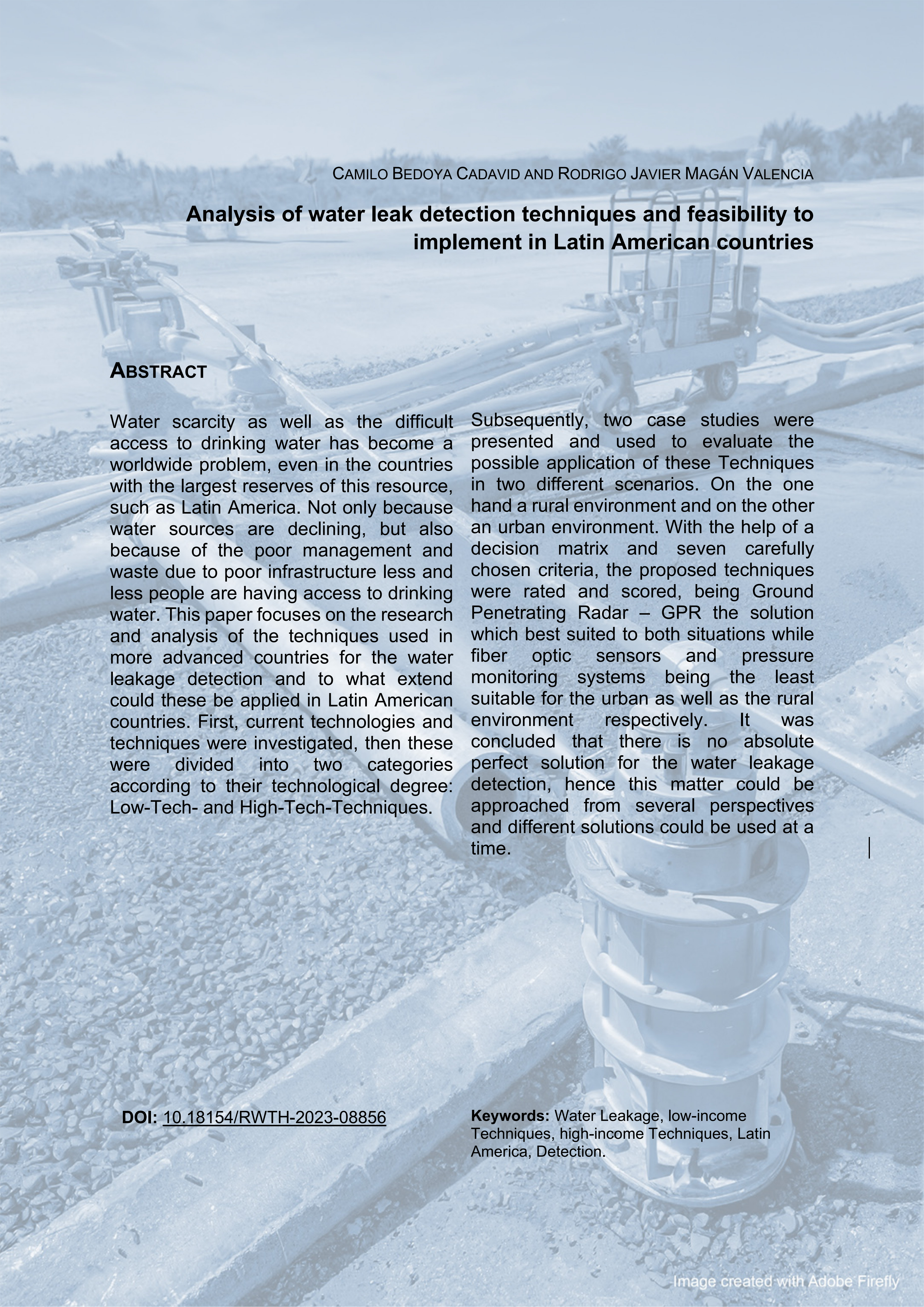

Image created with Adobe Firefly

1 Introduction

1.1 Motivation

“Latin America is the region with the most water sources in the world, however there are 36 million people - 6 times the total population of Nicaragua – who still lack access to drinking water.” [1]

Over time, people have become more aware of the importance of water globally. Water is one of the most abundant natural resources which, at the same time, is one of the most difficult to access [1]. Even Latin American countries, thus being the region with the most water sources, are being compromised by water scarcity. There are many reasons why the access to drinking water is being affected, from global warming to lack of maintenance of piping water networks in the cities.

In this Research Paper we will focus on the second reason. Despite having plenty of drinking water sources in the region, people are unable to access this "benefit". One of the reasons why water does not reach all the people in Latin America are water leaks. For instance, Peru is the 8th country with more water sources worldwide what is more they have 1.89% of the world's drinking water. However, approximately 8 million people do not have access to this resource. This is because 70% of pumped water is lost due to leaks [2].

Yet, this type of problem does not only exist in Latin American or third world countries, but also in more developed countries such as the United States or other countries in Europe. In the United States about 10,000 gallons of water per year are wasted in homes due to water leaks and at a national level it would be equivalent to 1 trillion gallons per year. This amount could be used to supply 11 million homes [3]. On the other hand, on the European continent, countries such as Italy and Croatia are also affected, with losses of 39%, 18% and 80% respectively [4]. While these numbers are not encouraging, there are other countries that have managed to keep their statistics at more optimistic levels, such as Germany with only 5.3% or Denmark with 7.6% [4].

The worrying situation in Latin America together with the encouraging figures from some European countries motivated the authors to investigate what technologies currently exist to prevent, detect, and solve water leaks; as well as which of these technologies can be applied in “low-income countries”. These technologies will be analyzed and evaluated in two possible scenarios: on the rural and on the urban area.

1.2 Methodology

The research question that guided the present paper was: How does “low-tech solutions and “high-tech solutions” in the water leak detection industry compare for rural and urban environments in Latin America. To address this question the research began with the collection of the different technologies and techniques to detect water leakage available in the market and the context of the problem across the globe. Subsequently these techniques were classified into the corresponding category: “low tech technique” or “high tech technique”. To analyze the impact of these techniques the researchers propose two cases of study: a rural environment and an urban environment. After that each technique was punctuated

Techniques	**Criteria 1**		**Criteria 2**		…		**Result**	
Case of Study	**Rural Env.**	**Urban Env.**	**Rural Env.**	**Urban Env.**	…	…	**Rural Env.**	**Urban Env.**
Solution 1	1-3	1-3	1-3	1-3	…	…	1-21	1-21

Table 1. Proposed Decision Matrix

according to its performance in each of the study cases. Finally for the discussion a decision Matrix with seven criteria was created to provide an easy visualization on how suitable each technique is.

2 State of the Art

Early detection of water leaks is crucial for addressing the issue and being able to repair and maintain the water distribution network on a reliable state. Currently there are numerous water leak detection techniques in the market some make use of latest technology advancements such as artificial intelligence, fiber optic or radars and some rely on existing infrastructure such as water meters and pressure sensors. In the following section these techniques will be described to provide a foundation for the subsequent comparison

2.1 Low-Tech Technologies

Pressure Monitoring Systems

The most common sensors to monitor water systems are pressure sensors, these calculate the water pressure and its variations over time in case of a drop down in the pressure. It is known that high pressures can damage the pipes network what is more cause leaks in them, that's why it is important to establish suitable pressure management practices [5]. To achieve this the use of sensors or pressure gauges to monitor the pressure as well as to locate probable existing leaks, furthermore the use of pressure reducers to reduce the flow of water is also important [6]. To reduce the probable area, where the leak is located sensors can be installed along the plumbing network. For example, by installing a valve (pressure sensor) in the pipe that connects the city central water supply to the house. We start measuring the water standard delivered water pressure. After this is established, we turn off or cut for a moment the water supply and let it stand for a few minutes. After this time, we can see if the pressure has changed or not, since in a closed system there should be no loss of pressure. A loss in the water pressure would mean that, somewhere inside the house, or in between the different allocated sensors, there could be a water leak or a broken pipe. If the pressure is maintained, we should check if between the main water valve and our pressure sensor there is any loss of water [7].

Water Meter Systems

One way that companies in Latin America use to measure the amount of water used in homes, is the use or installation of water meters in the main pipe, these meters control the amount of water consumed in the home to later issue a bill. Each family and/or each person can use these receipts to control their water consumption; if an unexpected difference in the monthly amount is noticed, it could mean the presence of a leak or a pipe in bad condition. While this does not reduce the percentage of water lost in a significant way, it can alert people in time to take the necessary action and avoid wasting large amounts of water and money in the long run. This type of consumption control works in one-family homes where consumption can be controlled and accounted for without any inconvenience. However, in a building with

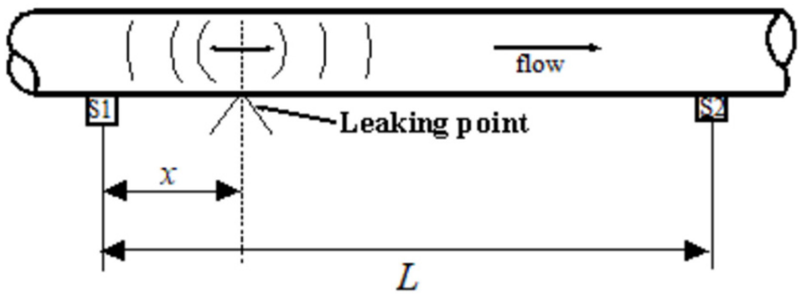

Fig. 1. Illustration Water Leak detection with acoustic sensors [11].

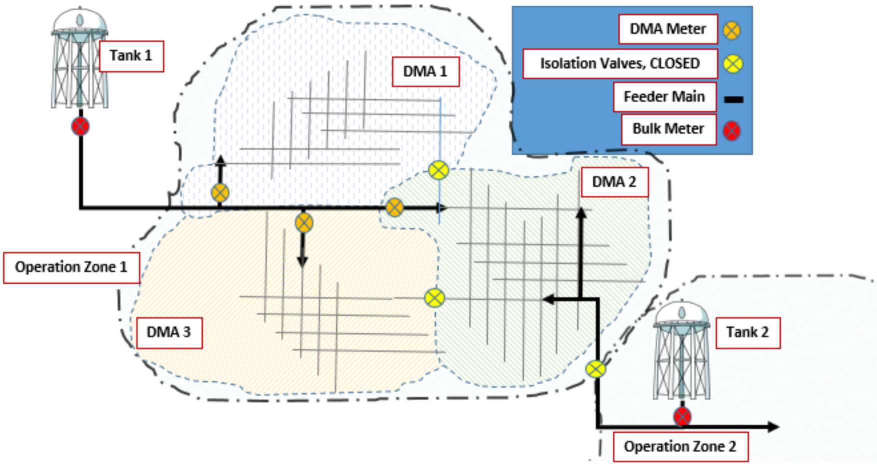

Fig. 1. Example of how a region is divided into DMAs [12].

several apartments it becomes meaningless, since it is not possible, or it would be too expensive, to install a meter for each apartment. For these cases there are other types of meters on the market that are simpler to install and do not require such a large investment, for example the DrizzleX [8].

Acoustic Methods

Acoustic methods are among the most frequently used technologies for detecting water leaks or damage in pipes. There are many operation methods to use acoustic sensors to detect leaks; there are those which are installed at fixed points along the pipe or portable ones that can be carried by an operator [9]. In both cases, the water flowing through the pipe serves as a carrier element for sound waves. Sounds along the pipes are related to different circumstances, such as material, length, or diameter of the pipe but also when a leak is present. For this reason, when the system is in optimal conditions, the waves generated usually don't make noise, which is different from those that may cause any type of damage (e.g., water leaks) [10], making them detectable by the sensors. Subsequently, when these waves spread in both directions, up- and downstream. As a result of this, with the help of mathematical models, the distance between the leak and the preinstalled, or mobile, sensors can be measured, thus helping to pinpoint the location of the leak [11].

District Metered Areas – DMAs

Leaving aside the systems for controlling water consumption in each home and concentrating on a more comprehensive way of controlling the water consumption of a country, a region or, on a smaller scale, within a city, the alternative proposed in the European Frameworks for Water Management can be used, which consists of dividing the water system network "into District Metered Areas (DMAs) by shutting valves permanently and installing meters equipped with telemetry data loggers" [4]. An extension to this is the "so-called virtual DMAs", which with the help of artificial intelligence software and monitoring and measuring the flow, consumption and pressure within a reduced space can identify the areas where excessive consumption is being generated, which can be the result of water losses [4].

2.2 High-Tech Techniques

Fiber Optic Sensors

Fiber optic is typically known as a way to transmit data (internet for example), but lately other use cases have arisen. One of this use cases is Fiber Optic sensors which are a type of sensor that use fiber optic cables to detect changes in the light transmission. A fiber optic-based sensing system operates on reflection and transmission principle, in which

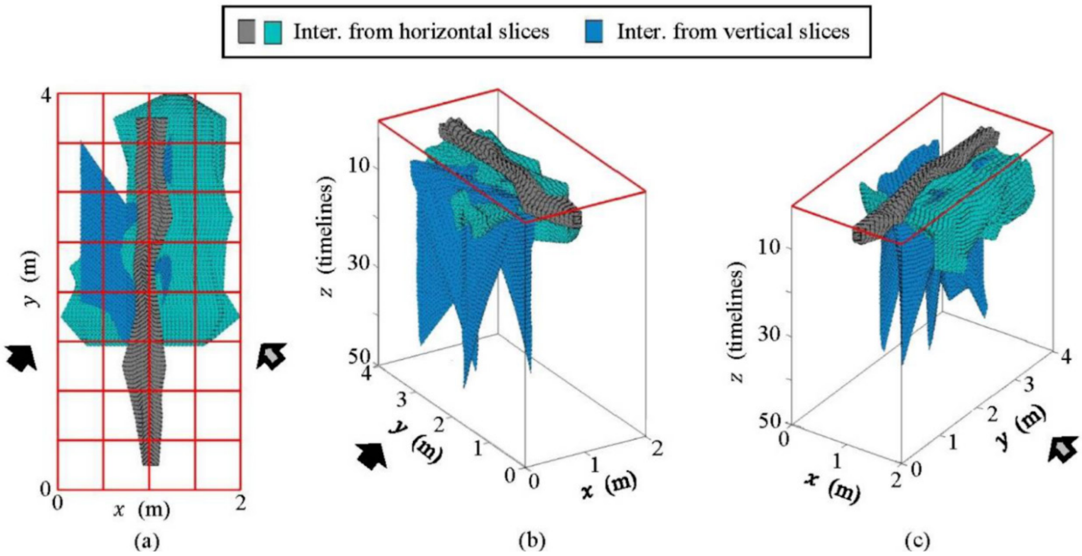

Fig. 2. 3D pipeline model generated from GPR raw images to detect leakages [14].

the fiber optic acts as a sensing component to changes in the external environment [13]. This changes in the environment can be associated to a leak in water networks. There are diverse types of Fiber Optic Sensor. For water leakage the sensor used is intensity-based sensors: These sensors measure changes in the intensity of light that is transmitted through the fiber. They are typically used to detect leaks in pipelines and other water infrastructure.

Ground Penetrating Radar – GPR

Ground-penetrating radar (GPR) is a non-destructive water leakage detection system that uses GPR images (radagrams) contrasts between the leaked water and the surrounding soil that are caused by differences in dielectric characteristics [14]. GPR works by transmitting radar waves into the ground, detecting them once they bounce back by an antenna. The time it takes for the waves to travel through the ground and back to the surface can be used to determine the depth and characteristics of subsurface features such as underground utilities, soil layers, and buried objects. In water leakage detection, GPR is used to locate, and map buried water pipes, sewers, and other underground infrastructure. The technique can be used to non-destructively locate pipes, identify their depth and size, and to detect leaks in buried water pipes. GPR has several advantages over other types of water leakage detection methods. It is non-destructive, meaning it does not damage the pipes or surrounding area during the detection process.

Machine Learning and AI

Machine learning is a branch of artificial intelligence (AI) and computer science which focuses on the use of data and algorithms to imitate the way that humans learn, gradually improving its accuracy [15]. They can be used to analyze data from various sources, such as smart water meters, drones, and ground-penetrating radar, to detect leaks in water pipes and other infrastructure more accurately.

In water leakage detection, machine learning and AI works as a compliment to process data and obtain better outputs from existing high-tech or low-tech sensors and other water leak detection systems, nowadays is commonly used for:

1. Analyze sensor data: Machine learning algorithms can be used to analyze sensor data from smart water meters, drones, and other sources to detect leaks in real-time.
2. Identify patterns: Machine learning algorithms can be used to identify patterns in sensor data that indicate the presence of a leak.

3. Predict leaks: Machine learning algorithms can be used to predict when and where leaks are likely to occur, based on historical data and other factors.
4. Optimize maintenance: Machine learning algorithms can be used to optimize the scheduling and routing of maintenance personnel, based on the likelihood of leaks in different areas.
5. Smart Water Network: Machine learning and AI can also be used to create a smart water network, where the system learns from the data and continuously optimizes the performance of the network by detecting and isolating the leaks, balancing the pressure, and predicting the future demand.

Fig. 3. A smart meter manufactured by the Swiss company Landis+Gyr [19]

Machine learning and AI are still in the early stages of being adopted for water leakage detection, but they have the potential to improve the efficiency and effectiveness of the process. In some projects already implemented it's observed reduction of around 20% in leakages [16].

Smart Sensors

Smart water meters are advanced water meters that use sensors and wireless communication to measure water usage and detect leaks in real-time. Smart water meters typically operate through reading inbuilt and calibrated magnetic pulses produced by the water meter as it turns [17]. They can also be used in water distribution systems to monitor water usage and detect leaks in large pipelines.

Smart water meters typically have the following features:

1. Advanced sensing: Takes. The sensors can detect slight changes in pressure, flow rate, and temperature that can indicate a leak.
2. Wireless communication: Smart water meters use wireless communication to transmit data to a central hub or cloud-based system. This allows the water company to monitor water usage and detect leaks in real-time.
3. Alerts: Smart water meters can send alerts to maintenance personnel when a leak is detected, which allows the water company to respond more quickly and efficiently to repair the leak.

This type of Smart Sensors is already deployed in projects worldwide. For example, the Denver's water company is already using an IOT device that connects to the current water meter sensors, to analyze and transmit data both the utilities company and the customer [18].

2.3 Cases of Study

Even though the paper is focused on the application on the before mentioned technologies in Latin American country, one more differentiation is made due to the drastic different scenarios present in the Latin American context. Therefore, this paper will analyze the water leakage detection methods previously researched and its application on two different types of scenarios, rural and urban environment which will be defined next.

Rural Environment

Rural area refers to the geographical region located outside of urban areas. It has a far lower population density than urban environments, and the Office of Budget and Management (OMB) of the United States classifies as rural any region with less than 50.000 inhabitants. In Latin America around 123 million people live in this kind of environment [20]. These areas usually are less developed than urban areas and face diverse challenges such as low investment funds which directly affects infrastructure and therefore water leakage detection programs. For rural environments the main challenges concerning water leak detection can be summed up in the following:

1. Accessibility: Many rural areas have limited infrastructure and rugged terrain, making it difficult for technicians to reach and inspect pipelines and other water systems.

2. Limited resources: Rural communities often have fewer resources available for maintenance and repair, making it harder to detect and fix leaks in a timely manner.
3. Aging infrastructure: Many rural water systems are old and have not been updated in decades, increasing the risk of leaks and making them harder to detect.
4. Limited monitoring: Some rural areas may not have advanced water monitoring systems in place, making it harder to detect leaks in real-time.
5. Lack of expertise: Limited workforce and technical knowledge can make it harder to detect and fix leaks in rural areas.
6. Low water pressure: in rural areas water pressure is often low, it can make it harder to detect leaks through pressure changes.
7. Remote location: Some rural areas may be located far from repair crews and replacement parts, making it harder to quickly fix leaks once they are detected.

Urban Environment

Urban Area is referred as the geographical region with a high-density human settlement. To be considered an urban area it is necessary to have a population of at least 50.000 people according to the OMB. in Latin America around 81.2 % of the population live in this type of area [21]. With this type of settlements many challenges arise such as the intense demand for natural resources such as clean water therefore big networks of pipe to supply this high demand make a pressing challenge for cities to detect leaks and maintain the infrastructure to guarantee its population with the much-needed resources. The main challenges of urban areas in terms of water leak detection are the following:

1. High population density: Urban areas have a high concentration of people and buildings, making it difficult to access and inspect pipelines and other water systems.
2. Aging infrastructure: Many urban water systems are old and have not been updated in decades, increasing the risk of leaks, and making them harder to detect.
3. Lack of expertise: Limited workforce and technical knowledge can make it harder to detect and fix leaks in urban areas.
4. High water pressure: Urban areas often have high water pressure, which can mask leaks and make them harder to detect through pressure changes.
5. Limited space: Urban areas are often built on limited space, which can make it difficult to access and repair leaks.
6. Noise pollution: Urban areas are often noisy places, which can make it difficult to hear water leaks.
7. Traffic and congestion: Urban areas often have heavy traffic, making it harder for repair crews to access and fix leaks in a timely manner.

3 Analysis

For the current paper, the studied technologies and techniques have been analyzed in each criterion and for each context provided. After a score from 1 to 3 (1 for poor performance, 2 for average performance and 3 for high performance) is assigned in the decision matrix in table two.

3.1 Effectiveness

Effectiveness corresponds to how well the technique helps in detecting water leaks. In the pool of techniques this paper is analyzing the effectiveness varies largely. For Urban Areas where there’s a dense network of pipes of different types, and several layers of material above the networks the most effective technology is the Fiber Optic Sensor since it’s laid across the whole network it can detect leaks of less than 1% the flow of the pipe [22], and while the congested and highly pressurized water in Urban Areas does not affect this type of systems, other lower cost systems like DMAs and conventional meters are more prone to error while trying to detect water leakages under this circumstances. For

Table 2: Decision Matrix

Techniques	Effectiveness		Cost		Human Resources		Accuracy		Ease of Installation & Compatibility		Scalability		Remote Monitoring		Results	
Case of Study	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.	Rural Env.	Urban Env.
Fiber Optic Sensors	3	3	1	1	1	1	3	3	1	1	1	1	3	3	12	12
Smart Meters	3	3	1	2	1	2	2	2	2	2	1	2	3	3	12	14
Ground Penetrating Radar	3	2	2	2	1	1	3	3	3	3	3	3	3	3	17	16
Machine Learning and AI	2	3	1	2	1	2	2	2	2	2	1	2	3	3	11	14
Pressure Monitoring Systems	1	3	3	3	3	3	1	1	2	2	1	2	1	2	9	13
Water Meter Systems	3	3	3	3	3	3	1	1	3	3	2	2	2	2	14	14
Acoustic Methods	2	3	1	2	2	3	2	2	3	3	3	3	1	1	12	14
District Metered Areas	1	3	3	3	3	3	1	1	3	3	2	3	1	2	11	15

Rural Areas, while high tech solutions are still considered to be more effective, DMA and conventional Water Pressure Sensors increase their effectiveness due to the regularly lower pressure network. For both Rural and Urban environments Pressure based systems perform in an appropriate way making it the low cost best ranked alternative in for this criterion.

3.2 Cost

Cost refers to the money required for this technique to be implemented in the appropriate manner. Contrary to the previous criteria, DMA and conventional water meter sensors present as a more attractive opportunity due to the financially low cost of implementing this kind of solutions for both cases of study. For Urban Areas techniques such as Fiber Optic Sensors become very expensive due to the amount of trenching required for sensor installation and the costs associated road disturbances as a poor performer, GPR technology is also included as a low performer in this category due to the cost of the sensors and the human resource required. For Rural Areas both Fiber Optic Sensors and GPR repeat as the worst performers.

3.3 Accuracy

Accuracy is defined by how close the technique is able to the detect the actual leakage point. This is especially important in environments like Urban Cities where the space is severely limited and is necessary to pinpoint exact locations on the network to address the issue with the lowest disturbance possible accordingly GPR Systems and Fiber Optic represent the best solutions for this as they are the most accurate solutions. Smart Meters pair with AI Monitoring present an intermediate solution since the AI and Machine learning models are able to more accurately locate where the leak is, and it can be used to even predict the location of future leaks. Low-cost solutions perform poor as usually these techniques provide an approximate of the location and a visual or other type of inspection is required to accurately find the leak. Which is especially critical in cities where layers of soil and concrete cover the water network and hide leaks.

3.4 Human Resources

Human resource refers to the required technical skills of the workers to successfully implement the detection system. This is a crucial factor especially for the high-tech techniques which by being more advance require more specialized skills. Also another factor to take into account is that usually high skilled workers tend to concentrate on urban areas making the access for rural areas harder. Based on this, as seen in the table the high-tech solutions rank lower, and for the low-tech solutions which are already usually implemented they rank as high performers.

3.5 Ease of Installation and Compatibility

Ease of Installation and Compatibility refers to how easy is to install and compatibility refers to how compatible is the system with the existing infrastructure. On Ease of Installation and Compatibility low cost technologies rank best since in most cases the infrastructure is already in place, for example in the DMA technique the sensors used to track water consumption are the ones in place for billing making it a matter of adopting the appropriate procedure, for water meters in most countries it is required by law that each establishment has its own water meter to monitor consumption therefore making it easier to monitor leakages using this devices. For Rural Areas, generally can be easier to install sensors due lower density and more space availability. But can be challenging depending on the site access. GPR even being a high technology technique, presents a big advantage as there's no need for installation which makes it the easiest to implement.

3.6 Scalability

Scalability refers to the ability of the technology to expand or change depending on the requirements of the system. In the higher end of this criteria, we can find once again the GPR as it is highly scalable to run this technique due to the lack of installation of new infrastructure to monitor. Taking the example of the technology provided by the Israeli Start UP Asterra, it will be highly scalable to deploy this monitoring system as it's only required to point the satellites to the required location and analyze the data both in rural and urban areas. In the lower end for both types of environments we have fiber optic sensors, as any modification or expansion of this type of systems requires trenching, which is a very complicated process, specially in urban environments.

3.7 Remote Monitoring

High Technology solutions in both Urban and Rural environments come as the best ranked, due to the versatile characteristics it presents, mainly in terms of ease of use and scalability.

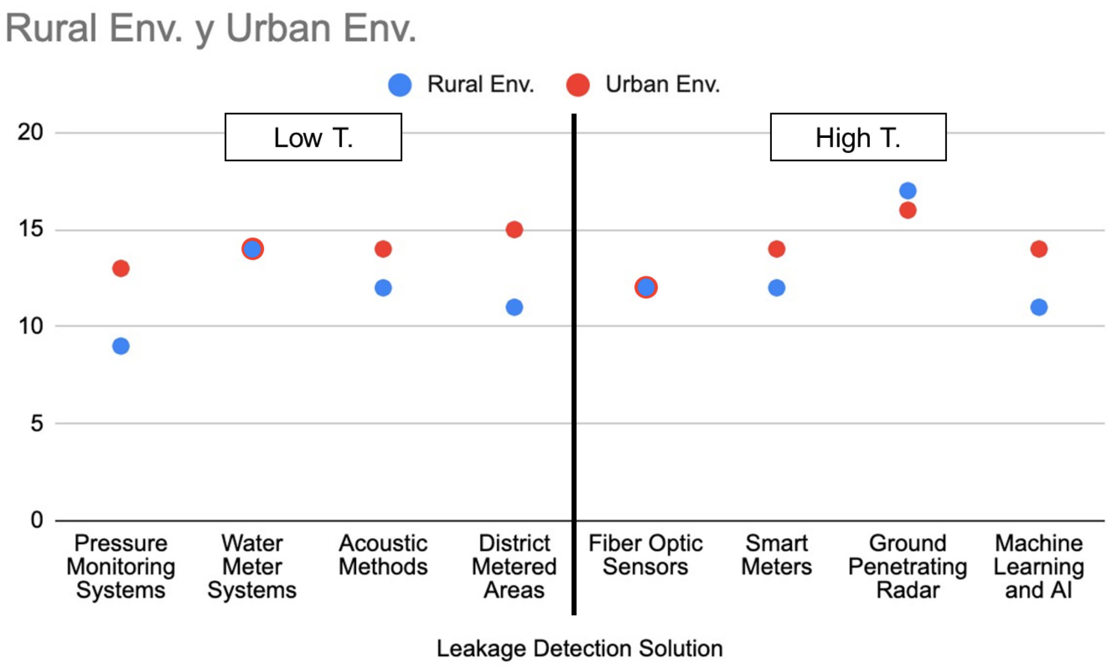

Fig. 5. Point-Distribution according to the effectiveness of each Technique in the different case of study

This criterion is specially relevant for Rural environments because this type of settlements usually lack local offices of the water companies and it's expensive to monitor the. GPR technology even though can become more expensive than the alternatives are widely adopted in high income countries and with the advancements in radar technologies costs are rapidly decreasing in the equipment area which makes it a suitable solution in the mid-term for low-income countries. While other forms of GPR like Asterra's satellites based GPR are erasing ease of implementation and scalability constraints, which could potentially be incurred in a fully automated remote monitoring system. Smart Meters are also a solution that due to its IOT capabilities provide a solid remote monitoring framework as they can directly connect to the water company systems and provide information. On the low tech solutions side water meter systems rank the highest with an average performance due to the fact that usually this are used to bill customers which means there are already systems in place to collect the data even if it's not in a real time automated way.

On the low-tech solutions, DMAs are the best solution in Urban Environments due to the high population density, which means a higher density of meters and a higher pressure in the system which are key factors for the DMAs to work properly. This solution provides developing countries with a useful and cost-effective tool to start investing in water leak detection programs, and the possibility to combine with Machine Learning and AI algorithms to detect more accurately leaks as well as to predict network behavior and preemptive maintenance. In Rural areas due to the low density of people meters and lower water pressures, Water Meter Solution becomes more relevant as it doesn't rely that much in these factors.

4 Discussion

As a fulfillment of the research question this research paper provide an overview on low tech technologies most used in low-income countries as well as the latest technology implemented in high income ones and compares their performance using a decision matrix. Furthermore, it is important to highlight that this these techniques vary greatly in the approaches to detecting leakages and as any other solution for leak detection they depend on different factors and conditions of use which means that it is always best to evaluate on a case by case basis to really be able to determine which is the most appropriate solution which usually involves a combination of systems [23].

Based on the research presented a decision matrix is presented in Table 2 and the following diagram (Fig. 5) it's possible to assess the performance across solutions and context. As seen in Figure 5 the best ranked technology for both study cases are GPR. GPR is a technology commonly used nowadays in high income countries and a series of different approaches are being developed [24]. Latest technology on GPR uses satellite images that can penetrate around 5 m underground [25] and leverages this to detect leaks in both urban and rural environments without human intervention on site, which could provide a big leap forward in terms of scalability and eliminate constraints of human resources and ease of installation especially for low-income countries in Latin America.

Also in the high technology side, Smart Meter and Machine Learning technologies are highly accurate in an urban environment inside the sensor monitored areas [26], better access to financial resources, talent, and current infrastructure, make them an attractive opportunity to start complementing current in place monitoring systems to expand their capabilities with more accurate detection and better remote monitoring capabilities. This is also suitable for a systematic phased approach where different parts of the water network are enhanced through time and therefore lowering the total initial investment cost which is usually critical in this type of projects.

For low technology approaches performances vary but are highly aided due to their low cost of implementation and generally fewer human resources are needed which makes them the default leak detection solutions used in Latin American Countries even if they are inaccurate. For example, in DMA's where machine learning methods are required to produce accurate results [27]. These approaches have been used until now, with the current expansion in Latin American urban areas and consequently the stress induced in the aging water distribution infrastructure and the scarcity of the easy access potable water resources. It is necessary to begin the transition towards a more modern leak detection infrastructure.

5 Conclusion and Outlook

This paper presented water leaks as a growing problem with some of its consequences, especially financial, in different countries around the world with the focus on Latin American countries. In addition, the techniques that are used today to detect water leaks, from the most common and simple (low-tech Techniques) to the most high-tech ones, were presented. After presenting and analyzing each one of them furthermore, later, evaluating them in 7 categories for 2 different scenarios, it was concluded that on the one hand low income countries rely on low-tech solutions for the water leakage detection due to the lack of experienced workers and the lower costs they have; while on the other hand, in more developed countries there are new technologies that could be applied even in the most rustic scenarios as in the rural areas of Latin America, for example the GPR. Furthermore, as mentioned by T. Amram, there is no unique perfect solution to mitigate water losses due to leakages, but it depends on several factors and conditions for which different solutions can be applied at the same time [23]. With the water pipeline leakage detection market in South America expected to grow from 47.31 million USD in 2021 to 72.48 million USD in 2028 [28], it would be important to further evaluate and analyze the cost-benefit of the investment in new technologies to better serve this market.

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Ramez Tawfik and Ebrar Enes Ucmaz

Cost efficiency: A comparison between labors and robotics in bricklaying masonry wall construction

Abstract

The use of robotic bricklaying robots in the construction industry is still in its infancy, and the precise characteristics and capacities of these robots can change depending on various parameters. The study compared between the use of human force against robotic machines as we go in-depth to understand those points of comparison between labor utilization in developing and also developed countries and the use of robotic bricklaying machines as semi-automatic and fully automatic robots. We have carried out a survey and an on-sites investigations for the usage of semi and fully automated in developed countries and the usage of labors in developing countries and we have reached the output that the market is still not yet ready to swallow the overprice of the automated machinery in either developed or developing countries. However, by boosting productivity, decrease the production cost of the machinery, be able to sustain the machine for longer time to be used on several construction projects and have a near return of investment from buying those type of machinery, those outputs were gathered from a survey that was published covering nearly 120 key personal from different construction projects in the developing and developed countries combined, so that these robots have the potential to completely transform the construction industry.

DOI: 10.18154/RWTH-2023-08858

Keywords: Robotic, Bricklaying, Labor, Automation, Productivity, Cost Efficiency.

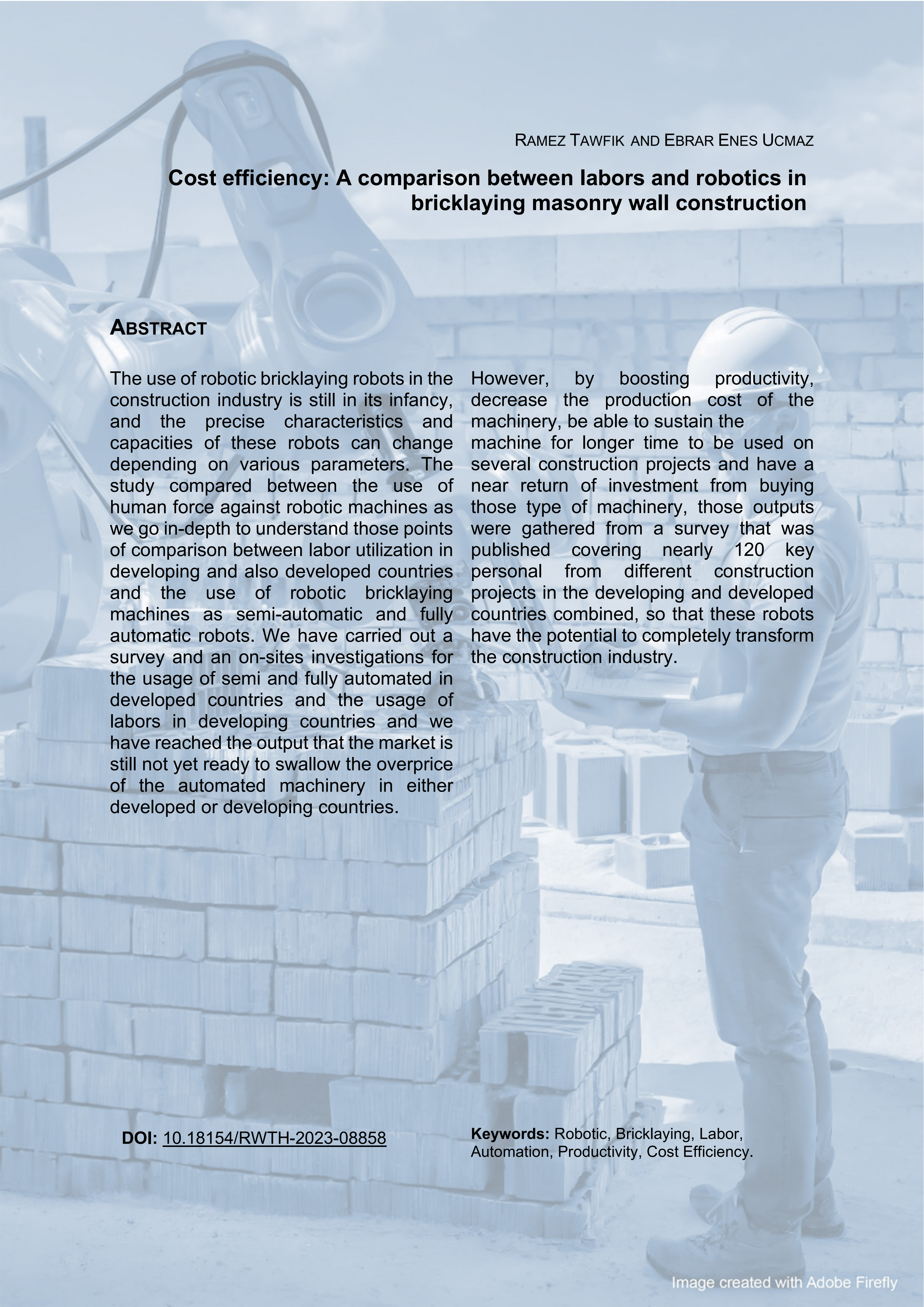

Image created with Adobe Firefly

1 Introduction

We are all living now in the booming effect and the quickly escalating automation, machine learning and artificial intelligence era [1], in which we have tried to automate non-automated tasks all around us, yet construction activities have a difficulty to automate their activities, due various reasons which are but not limited to their uniqueness and complexity, that is what make the construction industry set back in the innovation trend [2], We quite understand that every project is unique in its own way nevertheless there are repetitive activities that every project would contain.

Numerous factors influence the integration of novel production machinery into various sectors. Globally, several machine learning robots have been developed, specifically tailored for construction applications, despite international exhibitions showcasing the latest advancements in semi-automated and automated machine robotics for construction sites, their limited adoption raises questions. One aspect contributing to this phenomenon is the apprehension among laborers about potential job displacement [3]. The perception is that automation may gradually replace human roles [2]. This labor-centric viewpoint contrasts with the perspective of business owners, who prioritize cost efficiency in their procurement decisions. The current market conditions prompt a critical evaluation of whether investing substantial sums—ranging from hundreds of thousands to millions—in robotic bricklaying machines aligns with the profitability objectives of business owners worldwide. The prevailing sentiment among business owners is reluctance to embrace robotics on construction sites unless a clear and advantageous return on investment is evident. Thus, a fundamental question emerges: Is the utilization of robotic bricklaying machines more economically advantageous than relying on human labor?

However, the word “robotic machine” is a random non-specific word because there are always different kinds when it comes to machines [3], Moreover, considerations pertaining to labor necessitate clarification regarding the geographic context, specifically whether the research is tailored for developed, developing, or both types of economies.

We are going deep to understand the main point of comparison between the use of labor force in developing and also developed countries and using robotic bricklaying machine as semi-automated and fully automated robots [4]. We are measuring specific comparison points in the terms of advantages and disadvantages, between the labors in developed and developing countries as well as between semi-automated and fully-automated robots.

2 Method Statement for Bricklaying Robots

As previously indicated, the term "Robotics" is a broad encompassing various application, analogous to specifying the make and purpose when expressing a desire to purchase a car, Robotics, too, comprises distinct categories. Notably, the focus of this discussion centers on two particularly noteworthy types: the semi-automated bricklaying robot and the fully automated

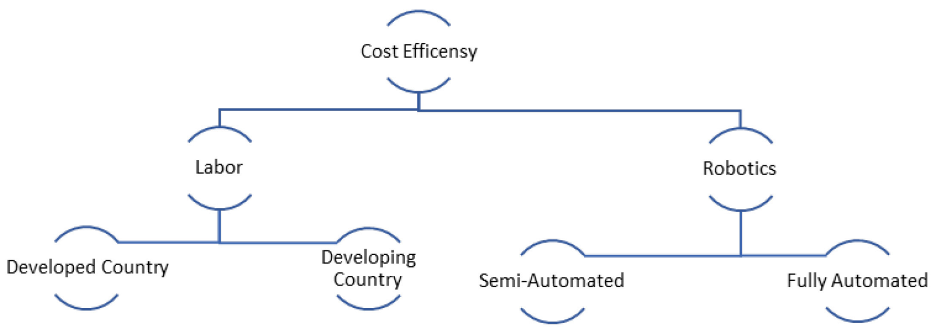

Fig. 1. The hierarchy in which the research is based on as a comparison between labors and robots, but each part has a more detailed two more segments

robot. The consideration of mechanical bricklaying robots is omitted in this study due to findings that indicate their optimal utility in scenarios involving heavy bricklaying and extended, rectilinear walls devoid of curves. These mechanical variants exhibit limitations spanning adaptation to production rates, accommodation of unique work specifications, and mobility, often requiring rail systems for linear movement. Consequently, our investigation concentrates on the nuanced exploration of the two aforementioned robotic types.

2.1 Semi-Automated Bricklaying

Semi-automated bricklaying robots are made to carry out particular bricklaying jobs, such as placing bricks in a pre-determined pattern. The movement of these robots and the placement of the bricks are normally directed by a human operator, Semi-automated bricklaying robots have a number of significant characteristics, including:

- Robotic arm: The robot's primary arm, which lays bricks, it has several sensors, including cameras and force sensors, which enable precision movement and precise brick placement.
- Brick-laying pattern that has been predetermined: The robot can be programmed to place bricks in a certain pattern, such as a grid pattern or a straight line. This pattern must be established by the human operator [5].
- Greater flexibility and efficiency are possible on the construction site thanks to the robot's remote control and monitoring capabilities.
- Human supervision is required for the robot to place bricks in the predetermined pattern; at this point, a human operator steps in to direct the robot's movement and manage the brick placement.
- Semi-automated bricklaying robots are less sophisticated than fully automated robots and are typically employed in smaller construction projects, such the construction of homes or modest-sized businesses, as well as they also cost less and need less upkeep than fully autonomous robots.

In general, semi-automated bricklaying robots are a viable choice for building enterprises aiming to increase productivity and save labor expenses but aren't yet ready to invest in completely automated technology.

2.2 Fully Automated Bricklaying

Fully automated bricklaying robots are made to carry out a variety of bricklaying operations, such as mixing and supplying mortar, laying bricks, and even shaping and cutting bricks to match particular patterns. These robots are frequently computer-controlled, enabling precise movement and precise brick placement [6].

Automated bricklaying robots have a number of significant characteristics, including:

- High-precision robotic arm: The robot's main arm, which is in charge of laying bricks, is a robotic arm. It has a variety of sensors, including force sensors and cameras, which enable precise movement and block placement [5][7].
- Automated mortar mixing and delivery: The robot is capable of mixing and delivering mortar to the work area automatically if it is fitted with a mortar mixer and delivery system.
- Automated brick cutting and shaping: Some robots are furnished with cutting and molding equipment that enables them to modify bricks to fit particular patterns or designs [8].
- Greater flexibility and efficiency are possible on the construction site thanks to the robot's remote control and monitoring capabilities.
- High speed and efficiency: Fully automated bricklaying robots can lay bricks much more quickly and precisely than humans, which can save a lot of time and money on construction projects [4].

The usage of automated bricklaying robots is still a relatively new technology overall, and the precise characteristics and capacities of these robots can change depending on the manufacturer and model. However, by boosting productivity and cutting human costs, these robots have the potential to completely transform the construction sector.

3 Masonry Wall building, Labors and Robots

By continuing, are those types of robots cost efficient than the labor usage, following that so there are main comparison points between the two parties and those points go as follows:

Production Rate
Average Daily Wage
Performance Curve and Wasted Material
Adaptation to unique work circumstances
Availability and Mobility

We are covering the above-mentioned different points [4][9] from the point of cost and financial aspects, that are affecting the usage of labor force in masonry wall construction activity, knowing that the comparison is based on standard bricks, brick in the average size that can be held by one hand for labors and placed in position nevertheless the exact dimensions because we are only comparing cost efficiency for the whole bricklaying activity not just for specific type.

The data were collected over a comprehensive survey [10] that covered the above points, plus the construction industry point of views over the robotic usages over the near future.

3.1 The Production Rate

Production rate as for labors

The unit that which will be used to measure the production rate is (m²/day) were one day in defined by the PMI -which is the Project Management Institute- as one working day in which it contains 8 working hours [4][15].

Before elaborating with the production numbers, we shall know that we are excluding the quality standards from the equation not entirely but partially.

we are also eliminating the time consumed in different hand-ins to consultants/quality controls and assume that the net amount of meter squares the labor can build up whether it is the same wall or different located walls - to avoid settlement, as a result the production rate is equal to 27m²/day [5] for the developing countries.

On the other hand, the developed countries the production rate is nearly the same which is 25.6m²/day [11], which is nearly equivalent a wall 6 meters width by 4.5 meters height.

Production rate for bricklaying robots

Depending on and including: Automation level, fully automated bricklaying robots can lay bricks more quickly than semi-automated or human-operated robots because they can do a wider range of activities [4] with little to no human oversight.

Brick handling: As it influences the entire production rate, brick handling speed is an important factor. A robot with a quick brick handling mechanism, for instance, will be able to lay bricks more quickly than one with a slower mechanism.

Wall complexity: The complexity of the wall being constructed has an impact on the rate of construction [12][13]. A wall that is straightforward with straight lines and right angles can be built more quickly than one with numerous curves and angles.

Brick quality: If the bricks are not uniform in size or shape, a robot may have to operate more slowly, which will slow down production.

Operator skill: A skilled operator will be able to program and operate the robot more efficiently than an untrained operator, which can also have an impact on production rate.

Environmental factors: Weather, temperature, and dust can all have an impact on how quickly a product is produced because they may need a robot to work more slowly to maintain quality and safety.

A fully automated bricklaying robot can typically lay between 200 and 1000 bricks per hour which compensate to 20m²/hr. and 150m²/day when operating under ideal circumstances. The actual hourly output rate, however, will be influenced by things like the operator's expertise, the state of the bricks, and the type of wall being constructed [14]. This would equate to a daily output rate of between 1,600 and 8,000 bricks over an 8-hour work shift.

Although semi-automated bricklaying robots require more human supervision and may only produce 200-400 bricks per hour on average 8m²/hr. and 64m²/day [15], over the course of an 8-hour workday, this translates to a daily output rate of 1,600–3,200 bricks.

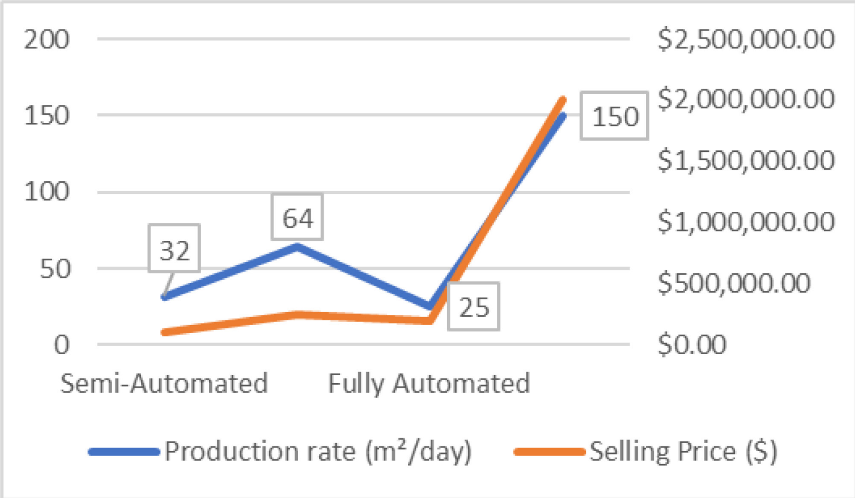

Fig. 2 the relation between the Production rate and the Selling price, for semi-automated and Fully automated Robotics.

3.2 Average Daily Wage

As for labors in different countries

Then, It is the average daily wage for the bricklaying labors, we shall also add that to reach the above numbers of the production rate, we need a number of 1 expert masonry labor and 1 masonry labor assistant, so we shall talk first about the developing countries in which the wage is 6.7$ for the expert masonry labor per day and 4$ for the labor assistant also per day [16], with a simple math you would pay nearly 10.7$ per day for 27m² masonry wall, then for the developed countries the average daily wage is nearly 200$ [17] and for the assistant it would cost as well 165$ per day, taking into account that the previously mentioned wages cover the social and medical insurances as well as this numbers is based on the exchange rate of January 2023.

Robotics on the other hand

The daily average wage for robotics whether they are semi-automated or fully automated are a little tricky to calculate because the actual selling price and you still have taxation which is completely different from one country to another and also the importing price which is also the same problem as the taxes, it is completely different from one country but always tend to be higher to another, and this is not the last variable, you still have the running cost, maintains and storage cost, plus for the semi-automated robotics you need a high qualified labor to work on the robot, those are all affecting the average cost per hour, so to overcome this variables, we will provide the average selling price from the providers, knowing that the selling price increase linearly with the increase in the production rate, so you end up for semi-automated robots with 100k$ for 32m²/day and 250k$ for 64m²/day, and for the fully automated robotics go way beyond those numbers, for 200k$ for 25m²/day and nearly 2Milo$ for 150m²/day, as seen in the below figure, (see Fig. 2

3.3 Performance Curve

About human involvement, involuntarily there must exist some human error also that this human error might decrease by hiring experts but that does not oversee the existence of the human error [18].

For human error existence [19], it has two sides of impact, either it is a waste material and/or excess use of material, for wasted material, the amount of wasted material when it comes to masonry wall construction it could reach up to 10% with an average of 5% [13],those materials are as sand, cement, water, the bricks itself, knowing that by past projects, we worked on, the cost for 1m² of masonry cost, would cost 0.7$ for developing countries and 14$ for developed countries [20].

As a conclusion, we end up with 10% waster material, 5% excess used material, and the average cost for the 1m² is nearly 0.7$

and 14$ for developing and developed countries.

Robotic bricklayers that are fully automated have sophisticated cameras and sensors that enable them to lay bricks precisely. Typically, these robots can lay bricks with an error rate of less than 1%.

While for Robots that are semi-automated bricklaying, which need more human supervision, they might make more mistakes. There is a 2-3% [4] mistake rate for these robots.

It's important to remember that the quality of the bricks utilized affects a bricklaying robot's error rate as well. If the bricks are not same in size or shape, a robot may make more mistakes. Environmental factors like weather and temperature can also have an impact on the mistake rate.

3.4 Adaptation to unique work circumstances

We have covered in the “Average Daily wage” section, the wage for a professional worker as our baseline for comparison and that is based on the hierocracy that we created that a professional labore will also be capable of overcome certain challenges when it comes to performing the required work, those challenges are:

Concrete beams may have a camper,

Concrete columns may have a slight deviation, and

The last bricklaying line just below the beams

All the mentioned points [16] go in the favor of the labore force as they can handle these problems on the spot, knowing that practical training is provided for labors in developed countries and from developing countries the workers usually start working in a very small age so that they gain a lot of experience as they reach their 20s, the experienced labore force will even have more advantage when it comes to building up a unique bricklaying wall, as round walls, curved walls, as well as walls with architecture decorative designs.

While for robots can overcome many of the challenges of building walls, including round and curved walls, using specialized bricklaying tools and techniques. These robots can be programmed to lay bricks in specific patterns, follow curves and contours, and make precise cuts to fit irregular shapes. Using 3D modeling software, bricklaying robots can be programmed to build complex walls and structures that would be difficult or time-consuming for human bricklayers to build.

However, the ability of bricklaying robots to build unique walls is still limited by their current technology and capabilities [21][22]. They may struggle with tasks that require fine motor skills or dexterity, such as cutting bricks to fit complex shapes or laying bricks in tight spaces.

Country	Unit	2015	2016	2017	2018	2019	2020	2021
BANGLADESH	mil	62	63.2	67.2	68.6	69.9	72.54	74.66
BRAZIL	mil	99	100	102	103	105	106.3	107.8
CHINA	mil	792	794	795	794	796	796.6	797.4
ETHIOPIA	mil	47.7	49.4	51.2	52.9	54.6	56.35	58.08
GERMANY	mil	42.7	43.6	43.8	43.9	44.4	44.79	45.16
INDIA	mil	470	473	476	479	489	490.6	495
INDONESIA	mil	126	127	130	133	136	138.2	140.8
JAPAN	mil	66.2	66.7	67.3	68.4	69.1	69.79	70.54
MEXICO	mil	52	52.8	53.5	54.5	55.8	56.51	57.44
NIGERIA	mil	56.5	58	59.6	61.2	62.9	64.44	66.04
PAKISTAN	mil	67.6	68.1	68.7	69.6	71	71.49	72.32
PHILIPPINES	mil	42.6	43.8	43	43.8	45.1	45.16	45.66
RUSSIA	mil	75	75	74.8	74.8	74	74.06	73.84
USA	mil	160	162	163	164	166	167.2	168.6
VIETNAM	mil	54.5	54.7	55	55.2	55.8	55.97	56.28

Table 1. Represent the gradual increase in the labor force for different countries across the globe.

3.5 Availability and Mobility

In most of the developing countries as well as few of the developed countries they have a good labore force participation as followed from multiple resources, but still the point of availability is affecting few counties [23] due to some specific reason but as follows in table 1.

The majority of developed and developing countries, have a wide availability of labore forces, as well as the construction field is a wide major that exist in every place in the world [23], but this is not always the case, as some countries are now located at the edge of having no labore force or even a few, as the United Kingdom which literally is now on the edge of have completely no labore force, and after following up from the UK and as based on our survey [11], it is assured that this problem is already in action, due to Brexit [24] a lot of EU labors and even non-EU labors were exported, so they are trying to solve the problem by relaying on robotic machinery for small and medium projects, as they start to use the bricklaying robots, but there are different specs that can be adjusted in order to fit for the required project, but still, since the bricklaying robots are still in their development phase, their availability may vary by region, manufacturer, and demand. They are frequently pricey, which may prevent some businesses from using them. Most bricklaying robots are made to be mobile and employed on a single building site. They can be moved to various locations on the site, but they are normally not made to be moved around easily between other building sites. Some bricklaying robots can be moved around a construction site on tracks or wheels, while others are installed on a stationary platform.

lthough certain bricklaying robot models are intended to be more mobile and able to move between different construction sites, these models are not yet commonly accessible and depend on the manufacturer.

But in big projects in UK for example, they are following up with the American system of adding cardboard and wood frames as interior separation and depend on cladding as an

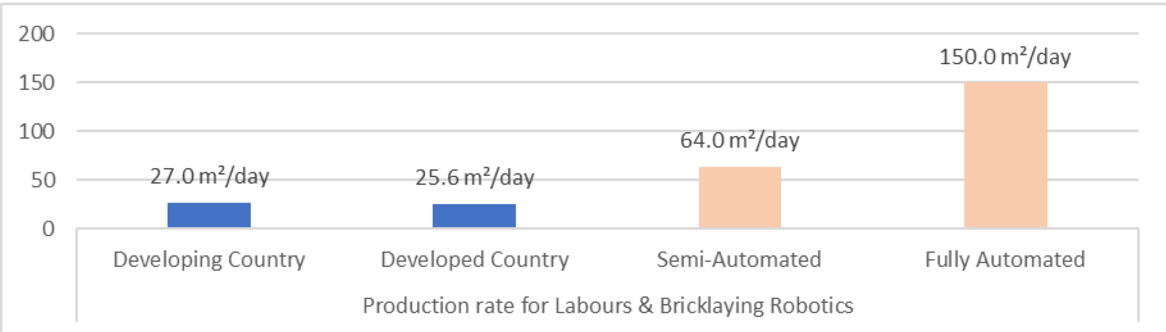

Fig. 3. Production Rate for different labors and robots' segments

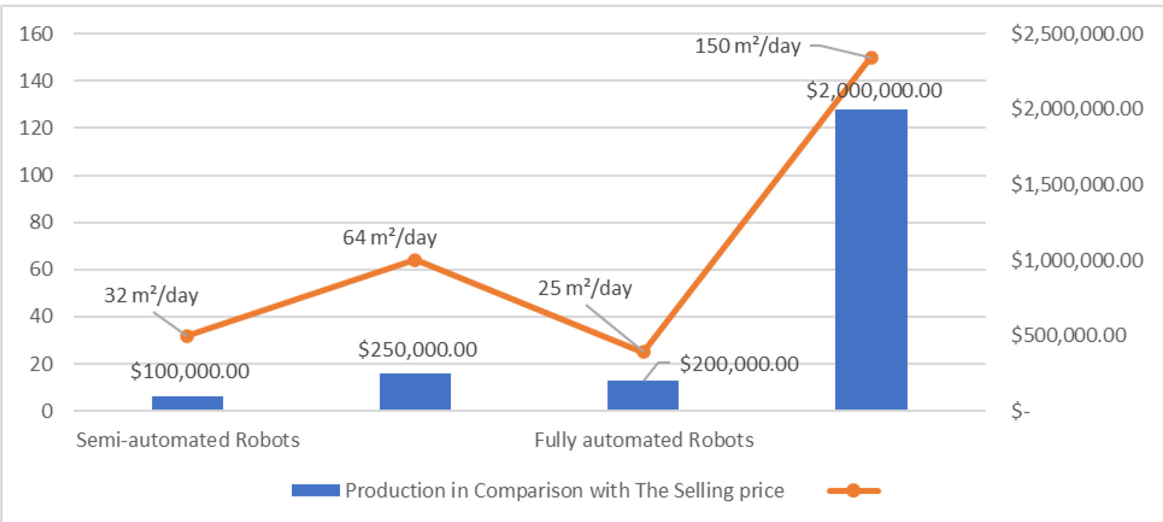

Fig. 4. Relation between productivity and prices

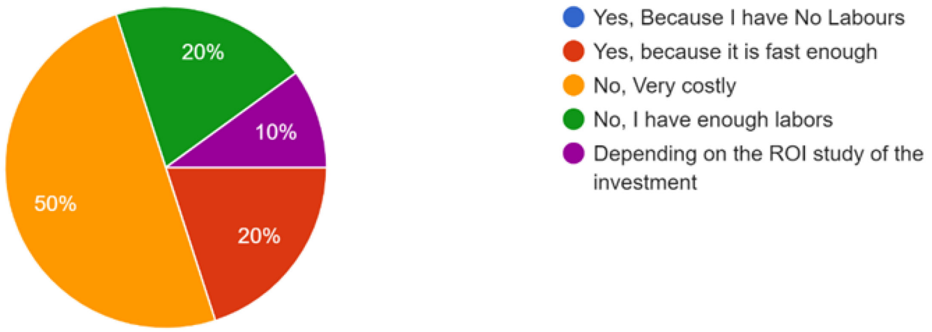

Fig. 5. The result from surveying whether construction projects would buy an expensive robot although it is more productive, or depend on labors.

exterior façade element, those two solutions might be effective for the time being but will it be effective on the long term, so we need to start depend on automation more even or/and adjusts the balance between countries with excess labor force and countries with few or nearly none labors [25].

4 As Results

As a result of the previously mentioned points and our published survey, the best production rate for labors against, the highest production rate that can be achieved by the semi-automated and the fully automated robots, figure (3),

you can see the quite difference between the two based comparison parties as the involvement of automation takes over the human's productivity by more than the double, but on the other hand the average cost for semi-automated robot is higher than the average, and for the fully automated robot even higher, as seen in figure (4).

By following our published survey [10], we reach the results that, 70% of the involved people in the construction decision making figure (5), they are againest buying such an expensive equipment even if they achieve such a high productivity.

Nevertheless, the labors in the developing country have an average of 10.7$ in a day and in developed country they have an average of 200$ a day, and assuming the you will buy the semi-automated machine for 250k$ to get double the productivity of the labor force with 64m²/day, plus assuming you will only pay the selling price without taxations, importing, shipping and running cost fees, you will end with 700$ per day, you can get 2 labors with less money and same productivity rate at the end.

The advantages of the labors does not stop here as well, both labors from developed and developing countries will be adequate and expert in this field with adabtability with diffierent and difficult job requirement, while forcing the robotics to adapt to different job requirements is difficult, even if you relay on the expensive fully automated models, they are still not capable of dealing with different bricks dimension in the same setup, but, the machinary have the edge on the waste material with 1% to 3% , in comparison with labors which could reach up to 10%, and as a summary in table (2) for the above mentioned number.

Leaving us with the avilability of both parties, as mentioned by many resarches and investigation the construction market in on the edge of not being able find enough workers in the upcoming future and we have already seen this impact on the UK [24] construction market, that is why we should start solving and clearing the air around the difficulties that the robotic bricklaying is facing right now to help with the expansion of the robotic in the upcoming near future

On top of the that and based on our survey, 60% of the construction site managers do believe that their sites are already capable of containing robotic bricklaying in anytime now, as well as 50% already think that the favor is with the robots when it comes to construction, maybe it is not ideal situation right now, but as

Comparison Points	Labor Force (Developing Countries)	Labor Force (Developed Countries)	Semi-Automated Robots	Fully Autonomous Robots
Production Rate	27m²/day	25.6m²/day	32m²/day - 64m²/day	25m²/day - 150m²/day
Average Cost	10,7$/day	200$/day	100k$ - 250k$	200k$ - 2Milo$
Performance Error (%)	5% - 10% Waste material	5% - 10% Waste material	2-3% Error rate	1% Error rate
Unique Work Requirements	Easy adapted	Training provided	Hard adaption	Hard adaptation
Mobility and Availability	Excess labors	Moderate availability with tendency to decrease And no longer available	Low availability with tendency to increase Lack of mobility	Significantly low availability with tendency to increase High Mobility

Table 2. The comparison points between labours (developed and developing countries) and Robotics as semi or fully automated.

we stated we think we shall start to clear the air for more automation and bricklaying to develop and adapted to the construction life.

5 Conclusion

As the use of bricklaying robots in the construction industry is still in its infancy, their use is limited and often expensive. Although the production capacity of robots is high, there are various limitations and accessibility issues due to the technology being in its infancy. Even if labor is economically advantageous in developing countries, labor quality is lower than in developing countries. While the labor force in developed countries is of high quality, it has problems such as cost and decreasing demand for labor.

In conclusion, in a comparison considering various parameters, in the financial choice between bricklaying robots and labors, labors are in the lead. When the technology for construction robots reaches a sufficient level of sophistication, this situation is expected to reverse, i.e., robots will be ahead in terms of financial efficiency.

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Robin Berweiler and Shady Saleh

Exploration of the advancements and potential of 3DCP

Abstract

The commercial environment for 3D concrete printing (3DCP) has grown rapidly since its debut, keeping pace with advancements in applicable materials, manufacturing techniques/know-hows and considers the state of the art of 3DCP technology in the construction industry. This paper aims to review current technologies in the field of 3DCP and define how far the technology has reached with the help of some experimental method to realize it in 3DCP houses. For that purpose, this paper starts with a market research, reviewing several promising 3D concrete printers, examples of wall layouts used by several companies, and at last some 3D printed projects already in the world, providing a solid ground of how far did this technology reach. The second part of the paper reviews the challenges in the printing process and limitations in architectural design to produce a large scale structure using 3DCP , as well as demonstrating a numerical simulation of distinct structures to validate the study’s findings. Moreover, there are some handpicked examples of competitive 3D printers that show great progress in the market, and real-world examples show what results can be expected. This information is then used to find out how 3DCP could evolve in the future and what opportunities this technology might bring.

DOI: 10.18154/RWTH-2023-08859

Keywords: 3D concrete printing, additive manufacturing, 3DCP specifications, 3DCP market study, challenges, limitations, numerical simulation.

Image created with Adobe Firefly

1. Introduction

There is a common argument that the construction industry frequently encounters difficulties in finishing projects within the allocated time and budget. Additionally, the industry experiences reduced productivity levels compared to other sectors. These problems are worsened by the shortage of skilled labor in both developed and developing nations.[1] 3D concrete printing (3DCP) is a form of additive manufacturing in the construction industry that promises cheaper, more efficient construction process due its less need for labor, faster, more efficient supply chain of materials, elimination of formworks and temporary scaffolding. Moreover, it provides a more flexible way to build freeform buildings with less cost and time than traditional construction techniques. Therefore, 3DCP is recognized as a mean to pave the way for the digitization of the construction industry, encompassing the building process from design to build.

Nonetheless 3DCP is a technology that is still in its infancy, where it still cannot deliver its promises to the construction industry especially for large scale projects. A lot of research has been done to develop this technology as shown in Fig. 1(a), a very steep leap in the numbers of researches was done from the year 2016 to 2022. Showing also that most of the researches that ~~was~~ were done mainly targeted to find the optimal material properties to be used, whereas it includes much more parameters to be developed to achieve its most efficient state. Moreover as shown in Fig. 1(b) the highest number of project done with 3DCP is in the housing industry to try to find an efficient solution for the current housing crisis that is all around the world according to Hilber and Schöni (2022).[2]

There are 3 types of 3DCP according to Mechtcherine et al. (2020) [3] , material extrusion, particle bed binging and material jetting. This paper will mainly review the state of the extrusion based method in 3DCP as it is the most dominant method, in not only small scale projects but also in large scale. By reviewing the latest market available 3DCP, ongoing or completed projects using 3DCP, reviewing previous studies and literature that identifies all main challenges and a numerical simulation technique for 3DCP, this paper is aiming to identify how far did this technology reach and how far it still needs to go.

2. Research Method

To achieve this goal, this paper commences with a thorough market analysis, examining various promising 3D concrete printers, examining wall configurations employed by different companies, and finally, scrutinizing existing 3D printed projects worldwide. This

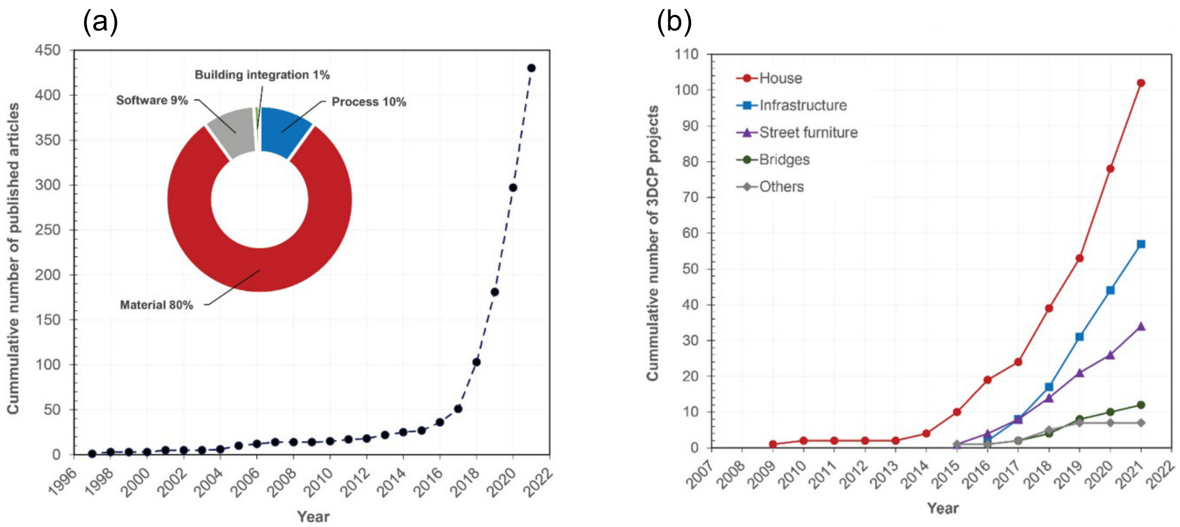


Fig. 1 (a) Trends of scientific publications on extrusion-based 3DCP since 1997 **(b)** Cumulative number of projects sorted by category. Ref.[1]

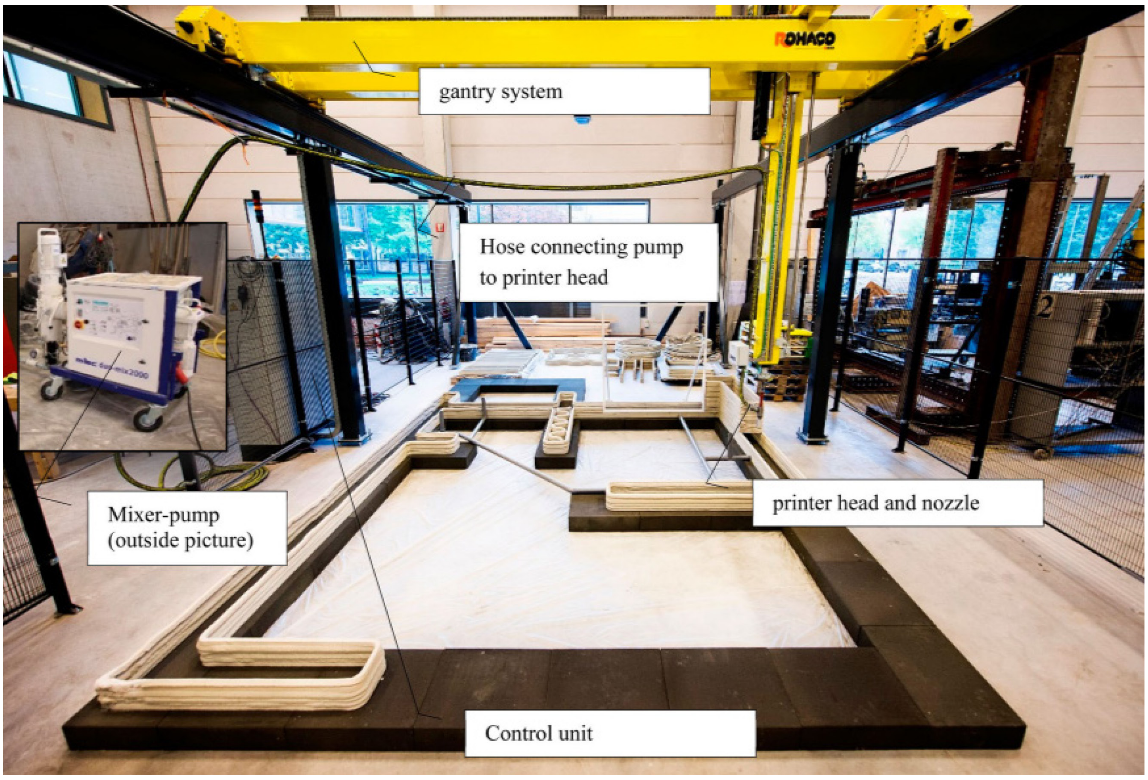


Fig. 2 Printing process using a gantry printer system. Ref.[4]

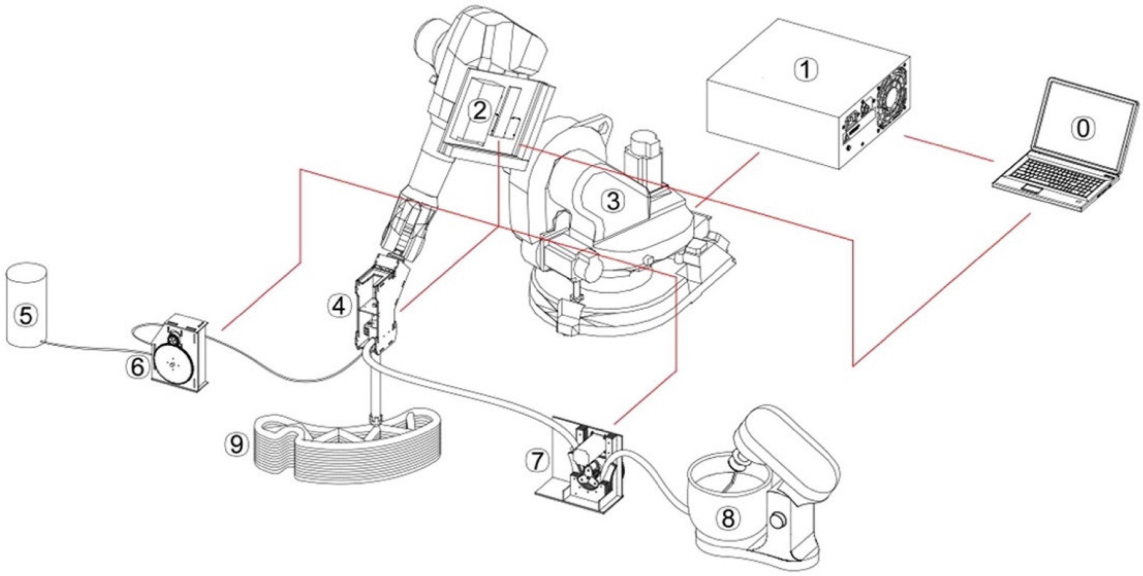


Fig. 3 Printing setup using a robotic printing arm system. Ref.[4]

establishes a robust foundation for assessing the extent of advancement in this technology.

The subsequent section of the paper addresses the hurdles encountered in the printing process and the constraints in architectural design when creating a large-scale structure using 3D Concrete Printing (3DCP). Additionally, it includes a numerical simulation of diverse structures to substantiate the findings of this study. Furthermore, selected instances of competitive 3D printers that exhibit significant progress in the market are presented, along with real-world cases that illustrate the anticipated outcomes. This data is then utilized to anticipate the potential evolution of 3DCP and the opportunities it may present in the future.

3. Market Study

3.1 Printers

There are several different companies which offer specialized 3DCP for on- and off-site manufacturing. These printers can be divided into Robotic printers and gantry systems. The former are 3D printers that use an extruder as the manipulator on a robotic arm of some sort and in the latter an extruder follows along rails which are supported by a fixed metal framework, also called the gantry.

All gantry concrete 3D printers, regardless of the size of the printed element, consist of the following main elements: the actual gantry system, which has a print head and nozzle mounted on it, as well as a mixer pump for mixing concrete and feeding it into the print head, a hose connecting the mixer and print head, and a control computer to monitor and direct the printing process **Error! Reference source not found.**. In Fig. 2(a) layout of a gantry printer is shown. The advantage of gantry systems are the greater accuracy in printing, which also results in smaller tolerances and the ability to expand the work space to a unlimited sizes.

A robotic system on the other hand is quite different, since these systems are usually way smaller and do not require much time to setup. A print head mounted atop of a robot, two pneumatic pumps, one for the premix and one for the accelerator, and a premix mixer, all of which are separate from the print head, and make up the robotic 3D printer. The pumps and the print head are both controlled by a microprocessor. An example for a robotic printer can be seen in Fig. 3.

One company that manufactures a gantry system printer is ICON, their printer, called Vulcan, is able to print on-site and provide a print head movement in all three axes while orienting itself perfectly vertical, which helps improve print quality [1]. Vulcan is able to print objects up to 3.2 m (10.5 ft) tall and 11.125 m (36.5 ft) wide while the length is without limitations, reason is that the system utilizes wheels to move the whole system in one direction [5]. The printer extrudes concrete bead, commonly used term for filament, similar to the FDM printing layer by layer [1].

Lavacrete, ICON's proprietary printing material, is used in conjunction with the Magma cement mixer and ICON's software, called BuildOS, for communication between the components [5].

COBOD designs and provides gantry system printers, called BOD, for automated construction companies. The printhead for BOD 2 is mounted on a metal structure that can freely move in three axes and print walls up to 14.5 m wide and 8.1 m tall at a speed of up to 1000 mm per second. However, this speed is restricted to 250 mm per second by EU standards. The length is, similar to the Vulcan, not limited in regards of, that more frameworks can be added to increase it [7]. The layers extruded from the BOD2 printer are anywhere from 30 to 300 mm wide and anywhere from 5 to 30 mm tall (depending on mortar consistency) [1]. A hopper is installed on the printing nozzle to improve consistency and test materials in small batches. Material feeding can be done by a printhead hopper, Mixer-pump, or reservoir. The BOD2 uses G-code data to create CAD files and sensor mapping to compensate for uneven slabs. [7] Further official printer specifications can be seen in the following tables.

Black Buffalo is another company which manufactures gantry system printers called Nexcon. It can print up to a maximum area of 8m x 8m x 8m and additionally it is able to print up to 3 stories tall. Similar to the BOD2, the NEXCON can be extended by adding tracks. Scalability is achieved by adding additional tracks, allowing relocation without disassembling the printer. The nozzle has an implemented hopper design, cameras, and swappable nozzle tips for different applications. Cleaning of the machine can be done by predefined interfaces and just requires flushing of the machine and rinsing of the nozzle. Black Buffalo also provides their own printing material, called concrete Ink, which is specifically designed to work with the printer[10]. Black Buffalo follows the Occupational Safety and Health Administration's standard of 249 mm per second (9.8 inch per second) [1].

SQ4D is also a company that manufactures 3D printers using a gantry system. Their printer is called ARCS and is like the previously mentioned printers also able to print on-site. Although SQ4D does not mention any specifications, it is known that they printed a 176.5 square meter object in 48 hours of print time [1].

Description	Unit	Value
Product	–	3D Construction Printer
Model	–	BOD2
Measurements (length x width x height)	[m]	Contact us to see size guide
Weight	[kg]	5390
Current	[A]	32
Voltage	[V]	380-480 3 phases, + N + PE (WYE)
Frequency	[Hz]	50/60
Short circuit current IKmin	[A]	500
Short circuit current, IKmax	[A]	1200
Leakage current	[mA]	300
Max. speed (X-axis)	[mm/s]	250
Max. speed (Y-axis)	[mm/s]	250
Max. speed (Z-axis)	[mm/s]	50
Sound level	[dB(A)]	Less than 70
Required bed plate flatness	[mm/m]	10
Movement system	–	Servo
Safety elements	–	The emergency stop function includes emergency stop push-buttons as input components, which are located in the following locations of the machine: • 1x on each of the Z-axis • 3x on the printhead • 1x on the operator’s controller panel • 1x on the main E-box
Connection	–	Wifi or LAN
Software	–	Soft-NA and COBOD Web Control Interface
Interface	–	Web Client (through browsers like Chrome, Safari)
Recommended operating temperature	[°C]	5-35

Table 1 BOD2 specifications [8]

Description	Unit	Value
Max printing length	[m]	No limit
Max printing width	[m]	14.6
Max printing height	[m]	8.1 + height of the concrete bases to which the printer is mounted
Max printing speed	[mm/s]	Up to 1000 (1 m/s)
Layer height	[mm]	5-40
Layer width	[mm]	30-300
Material flow	[m3/h]	Up to 7.2
Max aggregate size	[mm]	10
Printer setup time	[h]	4-6
Printer takedown time	[h]	2-3

Table 2 BOD2 additional specifications [8]

MACHINE SPECS	
PRINTABLE STORIES	1-3
RAIL SYSTEM	Stationary
PRINTER SIZE (W x L x H)	14.5m x 11.4m x 10.6m
BUILD AREA	8m x 8m x 8m
WEIGHT	19 tons
NOZZLE SIZE	35-50mm (diameter)
ASSEMBLY	
ASSEMBLY TIME	1-3 days
# OF CONTAINERS	3
# OF OPERATORS	2-3
MISC. MACHINERY	
SILO CAPACITY	10 tons
PRINTHEAD WEIGHT	100kg
POWER	
POWER CONSUMPTION	10 kW
TOTAL CONSUMPTION	33kW
RATED VOLTAGE	AC 3 Phase 220 V
FREQUENCY	50/60 Hz
MIN RATED BREAKING CURRENT	35 kA
MAX RATED BREAKING CURRENT	50 kA
SPEED	
MAX SPEED (X AXIS)	0.25m/second
MAX SPEED (Y AXIS)	0.25m /second
MAX SPEED (Z AXIS)	0.05m /second
PUMP	
ROTOR PUMP	Semi-Automatic
PUMP SOFTWARE	Semi-Automatic

Table 3 NEXCON specifications. Ref. [10]

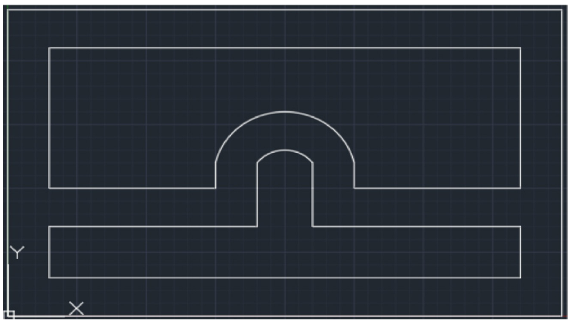


Fig. 2 Drawing Mimicking ICON wall configuration. Ref. [4]

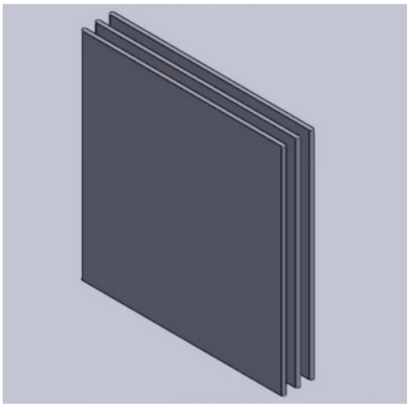


Fig. 5 Drawing Mimicking COBOD wall configuration. Ref. [4]

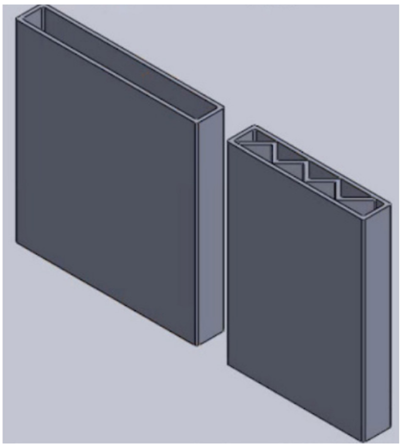


Fig. 6 Black Buffalo wall configuration options [1]

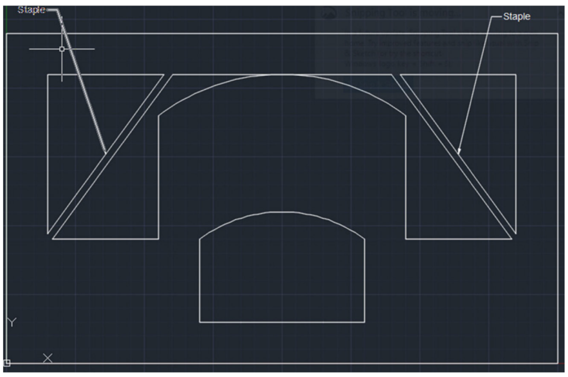


Fig. 7 SQ4D Typica wall configuration. Ref. [4]

CyBe is the first company that manufactures gantry system printers as well as robotic printers. They provide four different printer variations called CyBe G (Gantry), CyBe RT (Robot Track), CyBe RC (Robot Crawler) and the CyBe R (Robot). The Gantry 3D printer is a large-scale, stationary 3D printer used to print prefabricated elements for assembly on site. The robot track system can be used to prefabricate whole houses, with extendable reach for larger printed elements. The robot crawler system is a mobile 3D printer designed for on-site and factory printing, with hydraulic feet and a rotating nozzle to create complex shapes and wall-textures. The robot system is stationary and is designed for off-site and facility-based printing. The work area is shaped like a donut and has a range of 2.65 m x 3.2 m. The printer has a speed of 500 mm/s and can use different types of mortar [12].

3.2 Formwork configuration

Companies design formwork geometries with unique details to ensure stability and thermal insulation [1].

ICON for example prints hollow shells with a special design, which contains three cavity spaces. These cavities then are filled with spray foam for thermal insulation or rebar and concrete for stability [1]. A replication of this design can be seen in the following .

Walls printed by COBOD's printer are used as formwork for filling material and can be filled with or without vertical reinforcement. Also, for their walls that utilize three cavities, concrete is filled into the interior cavity, while the exterior cavities is filled with insulation to improve thermal insulation.

Black Buffalo prints hollow walls, which then are filled with insulation, concrete, and reinforcement. Also, during the printing metal reinforcement is placed between subsequent layers. Furthermore, Black Buffalo has experimented with zigzag pattern walls to create two cavities, which can be used each for reinforcement and concrete and insulation respectably [1].

SQ4D designs walls acting like formwork. The cavity present within the wall is able to be filled with structural columns, utilities, and insulation. While also putting strengthening materials inside the cavity SQ4D also inserts metal staples in the still wet concrete to better connect the inside and outside layer [1]. An estimated model of this was done with the information found on SQ4D's website and can be seen in .

3.3 Built Projects

The Chicon house, ICON's first creation, received the first American government approval for a three-dimensional (3D) printed home. ICON used the predecessor of their Vulcan printer to manufacture these houses. All walls (approximately 55.74-74.32 square meters (600–800 square ft)) were allegedly printed in 24h.The house itself cost about $10,000 to print in complete.

Another project of ICON is a whole community with 100 homes including 8 different designs, as shown in the following. These floorplans come in 24 different elecations ranging from 146 to 196 square meter (1.573 to 2.112 square feet). The project is located in Texas Hill country, US, and is called the Genisis Collection at Wolf Ranch. According to ICON, the project finishes in the near future reservations start in 2023 [6].

The first 3D printed house in Borneo, a large island in Asia, was designed by the company SCIB and printed with the BOD2. The house is a 90 square meter 3D printed house completed in around 46 hours. The total length of the print was over 9 km and was extruded in a total of 145 layers each of 2 cm height. Afterwards the walls were plastered to protect the walls from the high humidity which is common in that region.

SQ4D has listed the first 3D-printed home in the United States. The property was printed on-site with the ARCS 3D printer and listed at a price of $299,999, which is around half of what a similar property in the region would cost. This home, built with concrete using the ARCS 3D printer, is located in the United States and has approximately 130 square meters of living space, including 3 bedrooms 2 full bathrooms and an open floor plan plus a 70 square meter car garage [11].

4. Challenges and Limitations

Due to the nature of depositing concrete filament layer by layer, the outcome of the printing process is dependent on the interplay between the material, printing machine, and the design of the object to be printed. Hence, it is imperative to establish a cohesive relationship between these three components, as opposed to solely optimizing individual components [15]. Despite the substantial potential of 3DCP, the technology is faced with a series of challenges and limitations that must be addressed to attain its successful implementation. This brings us to the concept of the buildability of a 3DCP mass. In which it refers to the ability of the printed layers to maintain their shape with the gradual increases of load induced by the and limitations that affect the output of a 3DCP process.

4.1 Challenges in Printing Process

Time Intervals

The interval between each consecutive subsequent layers. The following sections aim to comprehensively state these challenges

layer during the 3DCP process is a crucial factor that can impact both the buildability and the strength of the interlayer bonds. Increasing this interval can result in better stability of the deposited layer's shape but may also decrease the interlayer bond strength due to the higher likelihood of air void formation at the interface. On the other hand, decreasing the time between layers can cause irregular deformations in the printed layers as the bottom layer may not have enough stiffness to support the weight of the next layer. This could ultimately lead to failure of the print as the continued load will become too much for the bottom layer to sustain.

According to a study by Chen et al. (2020) [15], the impact of time interval on air void formation between two consecutive layers was examined. As shown in Error! Reference source not found., the findings showed that before the upper layer was placed, the first layer's cross-section was rough. However, after 20 seconds the upper layer was added, the cross-section revealed a seamless and well-bonded connection between the two

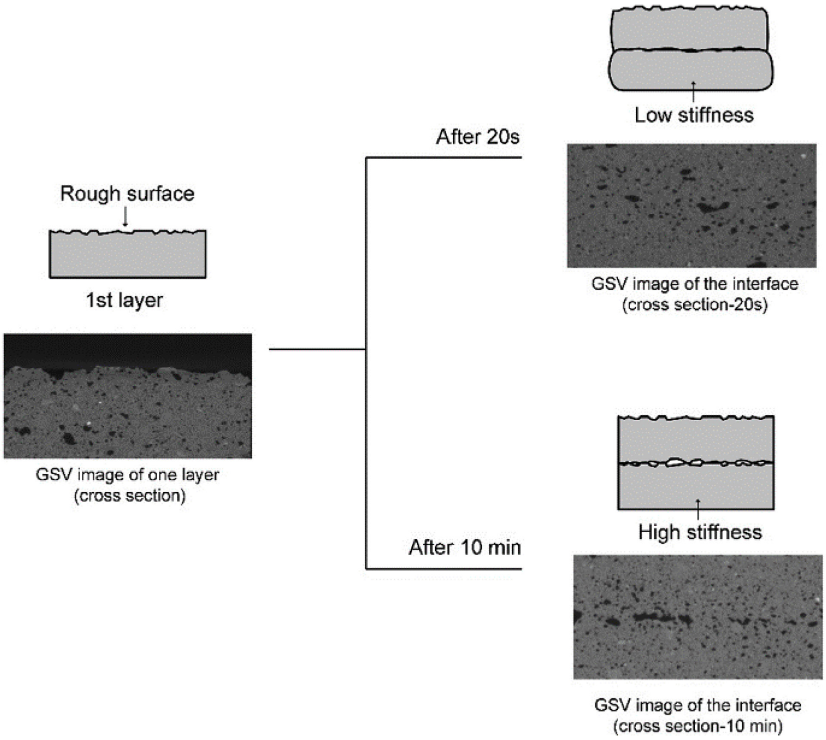


Fig. 8. Illustration of the influences of extending the time interval on air void formation at the interface. Ref.[16]

layers. The bottom layer, however, showed significant shape deformation due to the weight of the top layer. In a second test where the time interval between layers was 10 minutes, the bottom layer showed no deformation, significant air voids were observed between the layers, leading to a weak interlayer bond.

Extrusion Nozzle Variables

Another critical challenge for the buildability of a 3DCP process is the shape of the extrusion nozzle. In the case of a down-flow direction with a round opening Fig. 9**Fig.** (a), the new layer compresses the substrate layer upon deposition, leading to a combination of the weight of the new layer and the force applied by the nozzle acting on the bottom layer. The deformation of the substrate layers can be reduced by adjusting the nozzle standoff distance but may also result in material collapse once the load reaches the yield stress of the substrate, as shown in Fig. 10. A high nozzle standoff distance can cause buckling failure before material failure, which can be exacerbated by misalignment of the printing path or a dropped layer process. Using a back-flow or hybrid back- and down-flow nozzle with a rectangular opening Fig. 9(b) can increase the contact area between layers, resulting in a more stable printing process. [16] [14].

(a)

(b)

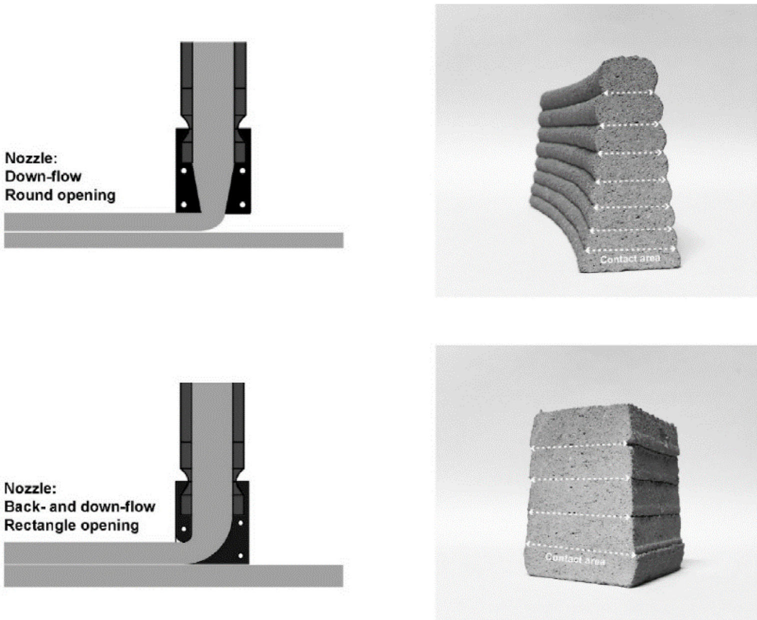


Fig. 9 (a) Illustration of the printing using the down-flow nozzle with a round opening and the cross-section of the printed sample. (b) Illustration of the printing using the back- and down-flow nozzle with a rectangle opening and the cross-section of the printed sample. The dashed line represents the contact area between layers. Ref. [17]

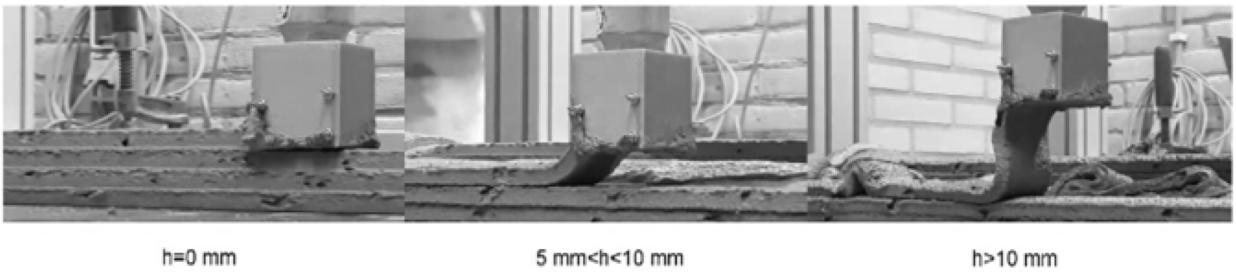


Fig. 10 Increasing the nozzle standoff distance h could lead to the inaccurate layer deposition Ref. [15]

Print Speed / Material Flow Rate

The ratio between the flow of material outside the extrusion nozzle and the speed of the nozzle is one of the other buildability challenges in 3DCP. Tay et al. (2019) [17] conducted an experiment to test the extruded concrete state with different material flow speed and print speed ratios. This experiment was done with all other parameters kept constant. As shown in Fig. 11, high flow rates and slow travel speeds resulted in a larger filament surface area. This was because a greater amount of material was extruded than expected, causing the material to be pushed in the lateral direction onto the substrate.

Although the excess material deposited improved the bonding between layers, leading to better mechanical strength, however, resulted in poor surface finish and poor geometric resolution. On the other hand, large breaks were found in low flow rates and fast travel speeds. These breaks were caused by the disproportionate slow flow rate of the material exiting the nozzle, causing a friction force between the substrate and the material which resulted in shear and breakages. Fig. shows a schematic overview of the results of the experiment and defining it into four regions. Each of which theoretically gives an

expected result for different flow rate and print speed ratio. Stating that printing processes in regions B and C produces the best extrusion output with a sacrifice of either the stability of the extrusion or the overall print time. [17]

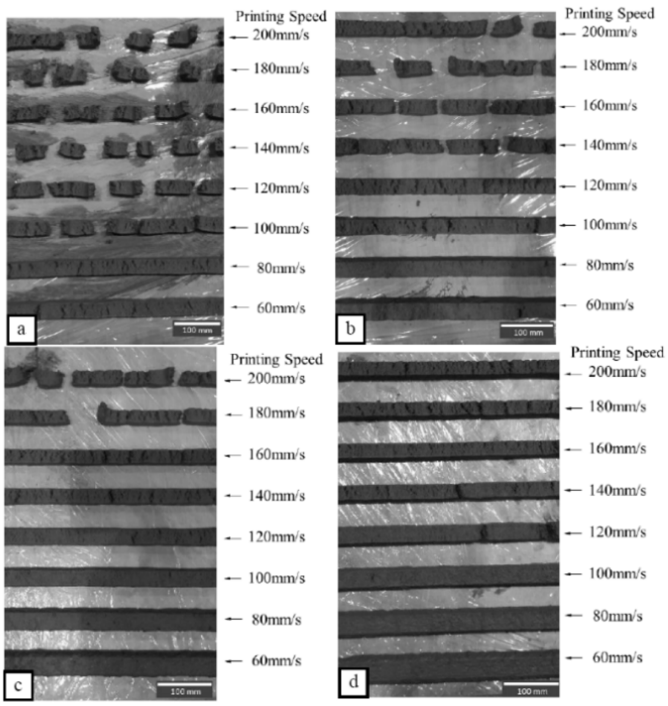


Fig. 11 Filament printed with different flow rate (a) flow rate: 37.9 ml/s (b) flow rate: 45.2 ml/s (c) flow rate: 48.0 ml/s (d) flow rate: 51.3 ml/s. Ref. [18]

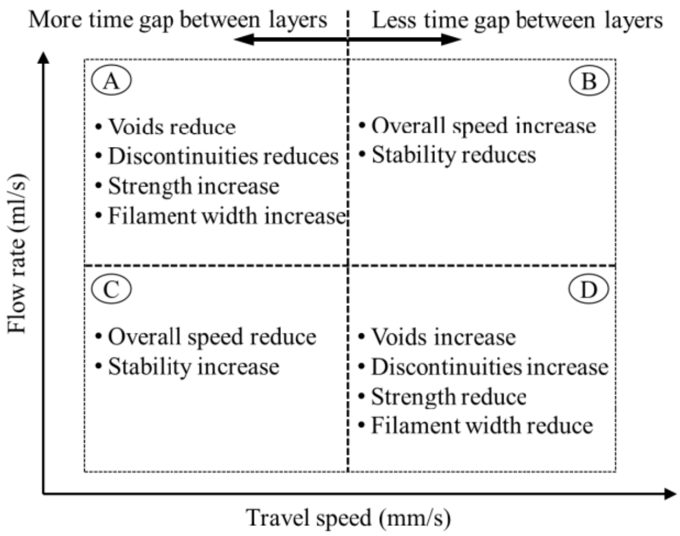


Fig. 12. Effects of flow rate and travel speed on the printed Ref. [18]

As discussed before the structural integrity of the printed layers is one of most crucial parameter to take in consideration in the printing process, whereas in a design point of view the flow rate and print speed ration plays an important role in the final look of the extruded layers. Fig. 12 shows the difference in the final output of a 3DCP object with a well implemented ratio and without.[18] Both experiments look like the object is stable but with the difference in the outer surface finishing quality, however inadequate material deposition can result in even more detrimental effects, such as the formation of voids that can weaken the structure. It is important to be cautious during and after the printing process to enhance the surface quality and precision of the dimensions.[15]

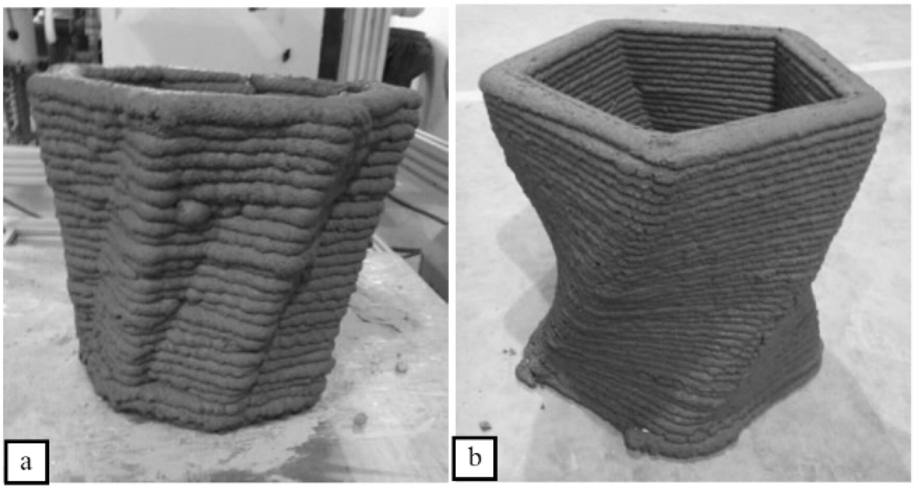


Fig. 12. (a) Poor balance between travel speed and flow rate (b) proper balance Ref.[19]

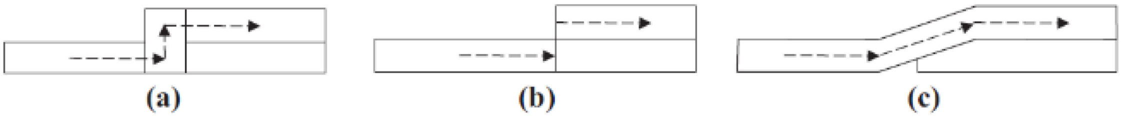


Fig. 13 Stacking strategy. (a)Moving vertically with extrusion. (b)Moving vertically without extrusion. (c) Moving gradually with extrusion. Ref. [19]

Transition to consecutive layer

The stacking of planar extrusion layers is the fundamental concept of 3DCP.In this stacking process a challenge is faced by setting the tool path of the nozzle to increase its height to start extruding the upper layer. Where a sudden up movement would cause a gap in between the endpoints of the printed layer, so some strategies were introduced by Bos et al. (2016) [20]. Fig. 13 shows schematically the tool path strategies that could be used to efficiently transition to the consecutive layer. Fig. 13(a) the toolpath moves vertically from the first layer to the second layer while continuously extruding the filament. This results in a vertical filament being extruded during the layer transition.

However, this vertical filament can be prevented if the nozzle stops providing the concrete material while moving to the next layer, as demonstrated in Fig. 13(b). The third strategy is that the print head moves upward gradually from the printing surface, with the upward movement evenly distributed over a significant portion of the filament deposition plane Fig. 13(c). Bos et al. (2016) stated that theoretically the second strategy shown in Fig. 13(b) would produce the smoothest results with no excess material and no voids between the layers. [20] A note to be taken that, the selection of stacking strategy may depend on material property, desired texture and extrusion mechanism.[19]

4.2 Limitations in Design

Geometry

When designing a structure to be 3DCP, many parameters should be taken into consideration to achieve the buildability and structural integrity of the print. Firstly, are the corners or the transition of the extrusion’s direction of flow on the same plane. Many factors should be taken in consideration while introducing a corner as it causes a disparity in the rate of material deposition between the interior and exterior of the filament, particularly near the corner center Fig. 14. This discrepancy can cause the outer edge of the filament to tear and the section to become distorted if it becomes too pronounced. To avoid these issues, it is necessary to maintain a minimum radius of curvature. However this radius depends on the extruded filament size, material properties, and print speed/flowrate ratio.[17][19][20]

Fig. 14 Excess material deposition while forming a corner. Ref. [24]

Overhangs mean the deviation of the central path of the extruding layer from the previous extruded layer, causing a cantilevered non-centrally stacked layer. Due the influence of gravity on elements that lack support structures and the limited tensile strength of a freshly extruded concrete, deformation or even failure in the print will occur as shown in Fig. 15. Thus, a maximum angle of overhangs should be taken in consideration in the design process to ensure the buildability of the structure Fig. 15(b). This angle is influenced by the properties of the concrete that is used as well as the overall shape of the structure.well as the overall shape of the structure. Concluding from this that in architectural structures openings could be printed with no lintel support to allow the layers to be extruded using the maximum overhangs angle slope design of the opening as shown in Fig. 16. [19][17]

Build Area

According to Appolloni and D'Alessandro (2021) [21] the minimum livable housing requirement for a single person is an area of 6m^2 and a height of 2.4m. Thus, in large scale printing process the build area is limited by the size of the printer. As shown in Table 4 the available capacities of 3DCP printers in the market thus architectural designs are limited with those dimensions. Furthermore, using a relatively large 3DCP with a single nozzle for the printing process may result in a prolonged build time as well as creating a new challenge of transporting and setting up the printer on the site. (Ko, 2021b). [19][24]

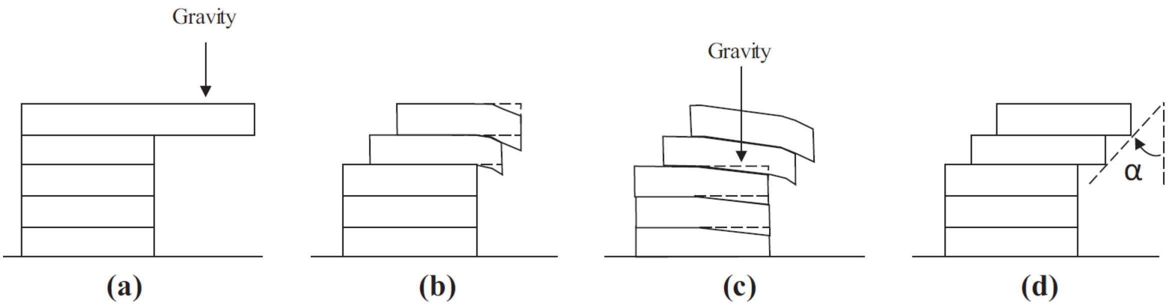


Fig. 15 Overhanging issues (exaggerated for demonstration). (a) Gravity effect. (b) Overhanging deformation. (c) Uneven deformation. (d) Overhanging angle (α). Ref.

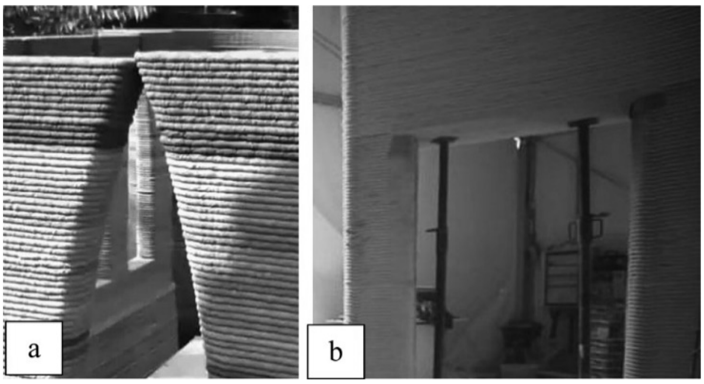


Fig. 16 Different techniques used for printing overhangs. (a) support-less closed structure design to support subsequent overhanging layer (b) wood planks with supporting scaffolding. Ref.

Manufacturer	Model	Process	Type of System	Materials	Capacity (m)
BETABRAM	*P1V2*	*Extrusion*	*Gantry Based*	*Concrete*	*16 × 8.2 × 3*
COBOD	*BOD2*	*Extrusion*	*Gantry Based*	*Concrete*	*1.9 × 2.1 × 1.5*[a]
Constructions-3D	*Maxi Printer*	*Extrusion*	*Robotic Arm*	*Concrete*	*13 × 13 × 10*
CYBE	*RC 3DP*	*Extrusion*	*Robotic Arm*	*Concrete*	
ICON	*Vulcan II*		*Gantry Based*	*Concrete*	*8.5 × 8.5 × 2.6*
MUDBOTS	*3D Printer 664*	*Extrusion*	*Gantry Based*	*Concrete*	*1.8 × 1.8 × 1.2*
	3D Printer 10,108				*3 × 3 × 2.4*
	3D Printer 18,189				*5.5 × 5.5 × 2.7*
	3D Printer 25,259				*7.6 × 7.6 × 2.7*
	3D Printer 252,512				*7.6 × 7.6 × 3.6*
	3D Printer 50,509				*o*
	3D Printer 501,009				*15 × 30 × 2.7*
TOTAL KUSTOM	*Stroy Bot 6.2*	*Extrusion*	*Gantry Based*	*Concrete, Polymer, Ceramics*	*10 × 20 × 6*
	Stroy Bot 7.1				*10 × 20 × 4*
	Labyrinth 3D				*5 × 5 × 3*
	Architect's Printer				*1 × 0.5 × 0.5*
WASP	*Crane WASP*	*Extrusion*	*Delta*	*Earth-based, concrete, Geopolymer*	*Ø 6.3 x 3*

[a] Custom Configurations offered.

Table 4 Commercially available Concrete 3D printers. Ref.[25]

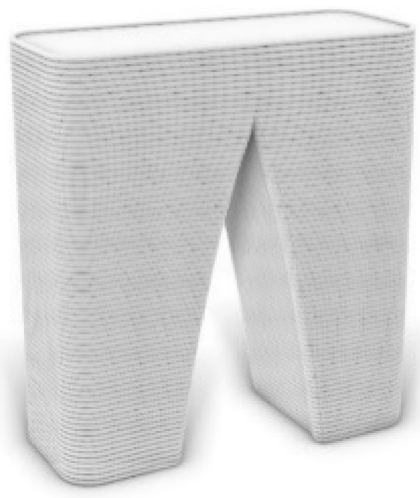
5. Numerical Case Study

The aim of this case study is to evaluate the buildability of three distinct 3D concrete structures using numerical simulation using CobraPrint (Rhino3D Grasshopper plugin) and Abaqus software, as well as testing the reliability of this type of simulation. The buildability of each structure was evaluated by changing a single factor, the print speed (mm/s), while keeping the material properties (Table 5) constant throughout the simulation. The study focused on the structural integrity of the printed objects , and the analysis was

Density	**2500 kg/m³**
Young's Modulus	0.0032 * t + 0.048 N/mm²
Poisson's ratio	0.22
Cohesion	0.00003 * t + 0.004 N/mm²
Friction angle	20°
Dilation angle	13°

Table 5 Material constant properties used in the numerical simulation.

(c)



(a)

(b)

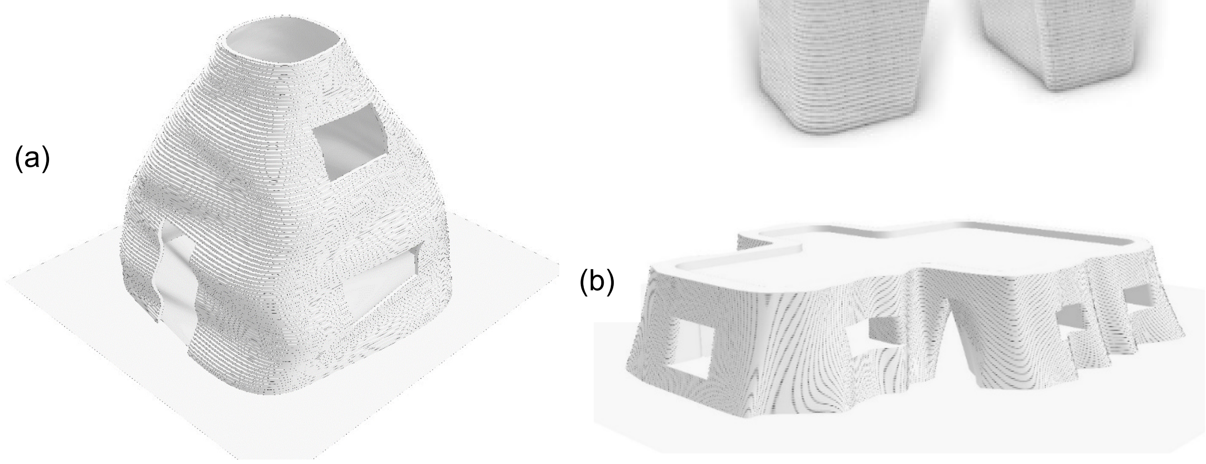


Fig. 17 (a)Structure I a semi roofed dwelling (b) Structure II was an extremely curved organic wall with an incline, (b) Structure III was a wall section with a door opening without the use of a "Lintel" support.

conducted without taking into account the presence of any openings. This study provides valuable insights into the buildability of 3D concrete structures and deformation of the mass due to the impact of print speed on the printing process, as well as an overview of the technical issues and analyze the numerical modeling and simulation techniques that have been used in related literature.[24][26]

5.1 Simulations Results

Structure I

In this simulation it aims to test the ability of printing of a dwelling (Fig. 18 (a)) that could be printed with the least about of human intervention in the building process by printing most of the roof of the mass with the maximum overhang angle of 45° was used as discussed previously. The material properties used in all the study was constant as stated before and is shown in Table 5.

As shown in Fig. 18 three trials were done on the dwelling structure. In the first trial Fig. 18 (a) a print speed of 100 mm/s was used. The simulation failed at the 14th layer which is at the height of about 3.4 meters or in other words the interlayer connection between the 14th and the 13th printed layers was not sufficient enough to receive further layers to print.

Thus, the high value of deformation so the misalignment of the layers to occur. Lower speeds was simulated at 60 mm/s (Fig. 18 (b)) and 15 mm/s (Fig. 18 (c)). In the 60 mm/s simulation it failed for the same reasons as the 100 mm/s simulation, but the deformation of the structure was less and continued till the 20th layer which is equivalent to the height of about 4.8 meters. A full print was achieved at the speed of 15 mm/s, the result will be discussed further in section 0.

Structure II

Structure II Fig. 19 was simulated to test an exterior walls of a 3 room house, its design aimed to show how 3DCP build organic formed walls with lower cost than traditional construction. The maximum overhang angle used to design the walls was 30°. Three simulations were done at 100 m/s, 70mm/s, and 25 mm/s.

Fig. 17 shows the results of 70mm/s (Fig. 19) and 25 mm/s (Fig. 20), whereas at speed 100 mm/s the speed was so high for the size of the structure so after printing the first layer the second layer was immediately misaligned with the first one as the deformation was too high.

As for the second simulation (70 mm/s) the simulation failed the 12th layer which is equivalent to a height of 2.3 meters, as the walls on the sides of the structure had a very high overhang angle similar to the rest of the building whereas it has a straight section profile thus there was no perpendicular

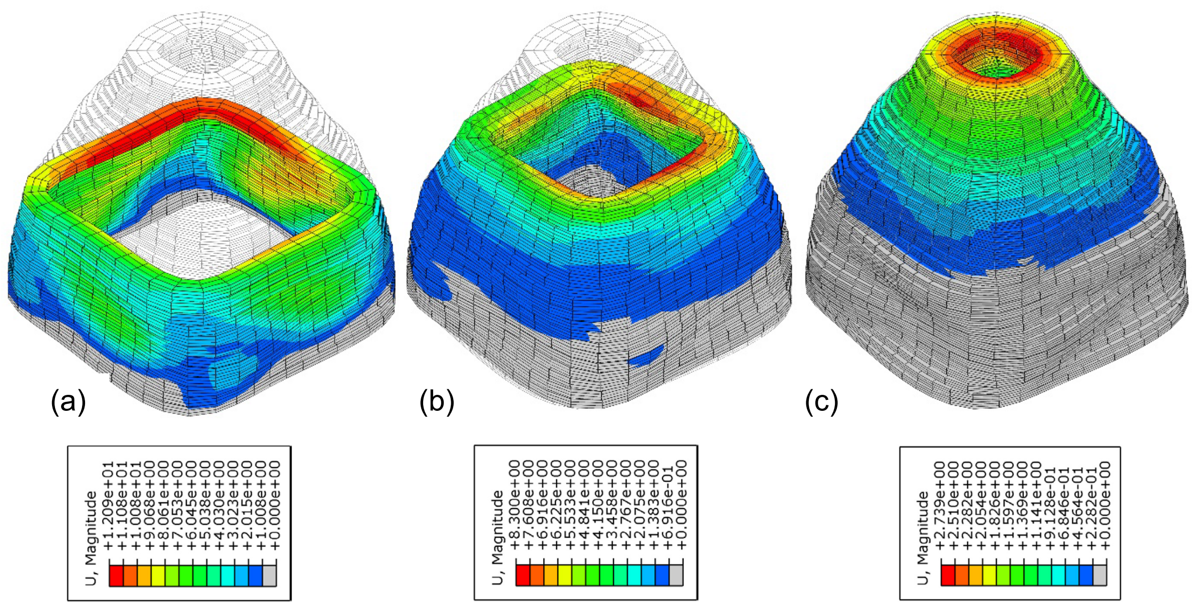


Fig. 18 Simulation final output at speeds: (a) 100 mm/s (b) 60 mm/s (c) 15 mm/s.

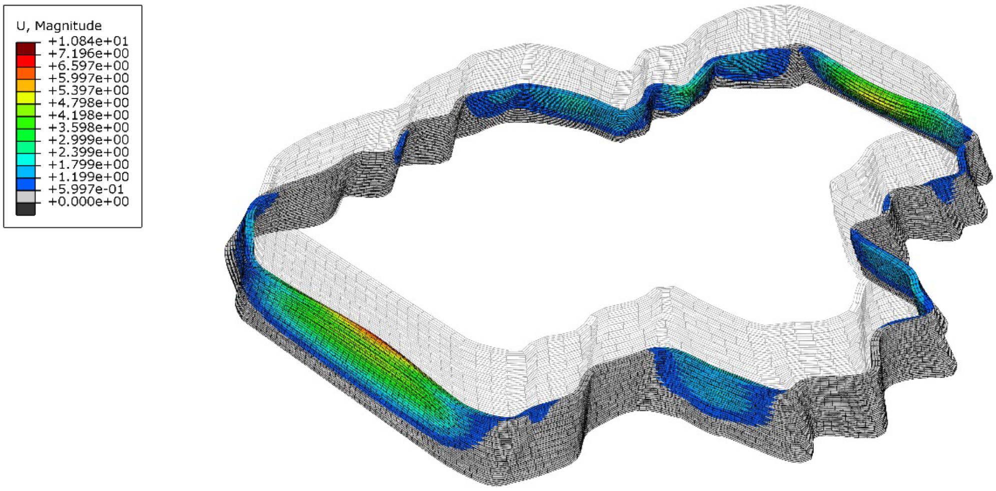


Fig. 19 Simulation of Structure II at speed 70mm/s.

(b)

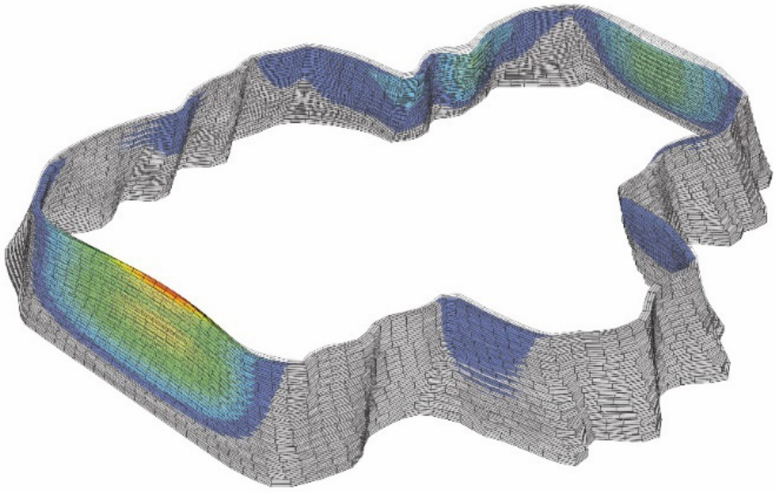


Fig. 20 Simulation of Structure II at speed 25 mm/s.

support to hold its weight while printing at this speed, before the concrete hardens and be able to sustain the compression caused by the upper layers overhangs. Furthermore, at speed 25 mm/s the print was successful and detailed analysis will be discussed in section 4.2.

Structure III

Lastly, a numerical simulation was performed for a section of a wall opening resembling a door as discussed in section 4.2. This way of design could open ways to create opening in 3DCP without any external support, but it raises the question of the value of architectural design aesthetics and functionality. However design has no limits and merging it with modern technologies could allow us to do what is now called the impossible. The door section has an overhang angle of 13° and not symmetrical, 2 simulations was done for this structure one at print speed 50 mm/s Fig. 21(a) and 10 mm/s Fig. 21(b). The 50 mm/s speed failed at the 11^{th} layer (height=3.1 meters) as the 2 sides of the mass got highly deformed and buckled not allow further layers to be printed. Whereas at speed 10 mm/s the print was successful with minimal deformations.

5.2 Simulation Findings

As seen clearly in the sections of the three simulations done (Fig. 22) the deformations are of a very high value which is imminent due to the elasticity property of the concrete used. On the other hand, as stated before the main purpose of this study was to test the effect of print speed on the value of deformation of the printed object, and that was proved positively. Form literature review it states techniques are

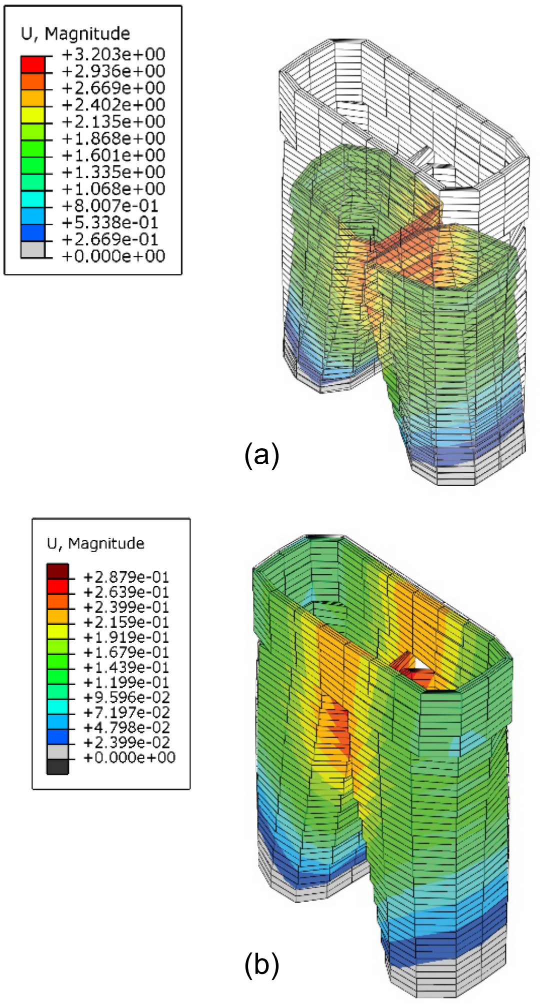


Fig. 21 Structure III simulation results at speeds: (a) 50 mm/s (b) 10 mm/s

used to spray or add rapid hardener to the extruded concrete to decrease the amount of time the concrete needs to have sufficient tensile strength to receive new layers loads, thus having a fast print speed with near to zero deformation in the structure.

Analyzing structure I Fig. 22(a), the final print was printed with all layers but due to the deformation and compressive loads the whole structure buckled downwards. whereas due to very long section of continuous overhangs , structure II Fig. 22(b) showed high tensile stress in the straight sections of the print with a very high deformation value but due to the slow print speed the concrete layers had strong interlayer bond to withstand the tension. Finally in Structure III (Fig.22 (c)) due to the compact design the deformation was not very high where as in the high print speed it collapsed after relatively low height. This proves that print speed cannot be a fixed number for all prints, it involves a study of the shape of the mass, material properties and much more.

This technique of simulation is very primary that does not take into consideration a lot of factors in 3DCP, which is a complex process and involves various physics stages, making it difficult to determine the impact of each parameter on mechanical performance during printing. Thus, the optimal process parameters are typically developed by trial-and-error experiments, which is time-

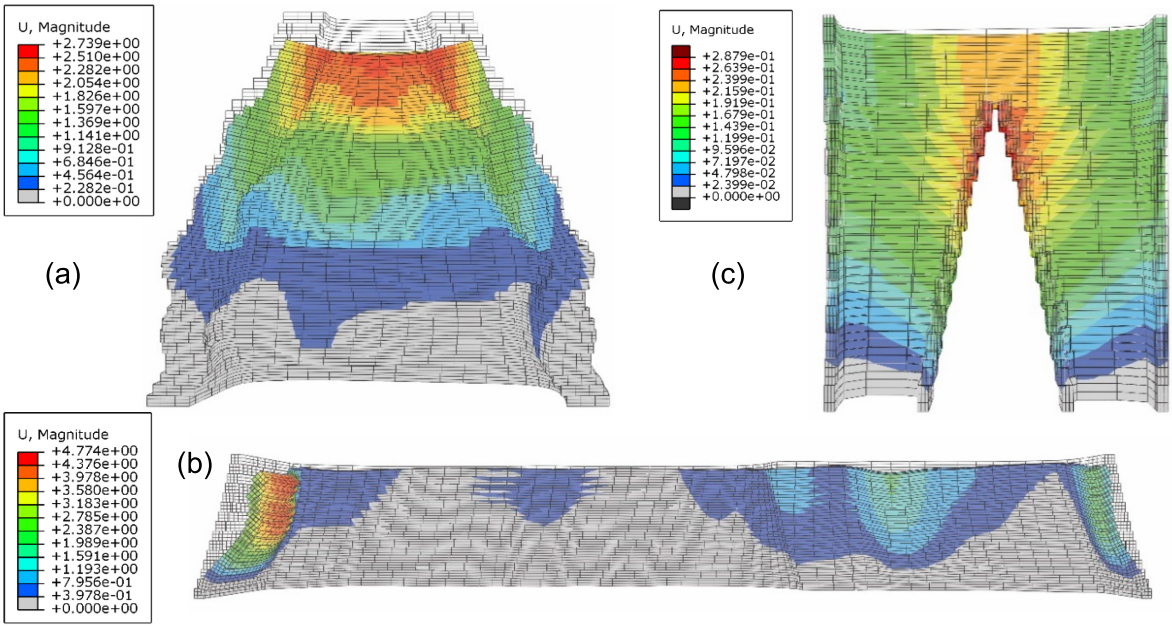


Fig. 22 Sections showing deformation of structures after print. (a) Structure I (b) Structure II (c) Structure III.

consuming and expensive for large structures. Numerical modeling and simulations are essential to predict material performance and avoid extensive trial-and-error, particularly for mature, larger-scale applications of 3DCP. [25]

6. Conclusion

Concluding from the market study , literature review and numerical simulation:

- High opportunities in market available 3DCP where presented, each type of printer has its pros and cons . As gantry systems has its advantage of high precision while a huge drawback in assemble and setting up it. On the other hand, robotic 3DCP are more compact and easier to set up, whereas produces less accurate extrusion-based prints.
- Market available 3DCP promises high speed printing, however, in realty due to the structural integrity for the prints, lower speeds are used and are not shared publicly to find solutions to make the technology faster, thus slowing the rate of development of 3DCP in construction.
- Due to the market competition 3DCP developments are taking a slow track due to the lack of information sharing.
- Standardized testing procedures should be implemented to make information sharing more efficient and reliable.
- Further investigation and research are required to enable greater integration of the technology into construction, as is the case with additive manufacturing in other sectors, in order to take advantage of the advancements made so far.
- Guidelines for geometry design and build tolerance control are required for better building integration, making 3DCP more buildable and reduction in testing costs.
- The importance of a more reliable digital twin or simulation of the printing process needs to be developed to make the technology develop in a faster rate and reduce experimentation costs is crucial.

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Ye Lu and Mia Obralic

How to contribute to reducing fall fatalities on construction sites: Cloud Computing and On-Site Automation

Abstract

The aim of this paper is to significantly reduce the incidence of accidents in the construction industry by discussing the possibilities of unconventional solutions to the problem of falling from heights in two different directions based on current technology: cloud computing and automation of on-site construction.

To explore more, a systematic literature review was conducted to understand the specific causes of fall accidents, and a new framework system was constructed to optimize the current measures. In developed countries, the accident rate of construction is decreasing, but in terms of accident risk, the construction industry is still the highest risk factor.

Doi: 10.18154/RWTH-2023-08860

Keywords: construction industry, fatal accidents, reduce falling fatalities, reduce, cloud, automation.

Image created with Adobe Firefly

1. Introduction

Compared with other industries, the construction industry is less industrialized, using traditional human resource-intensive manufacturing as a means. [1]. (See Figure 1) So until today, the construction manufacturing industry itself is inseparable from a large amount of manpower, taking over all aspects from the ground to the roof. The construction industry is one of the most dangerous industries in terms of safety. In the 10 years from 2009 to 2018, the number of deaths in various industries in the United States was 48,391, among which the number of work-related injuries in the construction industry was the highest, nearly one-fifth of the people were from the construction industry, and 8,792 people died (see Table 1 and Figure 1)[2]. Among them, falling is the main cause of accidents.

In recent decades, many countries have adopted many policy measures to try to reduce the accident rate in the construction industry[3]. For example, it is required to install fences in high-risk areas, and regular safety education is provided to construction workers. However, current traditional safety measures have not significantly reduced fatal accidents such as falls. Especially in countries with relatively low labor costs[4]. Even in developed countries, the accident rate of construction is decreasing year by year, but in terms of accident risk, the construction industry is still the industry with the highest risk factor[5].

This paper aims to substantially reduce the accident rate in the construction industry by discussing the possibility of unconventional solutions to the problem of falls on the basis of existing technologies in two different directions: cloud computing and automation of on-site construction. Concerning job site safety, decisions and trade-offs are made. To explore more, we conducted a systematic literature review to understand the specific c auses of fall accidents. And according to the conclusions drawn in the literature review, a new framework system is constructed to optimize the current measures to reduce the accident rate of construction sites.

2. Research methods

2.1 Determine the purpose:

In order to optimize the current measures to reduce the rate of fall accidents on construction sites, it is necessary to u

nderstand the reasons for frequent falls from heights, as well as the process and mechanism of their prevention in advance. Additionally, the limitations, strengths, and weaknesses of current solutions are being investigated. Based on the results of the

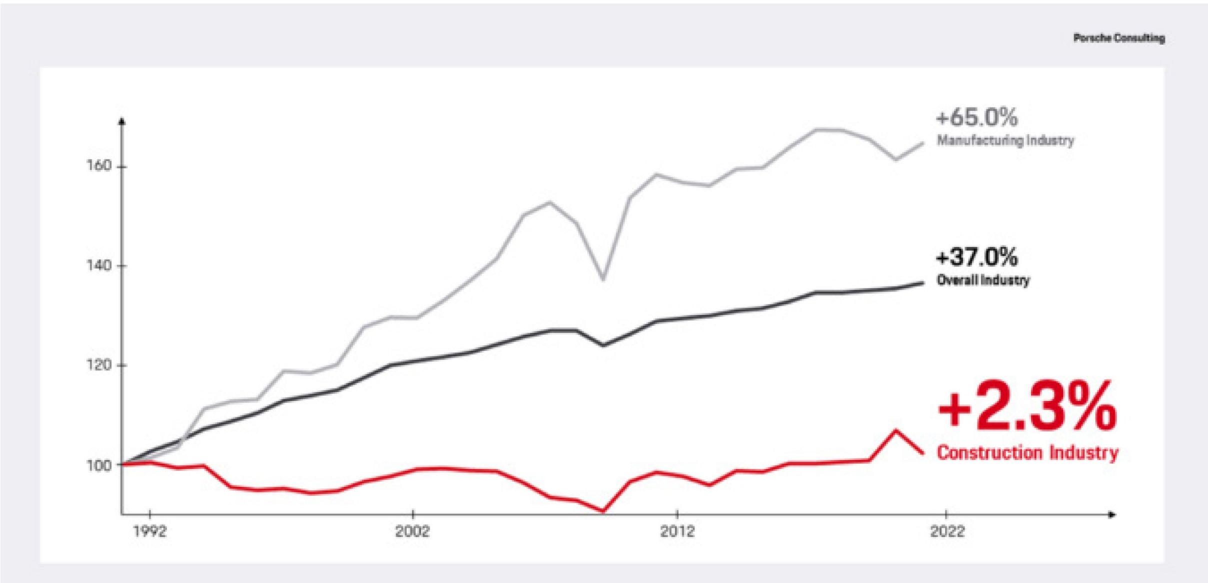

Figure 1. Labor productivity per hour worked in the construction industry in Germany lags significantly behind other sectors, but at the same time offers great potential for improvement

Year	Construction Industry	All Industries	Percentage%
2009	834	4551	18.33
2010	774	4690	16.50
2011	738	4693	15.73
2012	806	4628	17.42
2013	828	4585	18.06
2014	899	4821	18.65
2015	937	4836	19.38
2016	991	5190	19.09
2017	977	5147	18.98
2018	1008	5250	19.20
2019	1066	5333	19.99
2020	976	4764	20.49
2021	951	5190	18.32
Total	11785	63678	18.51

Table 1. Percentage of Deaths in the Construction Industry in Comparison with Total[1][2]

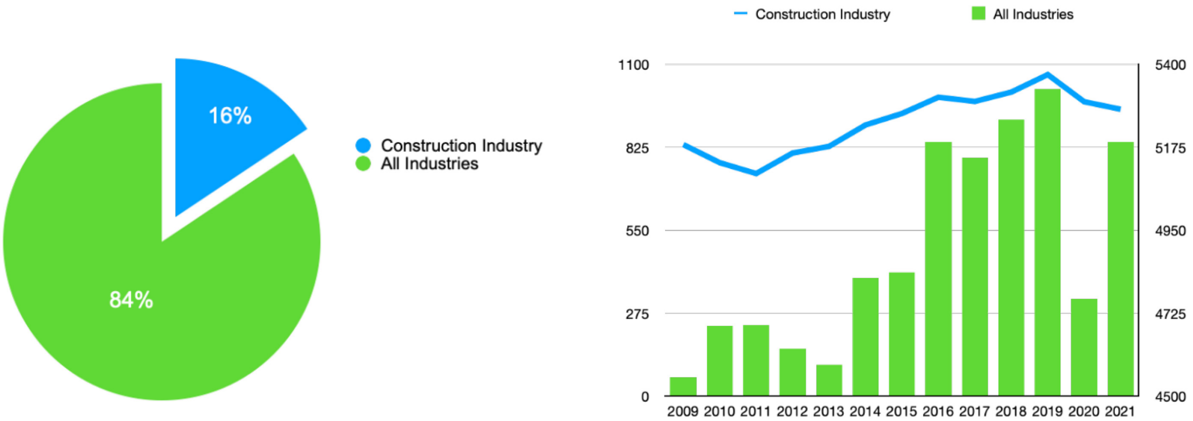

Figure 2. Percentage of Deaths in the Construction Industry in Comparison with Total Number of Fatali-ties across all the industries in the United States from 2009-2021

literature review, the height impact factors and high correlation results of the accidents caused by falls from heights are used as the basis for the establishment of the framework. And on this basis, start from two aspects of "optimizing existing technology and developing cloud processing system" and "on-site construction automation".

2.2 Select database

The data are extracted from official historical documents on construction site accident statistics in various countries as well as published literature. Considering the different results caused by different economic levels and policies, this paper selects the data of three countries for multiple comparisons. (See Table 2.) The choice of the United States, Germany, and China facilitates a variety of side-by-side comparisons: it demonstrates that safety in construction is not only a problem in low-cost labor-integrated countries, but also in developed countries and in countries with better safety systems. We will discuss this conclusion below.

2.3 Select keywords

Through the reading of a large number of literature (See Table 3.)and the first round of data analysis, it is concluded that falling is the primary factor leading to death, and the process and mechanism of preventing high-altitude falling accidents are further studied to find out the optimization plan[6]. earch keywords: combinations of ‘risk(s) of fall(s)’, ‘fall(s)’, ‘injury/injuries’, ‘risk(s)’, ‘fall(s) factor(s)/ factor(s) of fall(s)’, ‘Monitoring technology’, ‘digital device’, ‘cloud computing’, ‘automated assembly ‘and ‘construction industry’.

Countries	Data sources	Year
The United States	BLS: United States Bureau of Labor Statistics	2009-2021
Germany	AF: Statistik – Arbeitsunfallgeschehen	2010-2021
China	MHUR: Ministry of Housing and Urban-Rural Development of the People's Republic of China	2010-2021

Table 2. Data sources for collection of the national data.

Keywords	Reason	Number of literature
Fatality accidents national	Data sourse	10
Falling From Height national	Data analysis	7
Hazard Recognition	Safety solution	12
Reduce Falling Hazard	Safety solution	5
Automation Construction	Safety solution	13
Total		47

Table 3. The results of the first round of review of selected literature through the selection of keywords

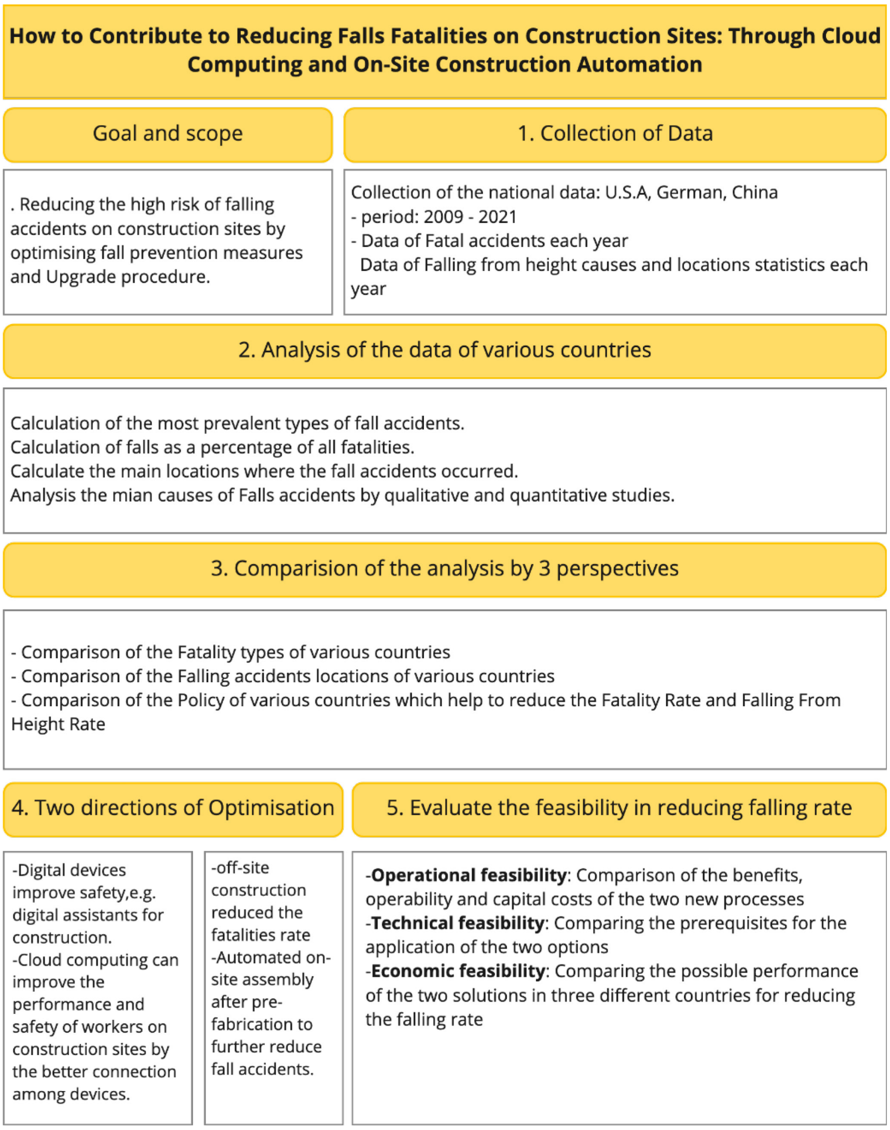

Figure 3. Research Process, made by YeLu

Year	FALLS, SLIPS, TRIPS	FIRES AND EXPLOSIONS	EXPOSURE TO HARMFUL SUBSTANCES OR ENVIRONMENTS	CONTACT WITH OBJECTS AND EQUIPMENT	VIOLENCE AND OTHER INJURIES BY PERSONS OR ANIMALS	TRANSPORTATION INCIDENTS	TOTAL
2011	269	11	113	132	33	221	779
2012	294	9	104	139	37	266	849
2013	305	13	112	147	37	239	853
2014	363	15	124	118	48	265	933
2015	367	17	139	166	32	263	984
2016	388	11	140	170	42	278	1029
2017	389	16	147	139	59	261	1011
2018	340	17	175	170	62	273	1037
2019	418	7	171	152	66	284	1098
2020	371	9	175	158	57	262	1032
TOTAL	3504	125	1400	1491	473	2612	9605

Table 4. Fatal accidents United States 2011-2020 [8]

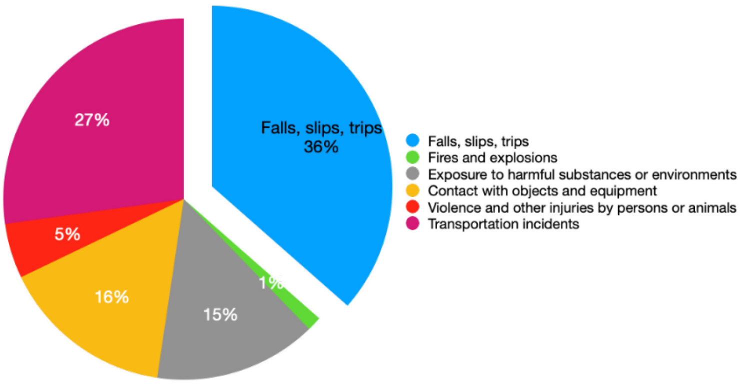

Figure 4. Fatal accidents United States 2011-2020 [8]

Search keywords: combinations of ‘risk(s) of fall(s)’, ‘fall(s)’, ‘injury/injuries’, ‘risk(s)’, ‘fall(s) factor(s)/ factor(s) of fall(s)’, ‘Monitoring technology’, ‘digital device’, ‘cloud computing’, ‘automated assembly ‘and ‘construction industry’.

2.4 Research process

The project aims to reduce fatalities from falls on construction sites by optimizing fall prevention measures and upgrading procedures. It involves collecting and analyzing data on fatal accidents and fall-related statistics from the USA, Germany, and China between 2009 and 2021. The analysis will compare various aspects of fall accidents in these countries and assess the feasibility of reducing the fall rate through cloud computing, on-site construction automation, and digital assistants, ultimately aiming to improve worker safety and reduce fatalities.

3. Literature Review Findings

3.1 The most prevalent types of fall accidents on construction site

Falling from height

Among all known fatal accidents, falling from a height is the most important accident type, And the type of fall is falling from a height. The highest ranking among the three countries for fatalities is China, followed by the United States and then Germany. It can be seen that regardless of the impact of objective factors, such as policy, insurance, workers' education level and other factors that are

YEAR	STURZ ODER ABSTURZ	%	ABSTURZ VON BAULICHEN ANLAGEN IN DER HÖHE	%	TÖDLICHE UNFÄLLE ANZAHL	%	INSGESAMT FÜR TÖDLICHE UNFÄLLE
2010	**54**	**15,40**	**46**	**13,10**	**122**	**0,348**	**351**
2011	**47**	**13,10**	**66**	**18,40**	**144**	**0,401**	**359**
2012	**51**	**14,00**	**52**	**14,30**	**131**	**0,360**	**364**
2013	**63**	**18,60**	**44**	**13,00**	**136**	**0,401**	**339**
2014	**64**	**19,20**	**43**	**12,90**	**142**	**0,425**	**334**
2015	**57**	**17,30**	**29**	**8,80**	**117**	**0,356**	**329**
2016	**22**	**9,20**	**40**	**16,70**	**76**	**0,317**	**240**
2017	**19**	**7,50**	**44**	**17,50**	**80**	**0,317**	**252**
2018	**22**	**10,60**	**40**	**19,30**	**77**	**0,372**	**207**
2019	**11**	**7,30**	**43**	**19,70**	**73**	**0,335**	**218**
2020	**21**	**9,00**	**46**	**19,70**	**82**	**0,352**	**233**
2021	**16**	**5,90**	**29**	**10,80**	**67**	**0,249**	**269**
TOTAL	**447**		**522**	**AVERAGE**	**104**	**0,357**	**291**

Table 5. Fatal accidents Germany 2010-2021 Falling or collapses and Falling from structures at height parts (Arbeitsunfallgeschehen: Überblick Unfallschwerpunkte von Arbeitsunfällen bei betrieblicher Tätig-keit Arbeitsunfälle bei einer betrieblichen Tätigkeit 2010-2021) [9]

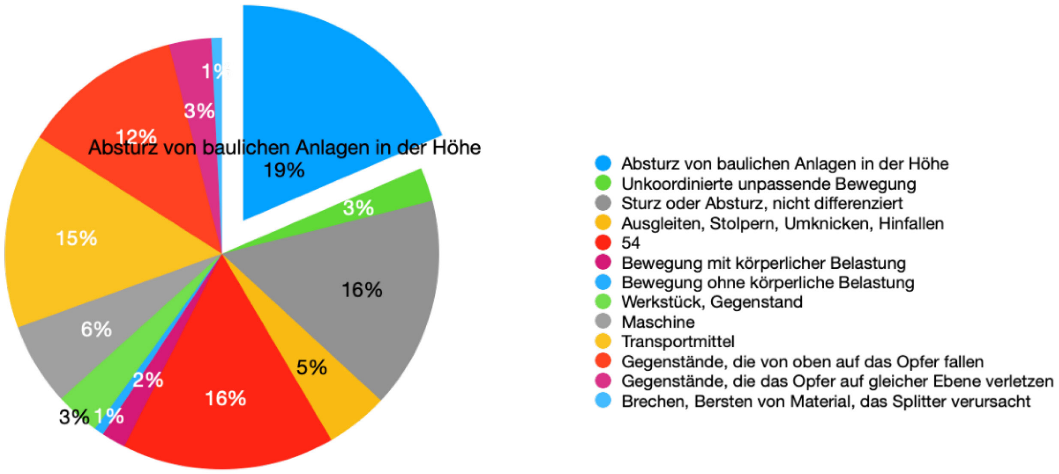

Figure 5. Fatal accidents tpyes Germany 2010-2021 [10]

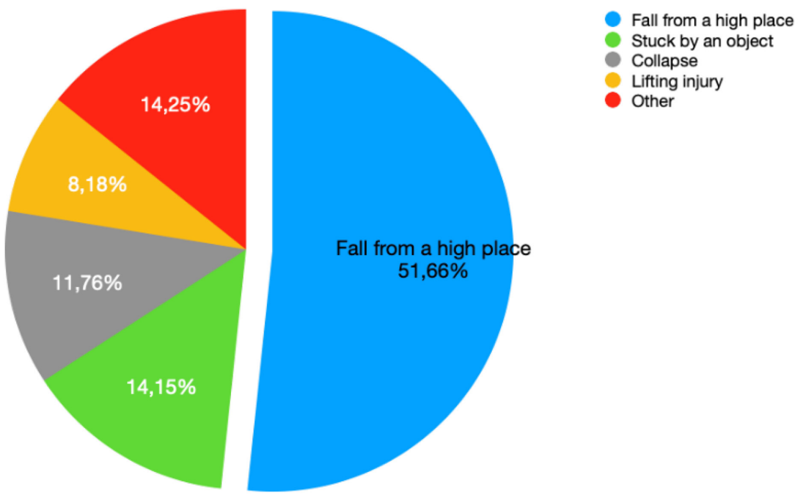

Figure 6. Fatal accidents types China 2021[11]

significantly different[7], falling is a high-risk accident that needs to be considered first.

3.2 The main locations of fall accidents on construction site

According to the comparison of the data in the table, we can see that in the United States, the roof is the most important place for falling accidents from high buildings, accounting for 33.3%. In Germany. Roofs, terraces, glass roofs, roof trusses, roof runners is the top 1 location of construction accident location, It accounted for 23.3% of the total. What China describes as "opening end edge" also refers to building edges that resemble uninstalled facades and roofs under construction[13].

All three countries show that the location of the fall is highly correlated with areas of large drop, as well as improvised facilities for climbing.

3.3 The main causes of fall accidents on construction site

Figure 7 ranks the macrovariables that directly affect the 'fall and injury risk' variable in decreasing order of link count and provides consistency with previous work. The top three causes of falls mentioned in this form include. (1) work surfaces and platforms (e.g. slippery surfaces, inappropriate concrete surfaces, slippery roofs, use of platforms, sliding of bamboo scaffolding and ladder bases); (2) worker safety behaviors and attitudes (e.g. safety procedures , perceived risk, assessment of risk, operating at unsafe speeds or playing at work); and (3) building structures and services (such as the stability of building frames and the reliability of building equipment). There is a high degree of agreement among the above three sets of national data[3]. Other highly researched and consistently rated factors contributing to fall risk include contractor/management safety practices, use of personal protective

Table 6. Fatal accidents types China 2021, Qingwei Xu and Kaili Xu[9]

Type	Fall from a high place	Stuck by an object	Collapse	Lifting injury	Other
Number	**2841**	**778**	**647**	**450**	**784**
Percentage%	**51.66**	**14.15**	**11.76**	**8.18**	**14.25**

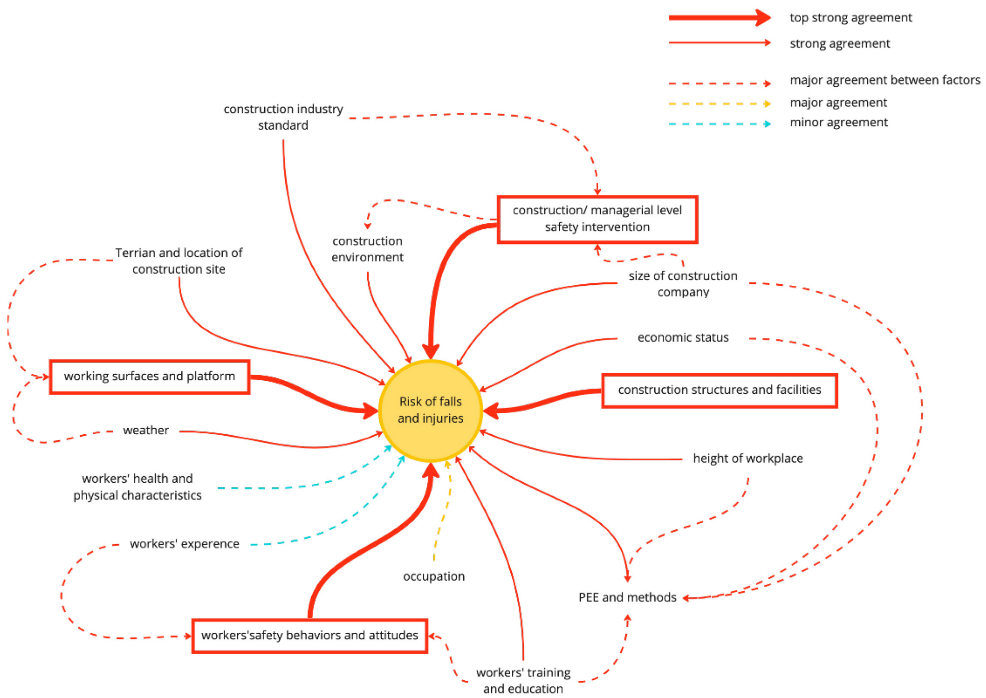

Figure 7. Causal relationships of macro-variables supported by qualitative and quantitative studies" (Hu etc., 2011, p. 403)[3][5]

equipment (PPE) and methods, worker health and physical characteristics, and construction site environment. Factors such as worker age, experience, and occupation are also often discussed, but there is less agreement on their impact[5]. The experience effect is compounded by the direct effect of experience on improving safety and the indirect effect due to overconfidence, which reduces adherence to safety procedures (Cellier et al., 1995; Hsiao and Simeonov, 2001; Lipscomb et al., 2003c; Bobick, 2004;

Haslam et al., 2005; Bentley et al., 2006; Choudhry and Fang, 2008; Lipscomb et al., 2008; Kaskutas et al., 2010). "Worker safety behavior and attitudes" was the primary influencing variable in terms of the number of studies that found the relationship between this variable and risk of falls. In addition, this variable is influenced by many other factors that directly contribute to the risk of falls as shown in Figure 6. Among them, "contractor/managerial level safety intervention" is also one of the most important variables directly affecting "fall and injury risk".[13]

3.4 Fall Prevention and Related Policies Are Enforced

People are using several measures to prevent fall accidents on construction sites, such as personal protective equipment (PPE), guardrails and safety nets, fall arrest systems, scaffolding and ladders, hazard assessment and training, housekeeping, and engineering measures[13].These are assure controls. for ensuring the safety of workers and reducing the number of fall accidents. Employers must implement and enforce these measures to create a safe working environment and prevent fall-related injuries and fatalities.

The US Occupational Safety and Health Administration (OSHA) sets minimum standards for protecting the health and safety of workers in construction and other occupational fields. OSHA's Regulation 1926.16 states that the prime contractor is generally responsible for workplace safety and each subcontractor remains responsible for maintaining the safety of its workers. Germany has a labour protection law called Staatliches Arbeitsschutzrecht, which includes the basic legal obligations of employers and employees. The laws are supported by the regulations or rules of a number of professional associations. For the German construction industry, it is mainly the Association for Employers' Liability Insurance in the Construction Industry ("BG Bau") that is responsible for maintaining and controlling safety.

BG Bau publishes regulations to set safety targets and define industry and process specific rules, including fall protection regulations. The construction site safety and health regulations (known as Baustellenverordnung BaustellV) have existed in Germany since 1998 and require contractors to provide a safe and healthy working environment. The involvement of a safety and health coordinator increases the total construction budget by 0.3-1%. However, the division of roles in construction safety can lead to problems. Communication of basic and required safety equipment can be an issue and often leads to problems on the project. In the United States, due to the different standards for the implementation of local state laws, there are relatively large loopholes in the implementation of the entire US construction industry. Implementation will be more difficult to monitor[14].

A similar system of joint and several liability is used in China to force vested interests to ensure the safety of construction workers by undermining their economic efficiency.The chances of compliance with the law are high once the number of people employed at a site reaches a certain level, but some choose to exploit loopholes in the legal system, leading to an increase in risk on small construction sites[5].

Overall, the factors that contribute to falls are relatively complex, but fall avoidance currently relies heavily on manual inspection and worker self-awareness. In the absence of strong and comprehensive legal requirements, this is all superficial[14]. And true compliance means significant expenditure of money and time in employing third party regulatory entities.

The aim of this paper is to intervene from 2 direct impact on the "risk of falls and injuries" variables, and there will be 2 directions of intervention strategies. Both are trying to reduce the influencing factors of this variable by non-manual inspection.

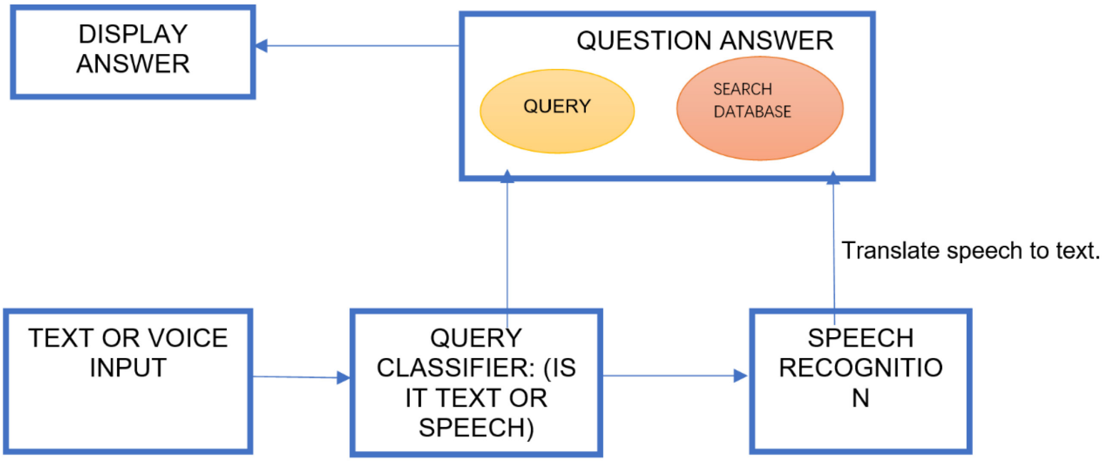

Figure 8 Architecture system of digital assistant [15]

4. Discussion: solution of reducing falling from height

4.1 cloud-computing

Current network infrastructure and system architecture

Digital devices can be used on construction sites to improve safety. Smartphones and mobile apps, wearable devices, and other IoT devices are among the most used digital devices.

Work and demand in the construction industry can be unpredictable, with many businesses relying on referrals and word-of-mouth for leads. During peak seasons, virtual assistants can also assist with construction, ensuring that safety protocols are followed and potential hazards are addressed as soon as possible. Construction professionals, such as project managers and superintendents, may become overburdened with work, making it difficult to prioritize workplace safety.

Figure 8 describes how the architecture of the digital assistant is designed to discern and efficiently process user inputs, whether presented as text or voice. Upon receiving an input, the system first employs a query classifier to determine its nature: textual or spoken. If the classifier identifies the input as spoken, the data is then directed to a speech recognition module which translates the vocal input into its textual equivalent. For textual inputs, or once the voice has been translated to text, the system further processes the query through a text analysis module. Here, the query is analyzed and matched against a database to extract relevant responses. Finally, the most pertinent answer is selected and presented to the user.

Using a construction virtual assistant can improve safety by assisting with construction-related tasks such as scheduling and tracking appointments, as well as managing communication and coordination.

Limitations and prerequisites of current systems and technologies

Processing requests and delivering results from local database can restrict the number of devices that are communicating, and the access of database is limited.

Effective communication is critical to the success of construction projects, especially when complex tasks, unpredictable work environments, and a diverse group of professionals are involved. Poor communication in these intricate projects frequently leads to faulty decisions and slow responses, which can result in serious safety incidents if not addressed. To avoid this, accurate, easily accessible, and up-to-date information must be disseminated to all project members, with a focus on construction site safety.

Discussion of solution

By making it possible to access real-time safety data and lowering the likelihood of incidents, construction sites' safety

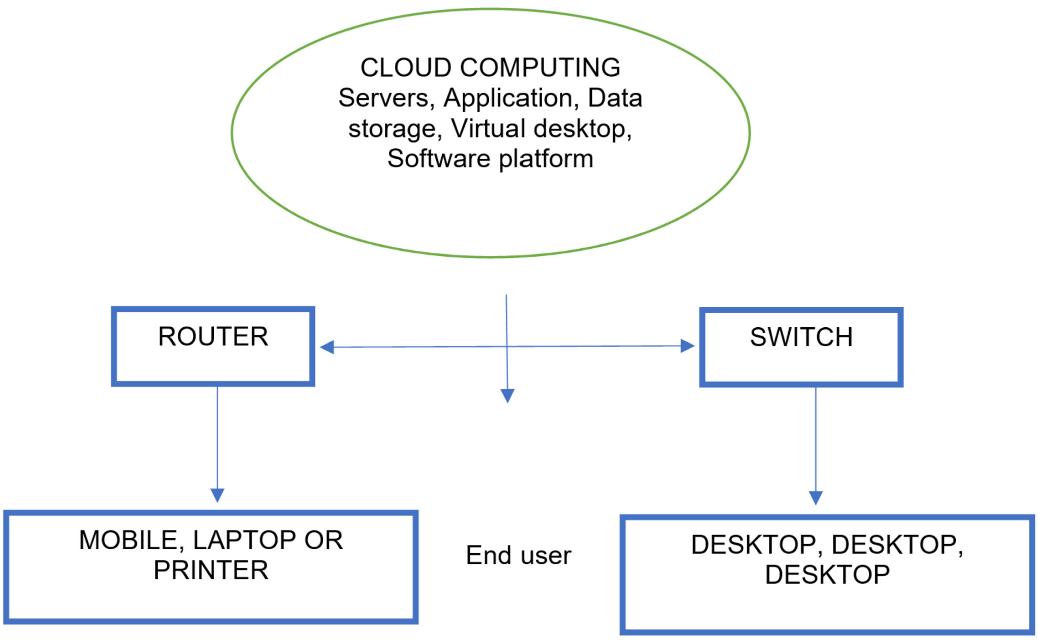

Table 8. Challenges, solutions, and operability of Cloud computing [16]

Challenges	Solutions and operability
Latency – delay of information	In order to avoid delays that could occur when using the Internet as a mode of transportation, construction companies could also be connected to the service provider via a dedicated link.
Trust, data privacy and security -increased fluidity of the security perimeter.	Implement internal data protection measures to prevent data leaks.
Data availability- where cloud provider can shut down their resources unexpectedly. Service Level agreement.	Service Level Agreement – 99.999% cloud service providers provide availability.
Poor broadband connectivity of construction site	with 5G network it can be solved

Figure 9. The network of Cloud computing [16]

performance is being enhanced using cloud technology. The use of cloud storage is also improving the accuracy with which safety risks for underground construction are collected and shared. In general, rapid construction safety decision-making relies on cloud data analytics. [3a] A discussion of the advantages and drawbacks of cloud computing can be found in Table 8.

Operability and cost control

One of the biggest security worries with the cloud computing model is the sharing of resources. The advancement of cloud computing is changing the horizon of information technology and ultimately turns the utility computing into a reality. However, it provides a large array of benefits, but also many challenges in this domain, such as automatic resource positioning, energy management, information security are only attracted the research community.[17]

These challenges are expected to be reduced as technology advances, and cloud computing adoption in construction is expected to increase.

According to the paper “Cloud Computing and its Technical Feasibility”, an organization who intended to expand their services to different areas is better to go for cloud computing service in order to reduce cost. Depending upon agreement with the cloud computing service company all the data is

Server size	CPU Cores	RAM(GB)
Small	1	2
Medium	2	4
Large	4	8
XL	8	16
XXL	16	32

Table 9. Server sizes for Cloud computing [17]

Provider	Small ($)	Medium ($)	Large ($)	XL ($)	2XL ($)
Amazon	0.07	0.11	0.21	0.42	0.84
Microsoft	0.06	0.11	0.21	0.45	0.89
IBM SoftLayer	0.05	0.11	0.21	0.39	0.72
Google	0.04	0.09	0.18	0.35	0.71
Internap	0.01	0.02	0.04	0.09	0.18
1&1	0.01	0.04	0.07	0.18	0.18

Table 10. Hourly cost regarding cloud providers [17]

secured and taken care by that company it means any risk like loss, hacking of data.[18]

The vendor takes into account the hardware, setup, and maintenance costs of maintaining the network. They also look at how much it costs to provide storage, whether a company uses its own storage hardware or buys new equipment to meet its needs. Finally, the vendor takes into account computing costs like CPU costs and licensing costs for the client organization's operating system. Additionally, the provider takes into account the price of providing virtual RAM for each gigabyte utilized by the business. [17]

The cloud cost depends on the server size.

Flowcharts

Cloud computing can benefit while working at height at the construction site. Having a virtual assistant that is connected to a cloud computing service can decrease falls by increasing communication and analyzing data from all connected devices.

Figure 10 depicts the flowchart outlining the integration of a digital assistant with cloud computing for construction site tasks. Initially, the worker provides an input, either as text or voice, detailing a task at the construction site. This input is then directed to a query classifier, which determines its format: textual or spoken. If it's a spoken input, a subsequent step involves speech recognition to convert it into text. Once the text input is established, the system activates the smart device's tracking mechanism to pinpoint the worker's location and further prompts the worker with a series of safety-related questions. Upon completion, the gathered data, inclusive of the worker's responses, is analyzed using cloud computing. The system then provides feedback based on the worker's inputs and answers.

4.2 On-site construction automation in terms of safety.

Off-site construction and prefabrication

Construction work is performed in two different ways: traditional construction processes and offsite construction. Traditional construction methods involve manual labour and raw materials, while offsite construction involves prefabricated material and components fabricated and/or pre-assembled in a factory-type working environment. Traditional construction activities involve activities such as excavation, temporary or permanent formwork erection, concrete work, roofing, steel erection, screeding, ceiling erection, block laying, carpentry, plastering work, reinforcement work, painting work, and bricklaying[19]. These jobs are intrinsically hazardous in nature and impact negatively the health and safety of workers on construction sites. Prefabrication and preassembly can improve construction site working conditions by reducing significantly work to be done on site, and moving work away from construction

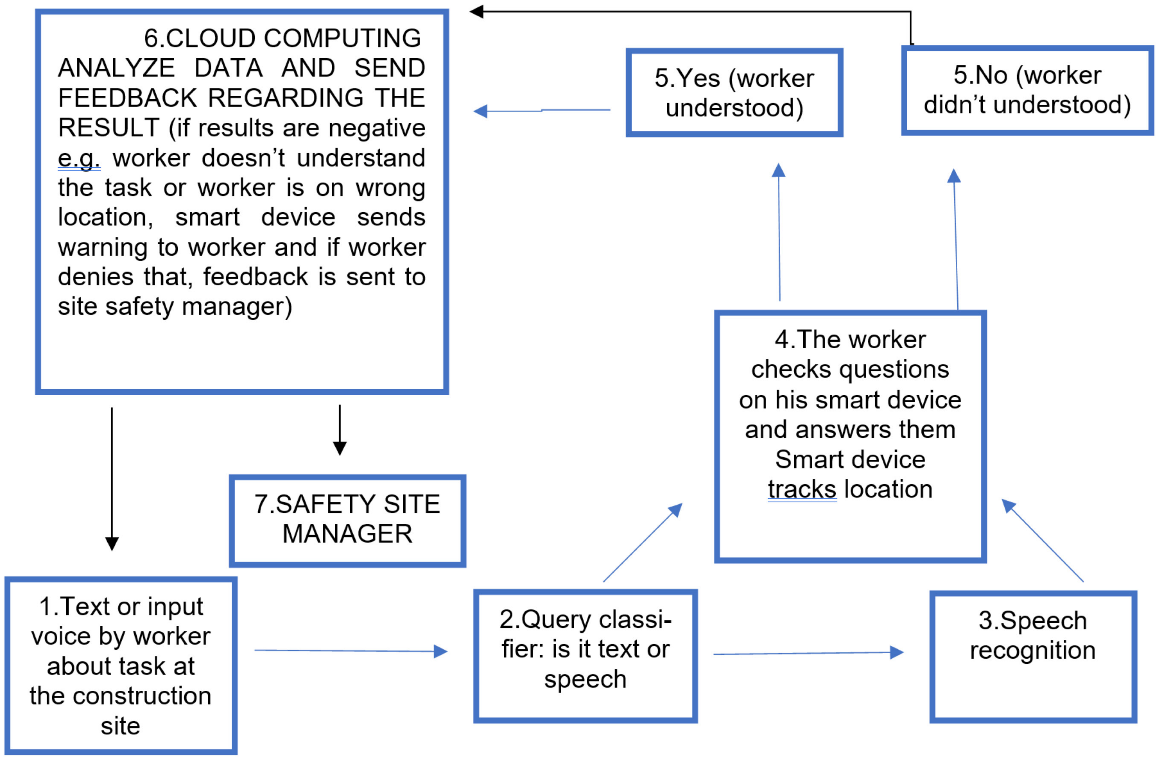

Figure 10 Flowchart of digital assistant with cloud computing

sites themselves could lead to less hazardous construction activities and, consequently, less risk[20]. Toole and Gambatese (2008) argued that prefabrication will not only improve health and safety but quality, productivity, performance, profit and the time frame for completion of the contract[21].

The findings backed up this theory by recognizing that using prefabrication might potentially lessen employees' exposure to steel reinforcement dangers and significant falls hazards connected with height-related tasks[20]. Prefabrication would imply a reduction in fall hazards by greatly lowering ascending and descending activities, repetitive body motions during onsite preparation of steel for strengthening, and silica dust, welding fumes, and organic solvents.

But even so, fatal accidents on construction sites have not been avoided.

Safety performance of remote construction sites

The most common type of injury in modular/prefabricated construction was 'facture', and the most common cause of accidents was 'fall'. According to report research, 44% of the causes were 'fall' and 36% were 'struck by object/ equipment(non-vehice)'[20]. Further analysis shows that 48.1% of the falling accidents occurred at the on-site stage. It is not difficult to see that even with the blessing of prefabricated construction, once it enters the assembly stage of the construction site. All the accidents about falling happened again. Basic on the analysis, the majority of the accidents (57.6%) occurred during installation of modular/prefabricated building or compents[20]. The result can be considered as evidence that off-site construction is potentially safer than on-site operations. It also shows that the fall accident cannot be completely avoided by reducing the time of on-site production only by prefabricating components without changing the way of using manpower to install on-site. The highest rate of 'fall' was 'falls from roofs'(34.5%), followed by 'falls from structures other than roofs' (25.5%)[20].Especially commercial buildings and super high-rise buildings, the lifting , moving and installation of heavy and large components is complex and dangerous. Although the risk of falling is reduced overall, the single-person risk factor of full-time workers assembling on site is increased[21].

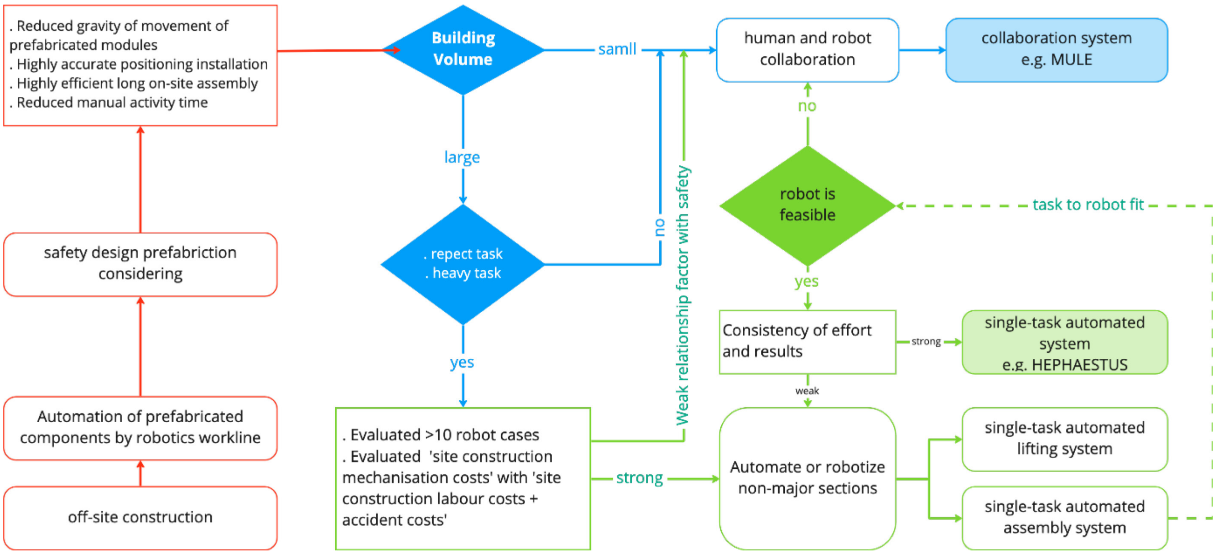

Figure 4. evaluation system workflow

Discussion of solutions

To sum up, freeing workers from some repetitive, high-risk and high-risk measures is of great significance for automated assembly in on-site construction. As discussed earlier in this article, there are a large number of primary and secondary factors in the causes of worker falls, and if all of these factors can be addressed, then the constraints on construction sites will also increase significantly. For countries with relatively expensive human resources, replacing some humans with machines for repetitive, high-risk and high-risk operations can actually reduce expenditures[22]. But for construction sites, they will be differentiated due to factors such as various environments and developers, so it is definitely uneconomical to simply automatically assemble a specific component, and it is necessary to develop an evaluation system first[23]. The most dangerous and repetitive items for a specific site are selected and corresponding groups and automation modules: robotic arms, feeding equipment, safety systems, etc. These automation modules are being developed by various academic institutions and commercial, such as the Hephaestus system, which aims to automate the on-site execution or installation process[24]. The system has the versatility to complete building structure scanning, prefabricated panel installation, painting, and curtain wall cleaning. , replacement of damaged components, repair of cracks, maintenance of solar cells and other tasks. (reference) In the future, it can be used to install the facade of some skyscrapers and even construct alien bases. The following is a simple evaluation logic framework. We even consider some large-scale weight-removing robotic arms to assist humans, such as the MULE system currently developed[25].

Operability and cost control of construction automation

Based on the data from the cases, all robots improved the accuracy of traditional tasks by 20-90% (55% on average) and reduced rework by over 50% compared to traditional techniques. Timetables improved by an average of 2.3 times, with productivity improving in eight cases, one increasing and one remaining the same. The median was 1.4 times, which is almost half the impact of manufacturing robots on productivity (an increase of 3.0)[22]. The fact that robots do not completely replace employees, but rather act as a tool to support or augment labour in dangerous or repetitive operations, is a key factor in this reduction in schedule impact. It is very important to further develop a fully automated autonomous system[25].

5. Evaluate the feasibility in reducing falling rate

The implementation of cloud-based information collection systems and automated on-site construction have the potential to reduce falling rate and worker deaths in the construction industry. Both processes offer benefits such as providing workers with real-time in-formation on site conditions and safety guidelines, Automating high-risk tasks, and reducing the risk of accidents and injuries. However, for the full potential of these processes to be realized, collaboration between workers and management, as well as the availability of resources, is necessary[26]. Compared to automated installation, the challenge of the cloud will be less, it is more software development, and technology upgrades for device connections. It does not affect the composition of the construction site at this stage. Especially in the training stage of workers, it is easier for them to understand and use.

In the United States, the construction industry is expected to adopt these technologies due to an increased focus on worker safety and efficiency. The regulatory framework supports the implementation of new technologies with a focus on reducing fatalities. In Germany, the construction industry is known for its high level of innovation and digitalization, with a strong emphasis on worker safety. The im-plementation of these technologies is expected to gain popularity and reduce casualties on construction sites.In China, the construction industry has developed rapidly but human resources are still relatively cheap, leading to slower adoption of new technologies. The government may enhance measures to implement safety regulations, but the cost of investment remains a factor. The performance of cloud-based information collection systems and automation may vary depending on the level of technology adoption, regulatory frame-work, and resource availability.

6. Conclusion

The analysis of the research process in this paper shows that falling is the number one cause of accidents in the construction industry, and human factors are the primary influencing factors. This identifies the forces acting on robots in construction, such as the need for construction to optimize productivity and cost, safety culture in construction incentivizing solutions to keep workers away from danger-ous tasks, and labor shortages. Other highlighted forces included available technology, quality requirements, willingness to adopt the technology, increased project complexity, and COVID-19 constraints. However, the imple-mentation of building automation at the cur-rent stage is still limited by the current technology and the low level of industrialization of the construction industry, especially in devel-oping countries. The unit cost of technology research and development and operation of building automation is much higher than the cost of fines caused by fatal accidents. Therefore, In the short term, the implementation of cloud computing to improve the safety behavior and attitude of construction workers to reduce the possibility of falling accidents is higher. The system development cycle is short, the cost is low, and the operability is high. In the future, the construction of the combination of the two will be unprecedentedly safe , will also develop more emerging occupations.

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Htoo Inzali and Rebeca Garcia Julio

An overview of assessment methods of construction energy consumption

Abstract

One of the major challenges in managing energy consumption in construction sites is to reliably monitor and report energy usage in real time. Given the complexity of construction projects, it is often difficult to keep track of all the assets and equipment being used in a particular project and monitor their energy consumption. To track the energy consumption of construction machinery and equipment at a construction site, it is essential for construction companies to implement a comprehensive energy monitoring system that can effectively capture and analyze the data associated with these assets. In this research paper, we provide an overview of the current state-of-the-art technologies that can be used to monitor energy usage in construction sites by reviewing and analyzing current literature on energy monitoring methods in construction sites. These methods were classified into four main categories based on the technology used to monitor energy usage. Afterward, a SWOT analysis was made to evaluate the strengths and weaknesses of each category and identify areas for improvement in the future. The results presented in this research paper show that there is still a gap in the methodologies to accurately monitor energy consumption in construction sites, and it calls for further research and innovation in this area. This paper aims to deliver a holistic overview of current methods and technologies in energy consumption assessment, which can serve as a reference for future research studies in the field as well as for determining assessment methods for practical applications.

DOI: 10.18154/RWTH-2023-08861

Keywords: Monitoring energy use, Construction sites, Energy monitoring methodologies, Energy savings.

Image created with Adobe Firefly

1. Introduction

The use of machinery and equipment on construction sites is an essential part of the construction industry's operations. However, most of this machinery consumes a large amount of energy from fuels such as diesel or gasoline (non-renewable resources), which negatively impacts the environment. According to IEA (International Energy Agency), “the buildings and buildings construction sector are responsible for 30% of total global final energy consumption and 27% of total energy sector emissions” [1]. For governments around the world, there is a growing need to protect the environment from the negative effects of energy production and use, and the energy consumption is therefore an important factor that needs to be monitored and controlled to ensure sustainable development.

From the construction industry perspective, energy consumption is a significant issue since the cost of running machinery accounts for a significant proportion of the total operating costs of a construction site. Therefore, it is critical to monitor the amount of fuel consumed by each machine and equipment in a construction site to ensure that their operating efficiency is maximized and consequently, operating costs are reduced.

There are currently various methods and technologies available for monitoring energy use on construction sites. These include smart metering systems, web-based dashboards, and energy management software, among others. However, despite the widespread of these technologies, the construction industry still faces big challenges regarding energy monitoring due to the dynamic and complex work environments [2]. Some main challenges are: 1) difficulty in collecting reliable site-based data with some of the current measuring systems [3] in a short period of time since data must be collected from many machines simultaneously performing different tasks, 2) determining the input parameters that influence the most fuel consumption in the construction machinery (CM) [4] 3) accurately calculating the amount of fuel consumed in each machine.

To address these challenges, researchers have been focusing on developing more sophisticated models and methods which can help better monitor and quantify energy usage in the construction projects. Some of these methods consider the manufacturer’s datasheets, database from past projects, etc.; some methods combine the information provided by different types of sensors to more accurately measure the energy used by the machines on a construction site. More recently, the use of artificial intelligence (AI) and sensor networks for energy monitoring is becoming increasingly popular due to their many advantages over other conventional approaches. For instance, IoT technology allows connected devices to communicate with each other. As a result, they can collect, analyze, and process data faster than ever. [5]

Each method has its strengths and weaknesses and should be analyzed carefully before determining which one is more appropriate for a given scenario. Even though some of these methods have shown promising results both in the laboratory and on the construction sites, there is still a lot of research that needs to be done before they can be implemented in the field.

To this end, this research paper provides an overview of the literature on current approaches for monitoring and quantifying energy consumption in construction sites as some limitations of these approaches and their possible implications in the future. Our first section provides a classification of the monitoring methods based on the type of data used to measure the energy usage (e.g., data from sensors or data provided by humans), and the approach used to estimate the total energy consumed by the machine. In this section, we briefly describe some of the key features of each of these methods, along with their limitations.

In the second section, a SWOT analysis was made to evaluate their strengths and weaknesses and identify areas for future research opportunities.

Finally, some ways in which these limitations could be addressed are discussed and future research directions that could be explored to improve our understanding of energy consumption in construction processes.

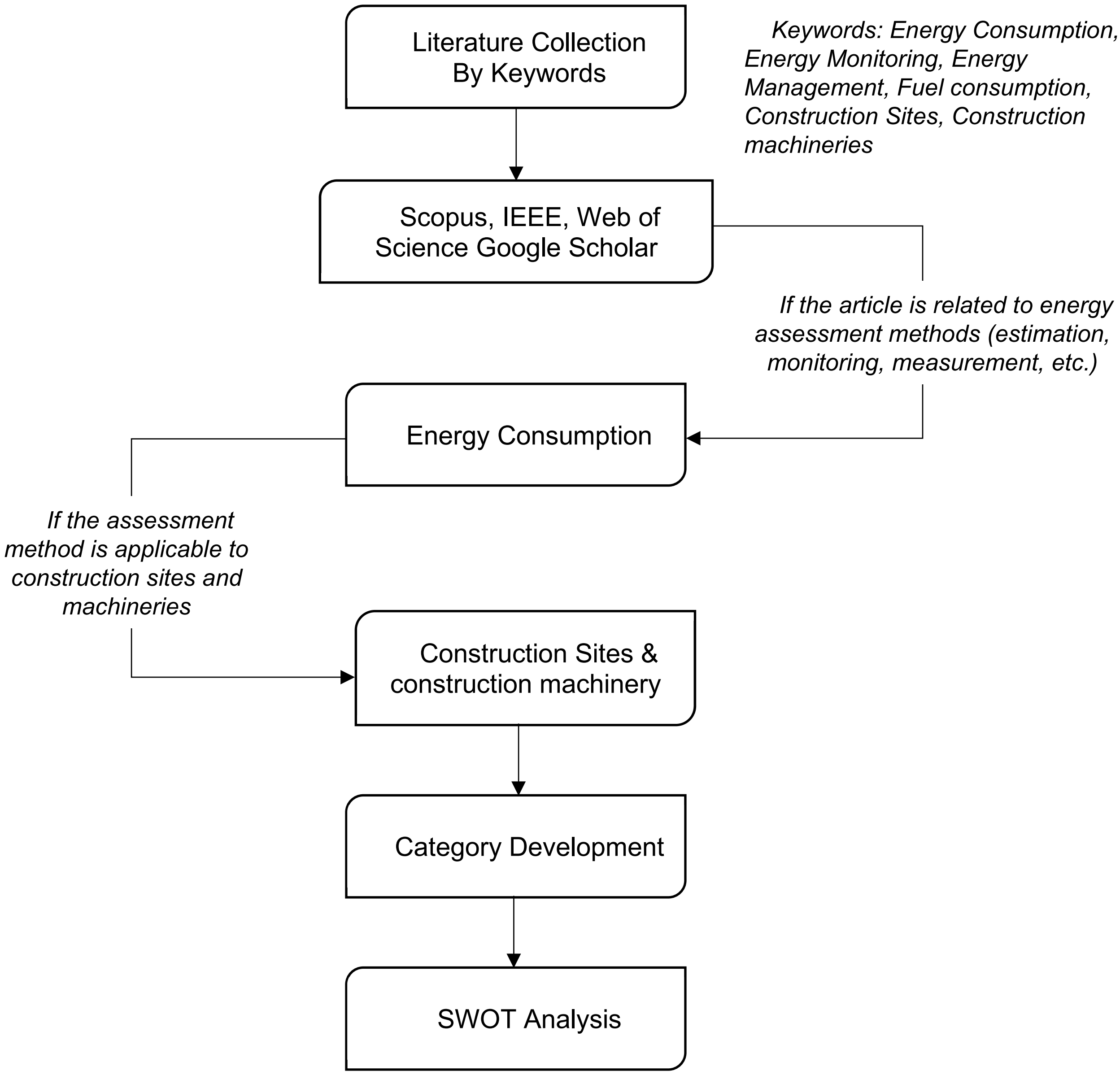


Fig 1: Methodology Diagram

2. Methodology

A combination of systematic literature review and content analysis methods were implemented to investigate the following research questions:

1. How is the energy consumption during construction being assessed (measured, estimated, and even predicted)?
2. What are the current technologies and equipment to assess the energy (either fuel or electricity) consumed during construction?
3. What are the factors to be considered when employing the current assessment methods/models?

As structured in Fig1, the relevant literatures were collected through various academic databases including Scopus, IEEE, Web of Science and Google Scholar, by using the keywords and limiting the publication years starting from 2005. Despite attempting to search the studies of the past 16 years, the number of literatures which are exclusively for energy consumption, is limited. Therefore, we employed the content review for the papers investigating emission on construction sites, a closer context to energy consumption. The studies, in which their energy assessment methods are not applicable to the construction domain, are then eliminated from in-depth reviewing. At last, a total of 19 articles were selected to analyze.

Category development & SWOT: The selected studies were thoroughly investigated. The method of energy assessment in each study, along with their considerations and challenges, were noted in an Excel file with their bibliographic information. The assessment methods are then grouped into categories that are characterized within a similar context in terms of assessment mode, technologies, and equipment and reliability of the result. Based on the resulting categories, the SWOT of each category was identified.

3. Results

Many researchers have studied environmental impacts and emission of construction sites, and there is a considerable number of literatures measuring the emission factors of various construction machinery. It is commonly regarded that the amount of energy consumed is directly related to the amount of emission produced, especially for the construction machinery, for which most of them primarily powered by fossil fuel [6]. As a result, the literatures studying the emission of construction sites, usually attempts to collect the data of direct energy consumption or its potential factors. Therefore, to achieve this study's goal, several relevant literatures on energy consumption as well as emissions were thoroughly reviewed. The methods by which they obtained data on energy consumption are then classified into four groups, namely model-based estimation, instrument-based measurement, vehicle-based measurement, and technology-based assessments. Each category, with its identified SWOT, is discussed in the following sections, with the focus on assessing energy consumption on construction sites.

To encapsulate the results of SWOT analysis for each category, Table 1 summarizes the limitations and the possibilities of the observed energy assessment methods.

3.1 Model – Based Estimation

Model-based estimation systems estimate or predict energy consumption from formulated methods and calculation system by using the appropriate concerning factors, which generally derived from project documentations and operation records.

For instance, *Jassim et al.* [7] proposed a detailed model for estimating energy consumption per hour (or per unit cycle) CO2 emissions by mass haulers in road construction. An optimized hauling schedule, based on the selected haulers' specification and the site and material characteristics, was generated from a planning software called DynaRoad. The plan is then used as a main input for predicting energy consumption and emissions of each vehicle involved or of the entire hauling fleet. Although the result of the proposed model was presented by using the actual data of a case study, their reliability and accuracy was never validated through a real-world consumption data.

Similarly, *Hong et al.* [8] suggested a standard assessment model for energy consumption and GHG emission of building construction by using LCA approach. The consumption and emission of a case study, divided into "material manufacturing, transportation, and on-site construction" phases, were calibrated from the existing lifecycle inventory (LCI) database published by a government authority (Construction Association of Korea, CAK). The database has lifecycle consumption and emission information of building and construction materials. The proposed assessment model evaluates the holistic consumption figure of the overall construction phase, rather than focusing on a specific type of construction equipment. However, it highly depends on the LCI database with the planned or used number of materials and the machinery, which are highly variable in constructions. In addition, the availability of such a database could be the main limitation in certain location. Furthermore, the authors also noted that the proposed model has no considerations for site characteristics except for soil conditions. This, in turn, results in high inaccuracy of consumption and emission estimation, especially when the fuel consumption and emission rate of earthwork operations are highly correlated to the site conditions.

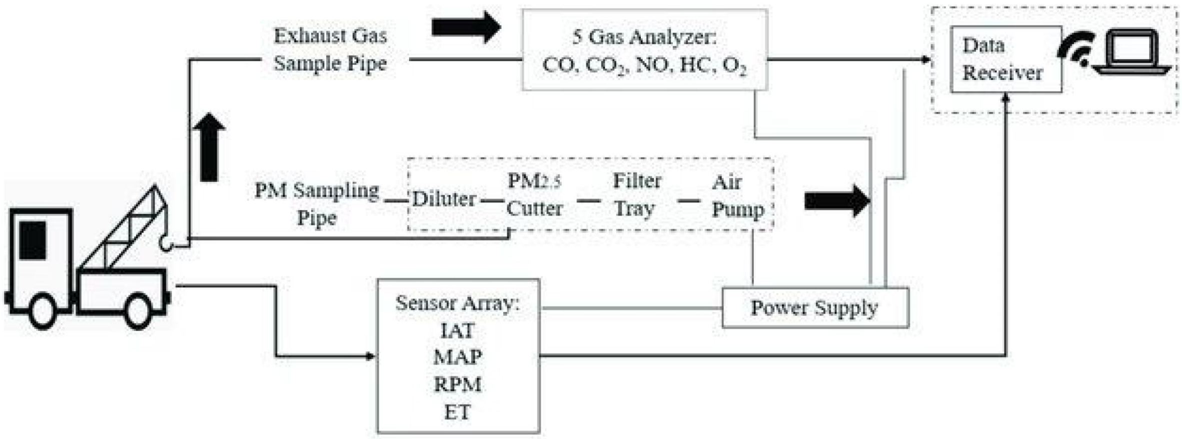
This LCI database approach was also deployed by *Seo et al.* [9] to carry out on-site measurements of CO_2 emissions of a building complex during construction. The evaluation of energy consumption and emission was similarly divided into material production, transportation, and on-site construction phase. Unlike the previous, the LCI was used only for material production while fuel consumption for other two phases was obtained by direct monitoring (e.g. site records) and electricity usage was monitored by implementing smart meter in distribution board allowing more accurate data. Even though the hybrid use of LCI approach and smart meter is presumed to have more accurate results, there is considerable space for improvements to achieve more reliable and robust consumption and emission results.

The preceding models above necessitate some external references and expertise in evaluating. A more comprehensible method was employed by *Li et al.* [6] to calculate energy consumption and carbon emissions of a large-scale public building project during construction in China. The amount of energy consumed, and emissions were mathematically calculated by multiplying relevant parameters such as energy consumption per unit shift derived from the published “Construction Carbon Emission Calculation Standard” and “Consumption Quotas for Housing Construction and Decoration Projects” and the total number of shifts from site operation records. The authors suggested that the method is feasible to implement in similar large-scale projects where there is “the difficulty of collecting data and the inability to measure in the field during the construction of large public building”. The applicability of the method was also demonstrated by calculating energy consumption and emission data of approximately 30 types of construction machinery used in the construction of the case study building. The study then examines the influencing factors of energy consumption and emission by using STIRPAT Model and found that the type of energy used is the most influencing factors on energy consumption and carbon emission. Like the previous model [8], the proposed method did not take the influencing factors such as site characteristics, conditions of equipment and its operation environment into account.

However, research conducted by *Yi et al.* [2] regards those dynamic factors which are highly variable for not only each construction site but also each operation cycle. The study aims to assist construction planners and managers by introducing a simulation model for estimating time-based patterns of energy use and greenhouse gas emission of an earth excavation and hauling operation while considering different operational factors, machine specifications and alternative combination of machines. Based on those varying factors, the data of fuel rate published by Korea Institute of Construction was taken reference to evolve the simulation scenarios. Again, the availability of such reference and its reliability could be the limitations.

As summarized in Table 1, it is observed that some approaches focus on a particular type of consumption, for instance, fuel consumption of specific type of machinery, while some provide an all-inclusive consumption data, i.e., both fuel and electricity consumption of all machinery and site office operations [8] [9].

Furthermore, it is also discovered that some proposed methods generally require the pre-established set of consumption and emission rate information which is not readily available in some locations and even when it exists, its accuracy and reliability is somewhat limited [8] [9] [2]. Similarly, some of the methods which consider the engine data of the machinery [6] [7] [2], rely on the manufacturer’s specifications that are sprung from engine dynamometer at a steady-state and in-lab testing environment. This, consequently, lead to inexactitude of consumption and emission result, particularly in construction sites with varying environment and moving activities. This fact has been highlighted by several researchers [10] [11] [12].



It is also found that the reviewed assessment models share some common characteristics which are (1) although collecting of project and machine information required as input is tedious and time exhaustive, the process is simple and (2) there is a lack in validity and verification of the outcome, especially with the real-world consumption result. The later part is crucial because it is proven that the model-based consumption and emission results are notoriously variant from the actual results measured by field instruments such as Portable Emission Measurement System (PEMS) [12] [13] [14].

3.2 Instrument – based Measurement

The instrument-based measurement methods access the real-time energy consumption data directly from the construction sites during operation. One of the most widely instrument is PEMS for measuring fuel consumption.

The primary use of PEMS is to measure and analyze the emissions of pollutants from equipment and vehicles. Nonetheless, it is possible to access fuel consumption relating from the measured engine data. The system is typically comprised of five gas analyzers, a particulate matter (PM) measurement device (to connect to tailpipe), a sensor array, a Global Positioning System (GPS) and either a tablet or a computer. A DC power supply module is required to operate the system. The main unit which is capable of measuring fuel consumption is a sensor array which includes sensors that can be temporarily installed on the vehicle engine compartment and measures IAT (intake air temperature), MAP (manifold absolute pressure), RPM (revolutions per minute) and ET (engine speed). The engine data measured from the sensor array is then sent to the computer on second-on-second basic and the amount of fuel used (either gasoline or diesel) is generated. Aside from sensor array, an alternative way to retrieve engine data is through Electronic Control Unit (ECU) linked with On-Board Diagnostic System (OBD) although the older model construction machinery and “light-duty gasoline vehicles” probably not equipped with ECU and OBD. A GPS is also assembled to the PEMS to track the real-time data of vehicles’ location, path, position, etc. allowing to observe the operation pattern of the vehicle. A schematic illustration of the PEMS is shown in Fig 1. A complete unit of a PEMS weights about 35lb and usually bulky. However, the upgraded models of commercial PEMS might vary in size and weight.

PEMS is particularly a popular method to measure the real-world emissions data from both light- and heavy-duty vehicles, including construction machinery. It has been widely utilized in evaluating in-use emissions and fuel use of construction machinery, as summarized in Table 2. For instance, *Abolhasani et al.* [14] assessed excavators' field-based fuel consumption, and emissions during operating. *Frey et al.* [16] compared emissions from backhoes, front-end loaders, and motor graders operating in real-world conditions with petroleum diesel versus B20 biodiesel. *Hajji et al.* [13] used PEMS data from 6 bulldozers to validate their developed program for estimating the total cost, diesel consumption and emissions of bulldozers. *Heidari et al.* [12] assessed the real-time emission data of 18 construction equipment by using PEMS and evaluated the result against other emission results from model-based prediction methods including NONROAD 2008, OFFROAD2011 and a modal statistical estimation model.

Rasdorf et al. [17] aimed to introduce a more efficient way of using PEMS by setting out a detailed standard procedure for collecting real-world emissions data from construction vehicles in use. These procedures have been successfully used to collect emissions' data from 39 different construction vehicles. And it is also claimed that "the implementation of a standardized procedure for data collection and quality assurance produced valid data for approximately 90% of the attempted data collection effort". The researchers also pointed out some significant challenges in implementing PEMS for field-data collection, which include weather, operating conditions, and site cooperation.

PEMS can provide considerably reliable and accurate consumption and emission data of real-world, in-operation measurement. It is flexible and applicable to both light- and heavy-duty construction machinery, regardless of the fuel type (diesel or gasoline) and site conditions. At the same time, there are some limitations and factors which need to be considered in using PEMS.

As mentioned by R*asdorf et al.* [17], PEMS is designed to operate in moderate environment and sensitive to adverse weather situations. Data collection is only possible under the temperature between 32F, a freezing point and 90F because moisture in the sample line would freeze. Furthermore, the operating conditions of the construction sites are highly variable both in physical environment and operational aspect. PEMS are heavy and bulky equipment and attached to the external body of the vehicle. They are susceptible to vibrations and improper placement of the unit tends to consequence in malfunction or limits the operational performance of the vehicles. Although the sensor array may be resilient to some extent, those conditions may result in sensor-to-PEMS communication failure. In addition, it requires collaboration from construction sites to install PEMS for monitoring, since data collection from actual field may implicate the operation schedule. Moreover, PEMS are more ideal for collecting real-time emission and consumption data in-use for a short period of time and concurrent monitoring for several construction machinery throughout their entire operation period is laborious and financially burdensome. For that matter, in their study emphasizing on non-road vehicle emission measurement, *Sepasgozar et al.* [3] noted that over the 10-year periods of monitoring and contributing into emission factor inventory, achieving reliable and robust results has remained a significant challenge.

3.3 Vehicle – based Measurement.

The vehicle-based measurement approach involves real-time acquisition of energy consumption related data from the consumption source itself while it is operating under actual site environment. The use of smart meter for electricity usage and the vehicles' Engine Control Module (ECM) or On-Board Diagnostics system (OBD-II).

Over the last few decades, the automotive industry has drastically evolved into extensive automation of vehicles using a network of sensors and computational systems. These sensors are managed by embedded electronic units (ECUs) that are designed to manage a wide range of functions from engine control to tiny fault analysis. It is said that a modern commercial vehicle is equipped with several numbers of ECUs throughout the vehicle and communicate each other via a Controller Area Network (CAN), a type of computer network with standardized, high-speed data communication system. The data from various ECUs is then transported into ECM, a computer system within the vehicle which processes the received information and executes real-time adjustments to the engine and other systems to achieve optimal engine performance with less energy consumption and risks. Additionally, some vehicles are also equipped with OBD-II which links to ECM and a diagnostics software to ensure the emission rate is within the regulated limit.

The use of this sophisticated technology in vehicles enables more efficient energy consumption and, in turn, reduces emission rate, especially in construction vehicles. It has been proven in the study conducted by *Hong et al.* [18] in assessing emissions and energy consumption of dump trucks and wheel loaders. The authors commented that the variability of emission and consumption results by PEMS is in trucks with OBD-II is not as dramatic as in wheel loaders without one.

Despite its capabilities, it is important to note that not all vehicles are equipped with OBD-II. Although there are regulations for on-road vehicles after 1996 in the United States (2001 in Europe) to install OBD-II for controlling emission, non-road vehicles such as construction machinery may not have OBD-II, especially older vehicles. Even when they are available, the level of diagnostic functions may differ depending on the vehicle model and manufacturer. And, the diagnostic software, to decode OBD-II data, is proprietary. Alternatively, a data logger or scanner are used to retrieve data from ECM [19][20]. It is essential to consider the cost of those devices, especially when simultaneous data collection from many CM is required. Another major concern is safety and security issues regarding CAN. Due to its lack of encryption, CAN is vulnerable to cyber-attacks and can jeopardize the safety of the operators and data security [21].

3.4 Technology–based Assessment

The last category of energy consumption measurements presents various approaches which involve using wireless communication technology to remotely monitor and collect real-time and continuous data on energy consumption. Technologies such as Radiofrequency Identification (RFID), GPS, sensors, Zigbee, Bluetooth, and other wireless communication technologies improve the efficiency in construction sites by allowing convenient data collection and remote monitoring [22] [23].

One example regarding energy consumption is the development of an IoT-based fuel monitoring system using an open-source capacitive fuel level sensor [24]. The proposed method was experimented in transit mixers and demonstrated that it is capable to measuring the total operational hours, fuel consumed, average fuel consumption, total amount of fuel filled and removed. The system is practical, low-cost, and open source. On the other hand, the applicability of the system is only suitable for overall fuel usage and location tracking. Improvements for new sensors' technology are required to observe activity-based consumption data.

Closing this gap, *Rossi et al.* [25] instigated the use of a “micro-controlled smart plug” which can recognize the activity-based power consumption. The smart plug is a combination of technologies such as GPS and power sensors, Wi-Fi to track and collect real-time power supply voltage data and the patterns of work cycle, etc. The data are then transmitted and processed on the cloud platform. The proposed system is prototyped for three electricity-powered equipment (hoist, sawing machine and concrete mixers). With fuel-consumption measurement methods, the accurate consumption data of construction sites can be obtained at activity level, operation level and project level. Bearing in mind that the novel technologies such as IoT become fancier and the affordability of sensors becomes greater, IoT is potentially the most feasible option to implement for real-time energy monitoring as well as in other aspects of improving site efficiency [5].

In addition, a closely related technology of IoT, telematics which is a combination of telecommunication and informatics, has been widely adopted to transmit and receive data remotely. In particular, the use of telematics for fleet management is a topic that, despite having some developments in other fields such as transportation and logistics, has not been given equivalent attention in the construction industry. However, in a survey conducted by *Jagushte et al*. [26] for investigating the usability of telematics for construction equipment fleet management, 90% of the participants recommended using telematics in construction.

Taking one more step further from real-time data acquisition through sensors and innovative technologies, there are some research endeavors which attempt to predict energy consumption by using Machine Learning (ML) and field-based actual data. *Pereira et al.* [4] scrutinized to develop a framework to estimate fuel consumption of construction trucks based on load, slope, distance, and pavement type by training the actual data collected from sensors and data

	Strength	Weakness	Opportunity	Threats
Model-based Estimation [1]–[8]	1 Simple and conventional process of data collection. 2 Flexibility - some estimation model can provide machine-level consumption while some can estimate overall construction site energy consumption. 3 Pre- and post-construction assessment 4 No significant upfront cost for energy assessment.	5 Limited access and availability of the public data for reference. 6 Time and resource-exhaustive data collection. 7 Lack of validity in outcomes of proposed model. 8 Requirement of technical knowledge to execute the calculation. 9 Operation environment, vehicle conditions and operational behaviours are not considered fully.		10 Accuracy and reliability of the outcome depends on multiple factors such as the purpose of the estimation model, quality input data for calculation, validity of data source, etc.
Instrument-based Measurement [1]–[8]	11 Reliable, accurate and real-time field consumption data 12 Applicable to both light- and heavy-duty using either diesel or gasoline. 13 Emission data in relation to fuel consumption is assessable.	14 Only fuel consumption and emission can be measured. 15 Susceptible to vibrations 16 Improper placement can result to inconsistency of measurement. 17 Limited implementation for smaller vehicles due to heavy and bulky unit 18 Real-time monitoring for multiple vehicles over time span is restricted by financial and operational conditions. 19 Upfront financial cost. 20 Pre-construction assessment is not possible.	Improvement on smaller and easier installation	21 Sensitive to weather and temperature 22 Corporation from construction site is essential.
Vehicle-based Measurement [1]–[8]	23 Reliable, accurate and real-time field consumption data 24 Both fuel consumption and electricity consumption of the vehicle can be measured. 25 Detail diagnostics of energy consumption pattern related to vehicle' operation mode (idle, moving or specific function) 26 Data synchronisation to a cloud platform is possible where OBD-II is available. 27 Availability of vehicle engine optimisation with less fuel consumption.	28 Not all construction vehicles are equipped with OBD-II. 29 Diagnostic functions differ for each manufacturer, model and year of the vehicle. 30 Manual data collections with data logger or data scanner for each vehicle is required where OBD-II is unavailable.	31 Regulations for non-road vehicle (construction vehicles) to require a standard ECM and OBD-II To improve CAN bus protocol to safer and secure network 32 To improve CAN bus protocol to safer and secure network	33 Safety and security issues of CAN bus
Technology-based Assessment [19]–[27]	34 Flexibility - possible to combine technologies and sensors for measuring both fuel and electricity consumption. 35 Convenient data collection 36 Data synchronisation to the cloud sever and	40 Specialist knowledge for sensor and communication network installation is required. 41 Upfront cost 42 Lack of incentives for construction site to implement.	43 Development of IoT-based integrated energy management system for monitoring energy consumption (machine-based, operation-based, project-based) 44 Incentive scheme for	46 Safety and security concerns 47 Data breaches and transparency

Table 1. Summary of SWOT Analysis

loggers installed on-site with ML algorithm. In similar context, *Jassim et al.* [27] proposed a prediction model using Artificial Neural Network (ANN) to estimate hourly energy consumption and emissions of excavators under various operation conditions. *Fukushima et al.* [28] predicted the energy consumption of new electric vehicles by ML trained with the readily available dataset of old electric vehicles.

Compared to the conventional estimation models, previously mentioned in Section xxx which established upon the assumed dataset while ignoring dynamic conditions, one can perceive that real-world data-driven ML models can predict a more robust and reliable consumption. To achieve the ultimate prediction capability, the ML models need to be fed not only with enough data but also with quality data. Despite having said that, a noteworthy articulation from machine learning models is not having adequate dataset representing the real operation conditions in construction sites to train the model and the difficulty to collect such data for all possible machinery on construction sites in various dynamic conditions.

4. Discussion

As shown in the presented paper above, researchers have put great effort into energy monitoring methods in real construction sites using various techniques, which we classified into four categories: 1) Model-based estimation: This category contains the most conventional approaches, which include static information such as manual field measurements, documentation data collection, etc. These types of methods are flexible in terms of overall energy estimations in construction sites and pre- and post-construction assessments. However, these approaches suffer from various disadvantages, such as the inability to provide real-time results, inaccuracy due to the limited access and availability of public data for reference, and data collection being time-consuming. They rely on certain assumptions such as easy, well-defined relationships or a strong linear relationship between input and output variables. This input requires significant human input and is therefore not scalable.

In addition, this approach generally requires the use of specific modeling tools, which may not be available or affordable in certain regions, especially in developing countries. Therefore, reliable, and efficient models need to be developed that consider the characteristics of construction projects in specific regions and that can reliably estimate energy consumption. 2)Instrument-based Measurement: These approaches use instrumentation for monitoring real-time energy consumption. One of the most widespread uses is PEMS technology, which provides both real-time data and detailed analysis with a high level of accuracy, and it's applicable to light and heavy duty using either diesel or gasoline as a fuel source. However, these technologies are expensive to implement and maintain. Furthermore, they are susceptible to vibration and an improper installation could interfere with the accuracy and quality of the collected data. As a result, they are not ideal for long-term monitoring, and it is not cost-effective to use them for large-scale projects.

3) Vehicle-based Measurement: This category involves the use of vehicles equipped with embedded sensors in the engine and the use of smart meter to monitor and analyze energy consumption during work activities at construction sites. With this equipment, it's possible to get reliable, accurate, and real-time field consumption data. Compared to instrument-based measurement, this category has some advantages such as reduced cost, easier implementation, and maintenance. Some downsides of this approach are that not all CM is equipped with OBD-11 and there's a lack of standardization among manufacturers, making it difficult to compare the data received across different types of vehicles from different manufacturers. Furthermore, data security can also be a challenge since this type of information is highly sensitive and not protected. 4) Technology-based assessment: This category relies on the use

of innovative tools and advanced AI technologies, which provide a more detailed and accurate picture of energy consumption for fast and robust data processing and analysis in real-time. It is also capable of identifying inefficiencies in project management and workflow processes, as well as providing recommendations to improve energy efficiency in pre- and post-construction stages. Data synchronizes to the cloud server where it is processed and analyzed to provide actionable insights on project performance and performance optimization in real-time. However, this approach is pricier than the others and requires in-depth technical expertise to implement it. Moreover, building an adequate database for a reliable pattern analysis from different CM and site construction is challenging as it requires data collection across multiple sites over a long period of time.

Therefore, an ideal solution for the data collection of reliable field data on energy consumption and production during construction is to combine the strengths of the different approaches described above. For example, a combination of automated vehicle tracking (using OBD-11 or GPS) and technology—based methods would allow users to access more detailed information about vehicle movement patterns across different sites and worksites at a lower cost.

Alternatively, IoT and telematics are the most promising technologies with great potential, and it is necessary to develop them further to be more effective and economical in providing accurate and timely information for decision-making purposes.

Machine learning algorithms have tremendous potential to improve the performance and cost-efficiency of the construction industry, but they are only effective when used with other advanced methods and technologies. Nevertheless, there's a lack of an adequate amount of real-world datasets to train the machine learning model.

Finally, we realize that currently there's no standard format for data storage that could be used in the future across different platforms. This complicates the process of collecting data and makes data collection and the analysis extremely difficult and time-consuming. The use of standardized formats would allow the easy exchange of information among various stakeholders in construction projects.

5. Conclusion

In conclusion, the paper presents a thorough analysis of energy monitoring methods in real construction sites, categorizing them into four main groups. Each category has its set of advantages and limitations, emphasizing that there is no perfect solution.

The paper suggests that combining the strengths of these different approaches, such as automated vehicle tracking and technology-based solutions, could provide a more comprehensive and cost-effective solution. It also highlights the potential of IoT and telematics technologies for more accurate and economical data collection.

The role of machine learning algorithms in improving construction efficiency is acknowledged, but the lack of adequate real-world datasets is a significant challenge. Additionally, the paper emphasizes the importance of standardized data storage formats to streamline data collection and analysis.

In summary, while no single solution is without limitations, each of these methods holds the potential to contribute to the development of smarter and more efficient construction sites in the future. Advancements in technology and data collection practices will be crucial to realizing this potential and enhancing energy monitoring in the construction industry.

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Ali Delfani and David Lukert

Qualifying existing reinforced concrete (RC) structures using non-destructive testing methods

Abstract

Qualifying and maintenance of reinforced concrete structures to extend their lifetime and create reuse opportunities by non-invasive techniques have been highly regarded by researchers from different disciplines since condition assessment of such structures is not only a complex process, but costly and time-consuming. In this paper a literature review on the most recent development of non-destructive testing (NDT) methods along with interviews with experts have been conducted to highlight the advancements, NDT trend, and research gaps in this field. Furthermore, a futuristic vision of NDT has been presented considering its trend towards the last generation of non-destructive evaluation (NDE), NDE 5.0. The outcome shows that implementation of UAVs, AI, and combination of different methods significantly improve the results. However, algorithms need to be developed and AI models should be published for transparency. Integration of NDT results and data formats have been identified as research gaps, which should be considered regarding the future vision. Provided that the requirements are met, condition assessment of RC structures will be revolutionized by NDE 5.0.

DOI: 10.18154/RWTH-2023-08862

Keywords: Reinforced Concrete, Non-Destructive Testing, Qualifying, Non-Destructive Evaluation, Condition Assessment, Structural Health Monitoring

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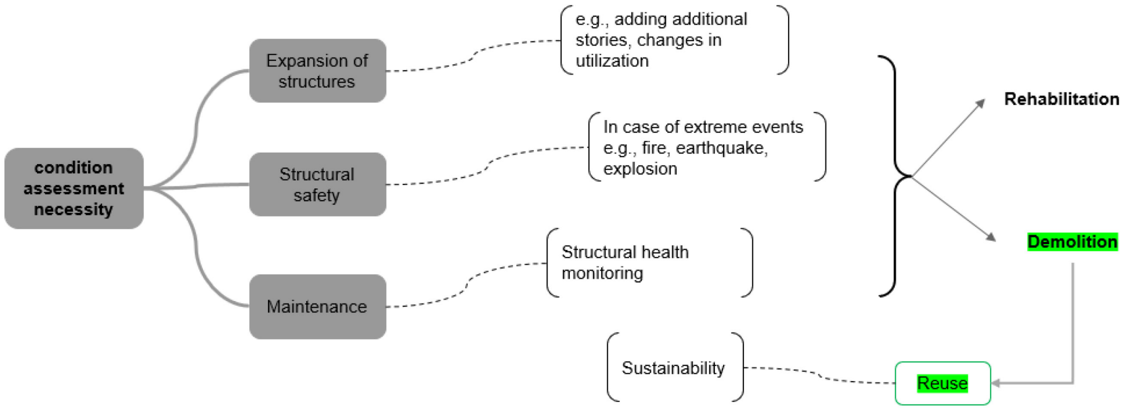

Fig. 1 Three main categories regarding condition assessment necessities

7. Introduction

Qualifying is too general a topic as we have to deal with different types of widely used materials, namely steel, concrete and timber, which have their own design codes and maintenance standards. Therefore, in this paper we have solely focused on Reinforced Concrete (RC) structures in order to undertake a literature review on the most recent developments in Non-Destructive Testing (NDT) methods and highlight the NDT trend as well as its future vision considering the essential requirements and benefits. Nevertheless, it should be noted that NDT is so complex a topic as it is an interdisciplinary field which encompasses many disciplines such as physics, chemistry, material science, computer technology and communication technology [1].

The reasons why we need to conduct a condition assessment of structures using NDT have been divided into three main categories. Expansion of existing structures is one of them. In order to ensure that an existing structure is capable of satisfying structural requirements so that it can be extended, it should be qualified whether an expansion would be allowed. Adding an extra story on top of a building is an example.

Furthermore, in case of extreme events such as an earthquake, an explosion or fire, structural safety has to be evaluated to confirm that the structure would be able to bear the loads regarding the extent of the damage.

Maintenance of existing structures is also one of the qualifying necessities. Considering the total number of existing bridges for instance in Germany, around 140,000 [2], it is evident that maintaining such structures is crucial in terms of sustainability and also construction costs. Therefore, health monitoring of structures plays a key role in extending lifetime of structures, which in long term saves significant money and material.

After assessing the condition of an existing structure, structural engineers end up having to decide whether the structure meets the requirements, needs to be strengthened or demolished. In case of demolition, splendid reuse opportunities could be created if suitable, non-invasive methods are at our disposal to efficiently evaluate the condition of the elements. Fig. 1 illustrates the main points.

1.1 Testing methods

In principle, material testing methods can be divided into two main categories, namely Destructive Testing (DT) and Non-Destructive Testing (NDT) methods. DT is performed to determine the mechanical and chemical properties of the material. Although DT is reliable and useful for design and evaluation purposes, it's not only expensive and time-consuming, but the tested specimen is destroyed [3].

Quality assurance of concrete has traditionally been performed mostly by visual inspection and collecting samples of concrete to conduct standard tests on hardened specimens, however, such

NDT method	Application	Advantages	Disadvantages
Acoustic Emission (AE)	o Cracks o Corrosion of reinforcement	Simple operation	o Vulnerable to electromechanical noise o Sensitive to materials
Infrared Thermography (IRT)	Cracks	Test different Materials	o Limited measurement depth o Time-consuming
Ground Penetration Radar (GPR)	o Voids o Corrosion of reinforcement	o Fast measurement speed o Easy operation	Susceptible to metals

Table1. Three examples of NDT methods

approaches do not provide information about "in-place properties of concrete" while NDT methods alleviate the problem [4, pp. 2].

ACI228.2R-13 [4, pp. 2] states that NDT methods provide information such as location of cracking, delamination and debonding, location and size of steel reinforcement, corrosion of reinforcement, and strength of concrete.

Although there are a number of different NDT methods, the Infrared Method (IR or IRT) has been briefly explained here. Its working principle is based on measuring the temperature changes on structures' surface as a result of compression or tension. As concrete structures with debonding or delamination emit infra-red radiation, "this

method uses specialized scanning cameras to capture the emitted heat at any temperature and convert the data into thermal images for further analysis" [5].

Zheng et al. [1] have conducted a literature review on seven NDT methods and summarized the advantages, disadvantages, and application of those methods. Table 1, which has been extracted from [1], shows three methods, by way of illustration in this paper.

Obviously, the working principle, application, advantages, and disadvantages of NDT methods are crucial factors in selection of testing methods. Additionally, "*the economy and environmental protection*" of such methods should be taken into account [1]. As mentioned before, NDT is an interdisciplinary field, therefore, development of NDT methods is dependent on the development of those disciplines.

According to ACI228.2R-13 [4], NDT methods are being increasingly applied for condition assessment of RC structures because of:

- Improvements in technology in terms of software and hardware for data collection and analysis.
- Economic advantages of investigating large volume of concrete.
- High speed of operation.

Furthermore, the ability to assess complex structures which could be created regarding advancements in Additive Manufacturing (AM) is also an important factor.

Considering all the mentioned points, the main research questions in this paper have been formulated as follows:

- How can existing RC structures be qualified more accurately using NDT methods to enhance the lifetime of buildings and create efficient reuse opportunities?
- What would be the future vision of condition assessment of RC structures by NDT methods?

8. Methodology

In order to provide answers to these questions, a literature review as well as interviews with experts [6,7] in the industry have been conducted.

8.1 Literature Review

We have focused on the literature published no more than two years ago from the date of final colloquium in Research

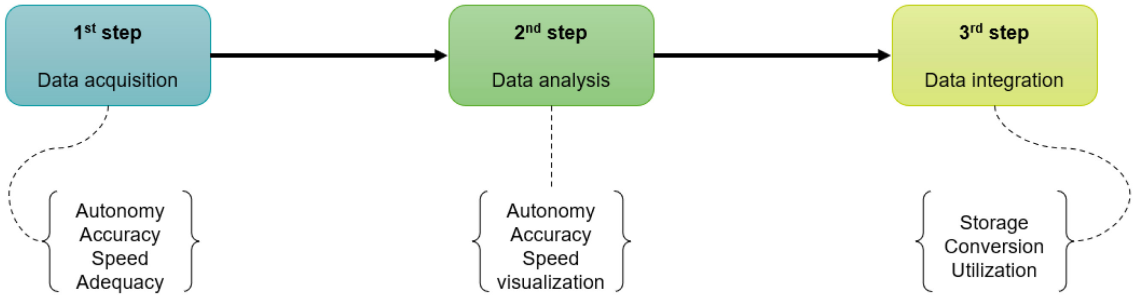

Fig.2 NDE process in three steps

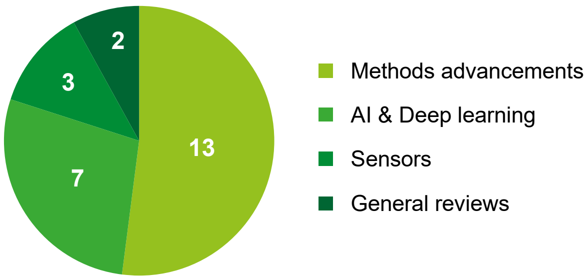

Fig. 3. Distribution of the reviewed papers according to their main topic.

Driven Project (RDP) course at RWTH, 01.02.2023. In this paper the Non-Destructive Evaluation (NDE) process has been divided into three main steps shown in Fig. 2 so that the results and insights can be categorized accordingly.

The field of NDT for reinforced concrete is very extensive, it is necessary to narrow down the scientific papers related to this topic. A search on *Google Scholar* lists about 42.500 articles, that contain the words “ndt”, “testing” and “concrete” [8]. As we have decided to focus on the latest trends, we searched for papers published in the last two years. Two recent reviews from 2022 and 2021 serve as baseline of the state of the art in NDT developments. All papers that have been read were checked for reference in these reviews and only when there hasn’t been written anything included in this paper. After this procedure 22 articles were reviewed, and the findings concluded in the following paragraphs. In Fig. 3. the distribution of topics of the reviewed papers can be found.

8.2 Current reviews

The first review by Kot et al. covers developments in the methods of Sweep frequency technique, ground penetrating radar (GPR), infrared technique (IR), fiber optic sensors (FOS), camera-based techniques, laser scanners, acoustic emission (AE) and ultrasonic techniques [5]. I n particular, the authors wish to highlight the use of sensors in NDT methods, emphasizing the arguments that sensors minimize monitoring costs and sudden failure accidents.

In the second review, advancements in NDT-methods for evaluation of concrete in bridge engineering are summarized [1]. Seven methods were examined and compared with application examples and limitations. The paper concludes with recommendations for further research including the following topics: Detection technology combined with unmanned aerial vehicles (UAV), wireless remote sensing and wireless sensor technology, machine learning (ML) and deep learning (DL).

3. Outcome

The paper of Solla et al. gives a comprehensive overview of different applications of GPR in the field of construction [9]. It highlights the capability of GPR to give good results in thickness and moisture detection of concrete and the advancements in recent years regarding the interpretation of measuring data using new algorithms based on artificial intelligence (AI). Also, it highlights the potential of combining GPR with other NDT methods and mount these to UAVs.

Another paper that deals with the GPR method is from 2022 by Lombardi et al. and focuses on a more widespread analysis of GPR in different practices [10]. It’s worth noticing that the findings were in general congruent with the previous paper. The researchers underline the need for a more encompassing framework when it comes to data acquisition. This is especially valid for geophysical problems, but it could also be applied to construction related tasks.

In their paper on structural health monitoring (SHM) using computer vision and UAVs, Sabato et. al. used Computer Vison techniques to refine Infrared (IR) images, so that they were able to detect subsurface cracks in pavements [11]. This could be achieved by applying the Sparse-principal component thermography.

In an experimental study, Deba Datta Mandal and his colleagues adopted acoustic emission-based techniques to monitor progressive damage mechanisms in reinforced concrete T-beams [12]. The results and parameters of the four-point bending test on three different samples were then used and implemented in different algorithms including machine learning based ones like Support Vector regression. An unsupervised ML learning approach based on the k-means method sorted the data into according to different types of damage.

Sajid and Chouinard provide a review on the Impulse response method [13]. The paper examines the state of art and point out possible directions for future research. Advanced data analysis methods as well as numerical simulations and a better understanding of the boundaries of the Impulse response method, are the suggested next steps by the researchers.

The same technology is treated in another research published by Sajid et al. The proposal is an algorithm to automatically locate and rank defects in concrete plates using the Impulse response measurement data [14]. The researchers programmed an unsupervised algorithm based on statistical pattern recognition that doesn’t need any beforehand calibration with the tested element. Two concrete plates were used as test objects to demonstrate the superiority of the algorithm against state of the practices.

Santos et al. propose a technique of image capturing with UAVs to detect exposed rebars on concrete structures [15]. The georeferenced images are then run through a deep learning algorithm that is based on the AlexNet CNN. Two case studies on large concrete structures were made and the accuracy of 99.1% from the training process could be validated under real world conditions.

Terrestrial laser scanning (TLS) is another method working with visual appearance of structures as base. In their review Wu et al. analysed applications of TLS in the AEC Industry. Research that has been done regarding combination of TLS with IRT is mentioned as well as the rising interest in deformation measurement and monitoring [16]. The authors point out the need for further research in order to improve data processing, automatization, and adaption of artificial intelligence tools.

In their recent study Mahmoudi et al. set up a study to determine the most efficient machine learning algorithm to classify damage in concrete shear wall buildings [17]. After they found out, that the K-Nearest Neighbor (KNN) algorithm was the most compatible, they build a framework and tested it against three benchmark buildings and in the end could verify the efficiency of the approach.

Another article that has been published in 2022 tackles the importance of identifying data anomalies in SHM data sets. Zhang et al. developed a new approach combining CNN and statistic features which yields in faster and more accurate results and is able to detect up to 94.26% of anomalies [18].

Taheri et al. created an overview which machine learning algorithms were used on data of different NDT methods [19]. In addition, the potential of artificially generated training data for ML is mentioned and concluded that AI/ ML based techniques can double the precision of defect detections.

The same topic gets covered in a survey by Lavadiya et al., where the research is aimed at various Deep learning models for NDT evaluation of concrete bridge decks [20]. It was found that the novel one-dimensional convolutional neural networks (1DCNN) can predict better results from IE signals then conventional CNNs. Furthermore, the authors underline the need for reliable datasets. More measurements from different structural buildings means more data to test the proposed algorithms against, resulting in more resilient algorithms.

The paper by Deng et al. contributes to the application of DL to NDT data. The proposal trained a customized Mask R-CNN on a set of Infrared Thermography (IT) images [21]. The overall average relative error of the model is 0.7%.

Kapteina et al. published an article in which they examined the assessment and restoration of chloride contaminated building components using Laser-induced breakdown spectroscopy [22]. Not only provides the LIBS method a fast approach to measure the chloride content in concrete structures, it can also be used to review the effectiveness of treatments. However, it is only seen as an additional technique to supplement renown methods.

An overview of corrosion monitoring techniques for rebars in concrete structures by Fan et al. compares different types of sensor systems and sort them into application due to the stages of rebar corrosion [23]. The researchers state various problems when it comes to application of sensors in RC structures. That is, for example the short lifespan of sensors compared to that of the RC buildings as well as the difficulty of retrofit sensors in existing buildings. A maintenance management system is proposed to help choosing the right sensor and find the best location for positioning.

Berrocal et al. worked on embedded sensor systems in reinforced concrete. Two distributed optical fibre sensors (DOFS), one with additional protection and one without, were put into an RC beam and tested for crack detection [24]. The measured data was then put into a function and transferred into a contour plot describing the crack pattern.

Another work that tested sensors in RC structures, evaluated the sensitivity of ultrasonic sensors. Chakraborty et al. validated the sensors and signal processing on 3 different concrete structures [25]. Also, the authors found out that the optimal distance to place the sensors lays about 1.5 meters apart.

To retrieve the best predictions for the compressive strength of self-compacting concrete, Beskopylny et al. compared different ML based algorithms. The result showed that all models had a mean absolute percentage error between 6.15 and 7.89%, with the k-nearest-neighbours as the most favourable one [26]. These models could be implemented easily within the construction industry, in addition the data gained from industry could be accumulated and provided for further research.

A paper on ultrasonic wave technology was published by Diewald et al. [27]. Their aim was to analyse how external loads influence the ultrasonic waves inside a concrete specimen. Due to implemented experiments, correlation coefficients could be created giving a more comprehensive view on the topic.

8.3 Expert interviews

Two interviews with experts, that were or are working in the field of NDT testing were held [6,7]. The goal of the interviews was to identify the state of the art in practical applications, as well as trends and challenges. The following conclusions were drawn from the interviews.

- NDT methods for estimation of concrete strength lack accuracy and can often only serve as a supporting method for assessing structures.
- Parking garages are a good example of where NDT methods in existing buildings come into operation.
- Importance of viewing data sets before training on ML / DL algorithms.
- Standardized qualification for engineers doing NDT testing should be implemented.
- End users need to be trained to understand the advantages and limitations of NDT.
- Emphasis on correct calibration that needs to be on site.
- Standards for permanent sensors in RC structures

9. Future vision

In this section, how NDT methods and the underlying procedure could look like in the future has been covered. These assumptions are made from the base of the reviewed literature and the expert interviews. For comprehensibility the proposed visions are put in the context of an example project. A parking garage has to deal a lot with moving forces and polluted substances and therefore the SHM for this kind of building is of great interest.

The easiest and fastest way to assess structures is to use visual inspections. As mentioned in the literature review, there is research that covers this area. Currently the main focus lies in mounting sensors like IR onto UAVs or using computer vision algorithms on pictures taken by a drone. Image acquisition can be extended even further. Civilians could use their smartphone to photograph visible defects in concrete buildings and submit the localized pictures through an app. If a certain number of people provide pictures, weak spots can be easily identified, and further measures can be taken. Surveillance cameras that are equipped with Lidar technology can help to measure long time deformations or sudden failures. In the future a lot of cars will also have this technology and therefore could also capture images in the parking garage.

Sensor systems will also play a major role when we think about how SHM of building will be executed in the future. The focus should lay on a holistic approach for a sensor system that not only evaluates the structure but also the surrounding environment. In the case of the parking garage several sensors could measure temperature, moisture content, vibrations, winds, air quality. Other embedded sensors in concrete could measure cracks, corrosion of rebars or compressive strength. Evaluation and correlation between all sensors could lead to a better understanding of which measures should be taken to have a longer living structure. It's important to develop sensor systems that not only can be built in during the construction process but also be implemented into existing concrete structures. Together with images or in-situ tests, the amount of data will increase significantly and only algorithms can take care of the sampling and sorting procedures. As today a lot of researchers are working to implement various AL/DL algorithms to NDT methods, the future will rely even more on these techniques.

The processes of data acquisition and interpretation need to be supervised by professionals to make sure models get trained properly and the obtained results can be applied to the real structure. These processes can be time consuming, therefore wherever there is a need for measurement or calibration on site, robotic systems should step into place. The data can be implemented in Digital Twins for a comprehensive real time model of the building [28].

This is what NDE 5.0 is striving for: a fully autonomous, self-learning system where human interventions are kept at minimum and actions are performed by robots [29].

The ideal case would be a parking garage that doesn't need to be demolished, through constant structural maintenance. Therefore, it has to be ensured that the conclusions drawn from the measured data are precise.

10. Results & Discussion

In this paper we have undertaken a literature review on the most recent developments in NDT and interviewed experts to highlight the advancements, challenges, and trend of NDT from a futuristic point of view. The findings can be summarized as follows:

- A great deal of research has been conducted into the implementation of DL and ML to improve the data acquisition and analysis processes. Although scientific results show significant improvements, insufficient amounts of data about these models are published and freely accessible. Therefore, it remains unclear whether these models are trained based on artificial defects data, and to what extent such models can be extended to have a comprehensive model which could be applied to different scenarios.
- UAVs are increasingly being employed to investigate RC structures. This could be regarded as a huge step towards increasing speed and accuracy of operation while decreasing time and budget as UAVs can be sent to inspect some areas which are hardly accessible to humans.
- Integration of NDT results could be considered as a research gap as this is a subject to which less attention has been paid. The NDT results could be stored in a cloud and converted into different interoperable formats for further processing. Additionally, such data could be integrated into the digital twin of structures so that defects can be predicted regarding NDE 5.0.
- A novel data acquisition system could be launched so that citizens can take part in the data acquisition and visual

inspection phase. For instance, they can send some pictures of the likely defects and it could be automatically analyzed.
- Coring or other testing methods need to be performed to verify NDT results.
- Training of engineers should also be considered. Civil Engineers should be trained during their studies about NDT methods so that they would have basic knowledge upon graduation.

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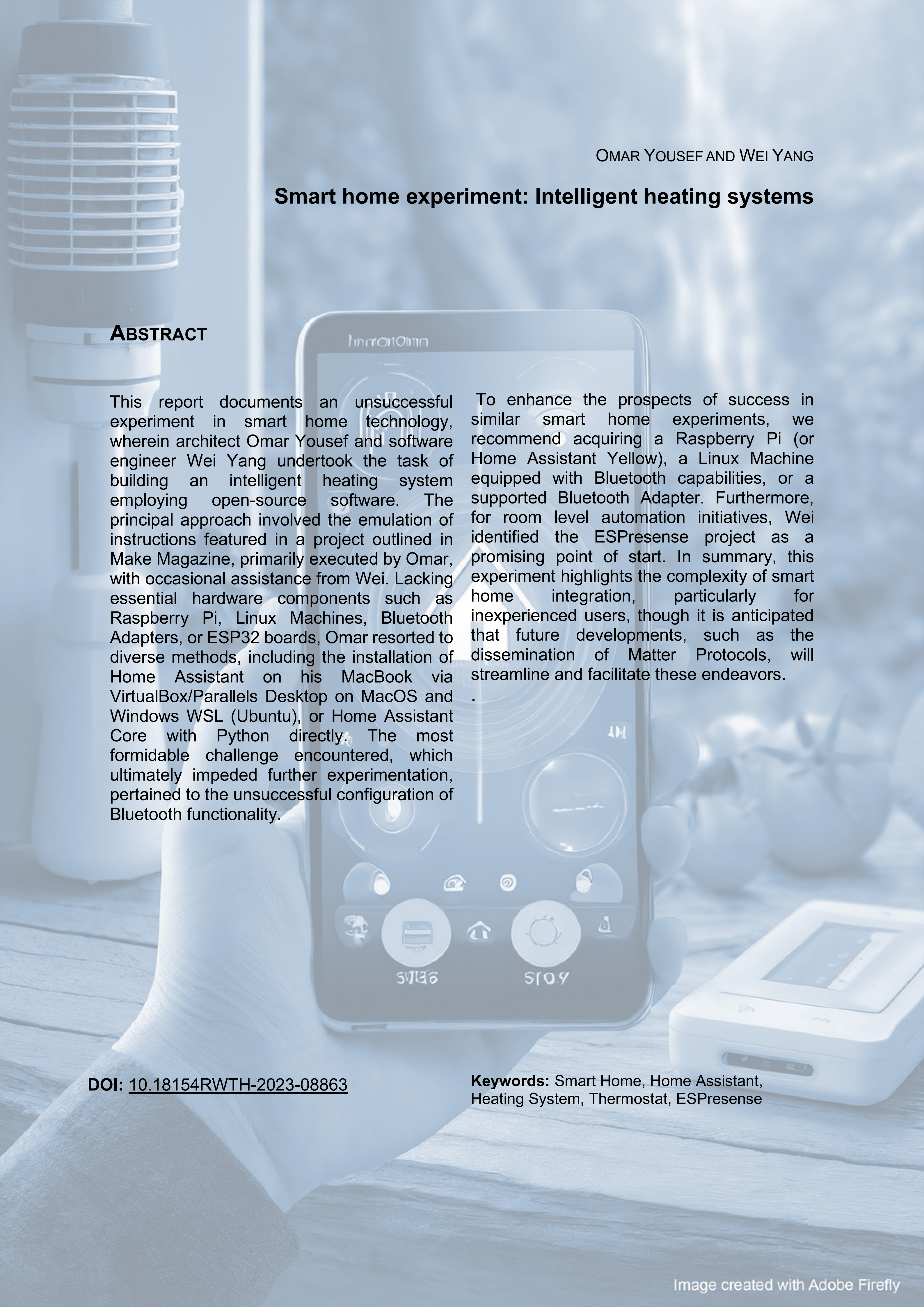
Omar Yousef and Wei Yang

Smart home experiment: Intelligent heating systems



Abstract

This report documents an unsuccessful experiment in smart home technology, wherein architect Omar Yousef and software engineer Wei Yang undertook the task of building an intelligent heating system employing open-source software. The principal approach involved the emulation of instructions featured in a project outlined in Make Magazine, primarily executed by Omar, with occasional assistance from Wei. Lacking essential hardware components such as Raspberry Pi, Linux Machines, Bluetooth Adapters, or ESP32 boards, Omar resorted to diverse methods, including the installation of Home Assistant on his MacBook via VirtualBox/Parallels Desktop on MacOS and Windows WSL (Ubuntu), or Home Assistant Core with Python directly. The most formidable challenge encountered, which ultimately impeded further experimentation, pertained to the unsuccessful configuration of Bluetooth functionality.

To enhance the prospects of success in similar smart home experiments, we recommend acquiring a Raspberry Pi (or Home Assistant Yellow), a Linux Machine equipped with Bluetooth capabilities, or a supported Bluetooth Adapter. Furthermore, for room level automation initiatives, Wei identified the ESPresense project as a promising point of start. In summary, this experiment highlights the complexity of smart home integration, particularly for inexperienced users, though it is anticipated that future developments, such as the dissemination of Matter Protocols, will streamline and facilitate these endeavors.

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DOI: 10.18154RWTH-2023-08863

Keywords: Smart Home, Home Assistant, Heating System, Thermostat, ESPresense

Image created with Adobe Firefly

1. Introduction

1.1 Motivation

As energy cost becomes higher, we wanted to build an intelligent heating system for a single apartment. The system should be able to be controlled by change in the room temperature and the presence of people in it.

Omar is an architect without much knowledge of programming or IoT devices while Wei is a software engineer with programming experience in C++ and python and some knowledge of IoT devices. Both of us have little experience with smart home projects or productions.

We hope to get some hands-on experience with smart home devices and software and interdisciplinary communication and collaboration, which may also enlighten us on why digitalization in construction is such a difficulty.

1.2 Research Question

How difficult would it be to build an easy smart home heating system for unexperienced people without a computer science background?

There are already several IoT devices and some open-source platforms for smart home. How do general people (not experienced) feel to setup a smart home system?

With devices and services from big companies like Apple, Google, Amazon, one could control lights, heating systems, air conditioners, curtains, security cameras by Siri, Google Assistant and Amazon Alexa. Could smart home devices easily be setup and be controlled by these hubs or smart phones?

1.3 State of the Art

One of the simplest solutions could be Tuya TRV603 Wifi Thermostat[1]. TRV603 (about 35 € with free shipping at the time of the paper, while normal sale price is about 64 €) could be controlled by your phone via Smart Life App which also contains a beta feature to control the thermostat, depending on your location.

This solution might not give us much enlightenment about how the smart home system works, however, it could provide comparison baseline for our experiment.

2. Research Methods

2.1 Make Magazine Project Instruction

The reference used, which was also the most helpful, was the article *Heizung unter Kontrolle* (Heating Under Control)[2] from the Make Magazine. For this project a specific thermostat, Equiva Bluetooth Smart Radiator Thermostat (CC-RT-BLE-EQ) (Fig. 2), and a thermometer, Xiaomi Mijia Smart Thermometer Bluetooth (Fig. 3), were required. The next step would be installing Home Assistant on the PC. This was the very challenging part which required a lot of research and effort, because unfortunately it was not designed for the typical user, and it needs someone who is very familiar with computer science and some specific modern technology. The Home Assistant website has a guide to run the application on each of the operating systems, whether it was a Linux Machine, MacOS, Raspberry Pi, Windows, or even others. The experiment carried out by Omar was on a MacBook (Intel CPU model) while Wei did some more exploration on a Raspberry Pi 4. As we worked in different countries during the experiment, we could only collaborate online, which made the experiment even more challenging.

Fig. 1: Control Logic of TRV603 [1]

Fig. 4 Overview of the Heating System

2.2 Market Research

We wanted to check the possible products from Amazon (or AliExpress), compare their features, costs, and complexity, so that we could understand the state of art for smart home. The review from customers was also helpful for us to find current problems for smart home.

2.3 Paper Research

We wanted to check previous research status for smart home controlled heating system, their concerns and protential.

2.4 Open-Source Projects Research

As smart home devices are controlled by complex software, we hoped to find potential open-source projects from GitHub or GitLab. This might also give us some overview status for the smart home community.

3. Results

3.1 Architecture

It is basically the use and connection of the thermostat and the temperature sensor with Home Assistant, and this happens through WIFI and Bluetooth connections (as shown in Fig. 4).

3.2 Market Research Results

Most of these thermostats can be found on the German Amazon Store. These are some examples that could give an overview of the market regarding choosing the best thermostat. The last two options are not smart thermostats, but they are used in the table as a reference to show the difference between smart thermostats and normal ones.

Picture	Type	Cost	Method
	eQ-3 Heizkörperthermostat – basic HmIP-eTRV-B	59,99 €	via app MagentaHome App Pro Magenta SmartHome Pro
	Hama 00176592 Smart Radiator Thermostat	39,99 €	via app Alexa
	AVM FRITZ!DECT 301	58,00 €	via app
	Equiva Bluetooth Smart Radiator Thermostat	24,87 €	via app
	TP-Link Kasa Smart Radiator Thermostat	49,90 €	via app Kasa Smart App Alexa Google Assistant
	Heimeier K Thermostat Head	14,00 €	Manual
	Oventrop Thermostatkopf Uni-LH	17,99 €	Manual

Table 1: Thermostats in the market

3.3 Home Assistant Setup & Configuration

In the guideline of the Home Assistant page for MacOS[3], it states that another operating system should be used on the MacOS, which meant that a 'virtual' Linux operating system needed to be used to make the Home Assistant application compatible with the MacOS. This could be done by downloading an image called VirtualBox, where it enables the user to run a Linux on their MacOS. From a link on the website, VirtualBox can be downloaded, and all the steps are available on how to install it,configure the new virtual

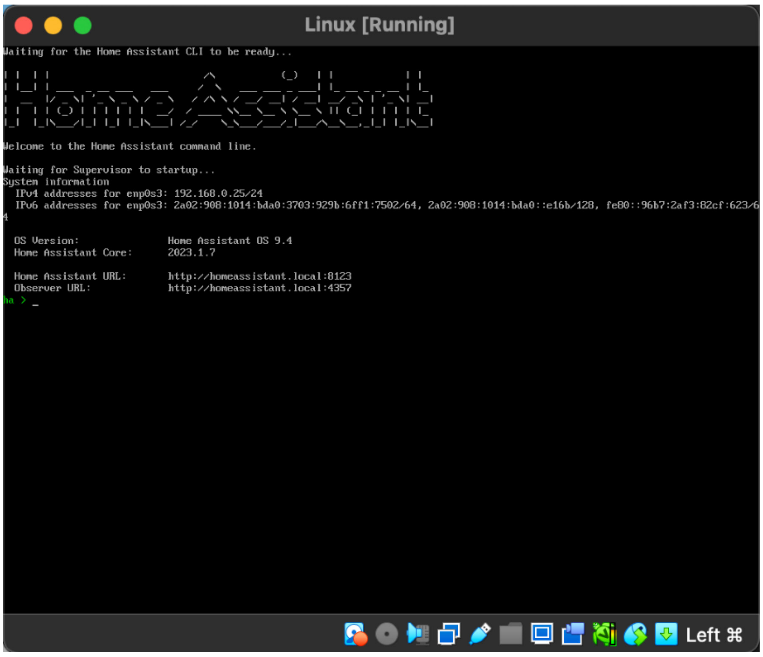

Fig. 5 Home Assistant OS in VirtualBox

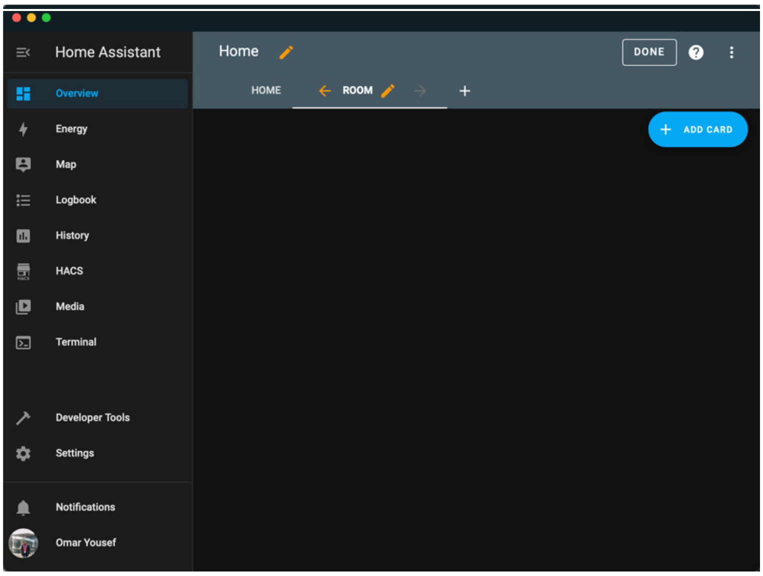

Fig. 6 Create Room in Home Assistant

machine, set it up and run it. Once the Linux virtual machine is up and running (Fig. 5), Home Assistant can then be normally run, with instructions on how it could be run, available as well on the website.

Home Assistant can then be accessed through the address (http://homeassistant.local:8123) in the browser or directly on through the companion application, simply installed from the App Store on the MacOS or iOS/Android. When Home Assistant is then started, the steps were followed from the Make Magazine article. The first step was creating the room which was experimented on Home Assistant, naming it, and optionally giving it a logo (Fig. 6).

Then, a very important step was to go to the settings and enable Advanced Mode, which then allowed the download of the installation of SSH & Web Terminal as one of the add-ons of many available on Home Assistant. It was a bit tricky to actually run it and make it work, since a very small detail was required to be known. Before it could be run, a password was required to be typed in the password line under ssh, via the Configuration tab, and then the add-on was launched (Fig. 7).

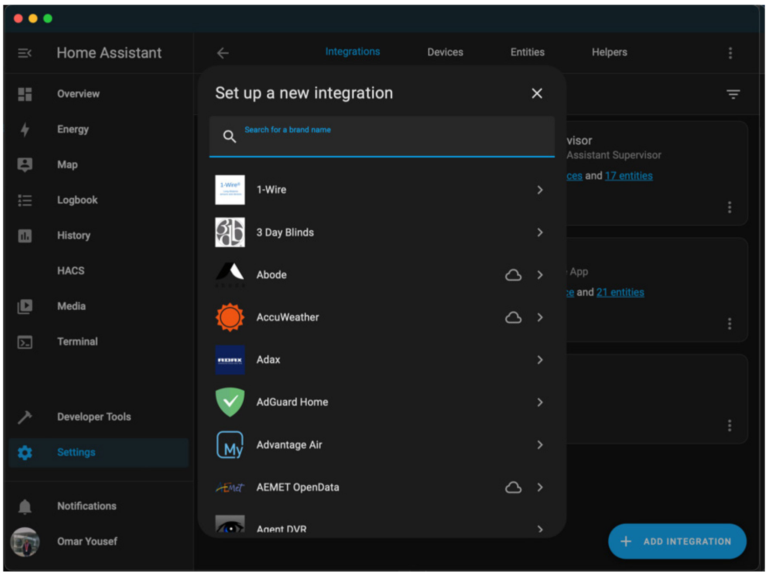

Fig. 7 SSH & Web Terminal Addon for Home Assistant

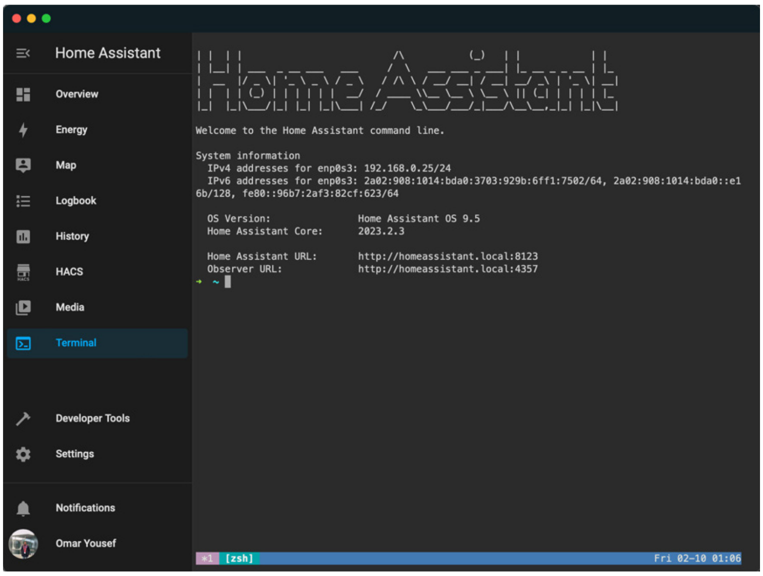

Fig. 8 Terminal for Home Assistant

At that point, the terminal option was then available (Fig. 8).

After that, the command *cdconfig* was written to switch to the configuration directory. The next step then was to install the Home Assistant Community Store (HACS), which is an integration that finds user-made addons on GitHub and makes them available for installation. This was done by simply writing a command (also provided in the Make Magazine article) in the terminal.

wget -q -O https://install.hacs.xyz | bash

After that command was written, HACS needed to be searched for through Settings > Devices & Services > Integrations (the tab from above), and then + ADD INTEGRATION (Fig. 9).

A problem that occurred during the installation of HACS was that it could not be found while being searched for in the integrations search menu. The solution to that was simply by clearing the cache of the browser. Once this had been done, searching for HACS was no problem and it was shown in the search results (Fig. 10).

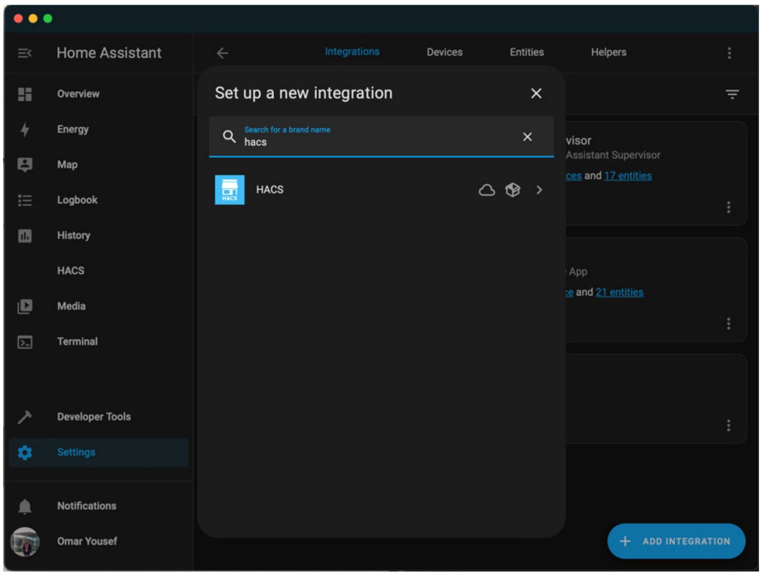

Fig. 10 Searching for HACS

To install HACS, a GitHub account was required. It would require a code to be entered to the GitHub account to activate the device. After having been redirected and logged into the GitHub account page, it was then where the HACS installation was successful and ready to use, where it had then appeared in the integrations list as well as in the left menu of Home Assistant.

MAC Address vs UUID on MacOS

The next step was to try to find the MAC (Media Access Control) addresses of the thermostat and the smart thermometer. We came to a realization that the MacOS operating system doesn't really work with MAC addresses, but it works with UUID (Universal Unique Identifier). It was basically the same idea of each device having its own unique code. The format is different than how a typical MAC address would look like. As python-eq3bt (used by Home Assistant Core) also uses bleak to communicate with Bluetooth devices and someone mentions that

"You can use the address attribute of the discovered device to create the client object. Bleak knows that MacOS uses the UUID instead of the Bluetooth address."[4]

so we might just find the UUID (with CC-RT-M-BLE) and add it to the MAC address of the configuration on MacOS.

Thermostat

UUID of Thermostat on MacOS:
7294D8FF-CCF9-9074-97E0-80BDE549787C

The first problem that occurred was that if the thermostat was connected via Bluetooth to any other device, it wouldn't show with the list of visible Bluetooth devices. Another problem that occurred was that the MacOS needed to be very close to the thermostat in order for it to detect it. The distance where it was visible was no more than 50 cm. Although we got the UUID of the thermostat with a python script, homeassistant warns us that such use needs more support and ran into some errors to get the integration work properly. Even the eq3cli tool from python-eq3bt could not work properly with UUID. A command can be used to check the availability and get some data from the thermostat.

eq3cli --mac 7294D8FF-CCF9-9074-97E0-80BDE549787C

When this problem occurred, we thought that maybe using the Windows operating system might help us, since we would be able to find the MAC address instead of the UUID, and maybe this was the problem that was stopping us from proceeding. So a switch to Windows WSL was then required to try to find the MAC address of the thermostat. Again, we found the Ubuntu (WSL) lacks Bluetooth

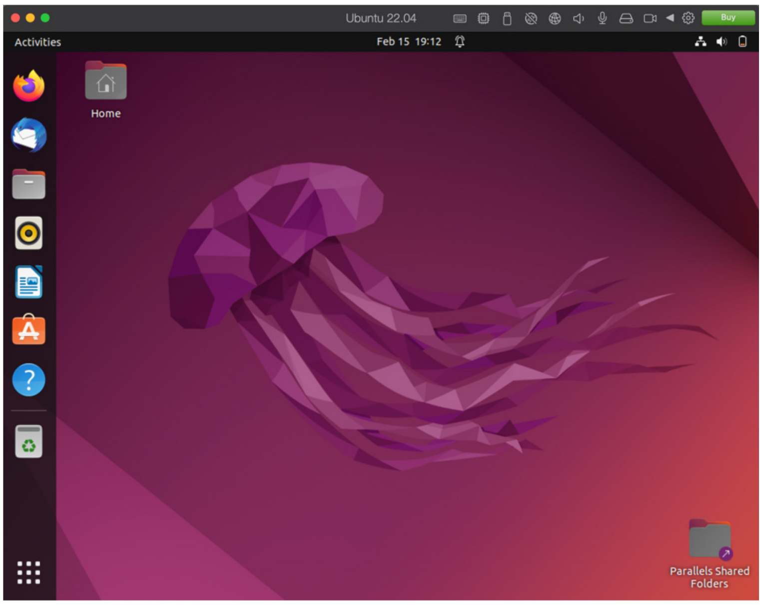

Fig. 11 Ubuntu Linux in Parallels Desktop

devices, and according to the discussion of this issue[5], we have to compile customized kernel for such use.

MAC Address of Thermostat on Windows: 00:1A:22:12:B3:A9

This was us experiencing how complex it could be without owning a Linux PC or a Raspberry Pi. Unfortunately, since the Windows WSL trial was not successful, we had to try another approach. We went back to the MacOS operating system to download Parallels Desktop with Bluetooth Sharing enabled. This would enable us to download Ubuntu Linux, which basically acted as an individual independent Linux PC (Fig. 11).

It came to our surprise that the MAC address on the Linux operating system was a different one.

MAC Address of Thermostat on Ubuntu Linux: F9:CC:FF:D8:94:72

Although we could find the thermostat and its MAC address, the eq3cli could not connect it. It might be that the virtual Bluetooth Adapter is not stable enough for such use case.

Smart Thermometer

The smart thermometer process was the same, it also needs the adapter and the MAC address, and we faced the exact same problem that occurred with the thermostat.

3.4 Thermal Comfort & Dew Point

The optimum thermal comfort of the human body:

Temperature: 23-26 °C (Summer), 20-23.5 °C (Winter)
Relative Humidity (RH): 30-60%

This is mostly through the ANSI/ASHREA Standard 55, which is an American National Standard published by ASHREA, which establishes the ranges of the most optimum indoor environmental conditions to achieve thermal comfort.

There could be other factors affecting the thermal comfort of the human body.

- Local Climate
- Country and its Weather Conditions
- Building Type, HVAC Mode
- Body Build, Age, Gender

3.5 Room Level Automation with ESPresense

ESPresense is an ESP32 based presence detection node for use with the Home Assistant mqtt_room component for localized device presence detection. This is a

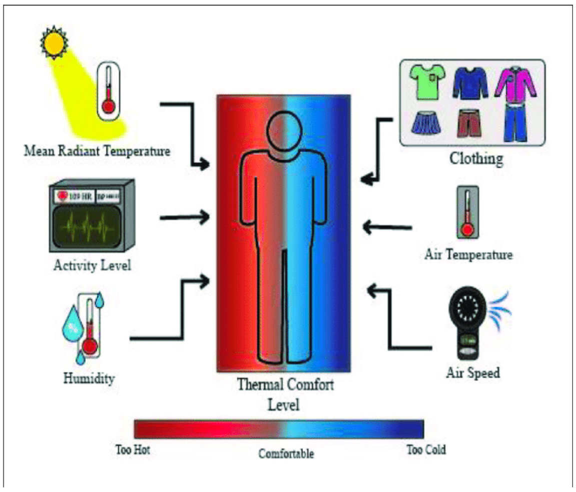

Fig. 12 Factors Affecting Thermal Comfort [6]

Temperature, Relative Humidity and Dew Point

Temperature °C	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	Temperature °C
38	17.42	19.88	22.05	24	25.77	27.39	28.88	30.27	31.57	32.79	33.94	35.03	36.07	37.06	38	38
37	16.56	19.01	21.17	23.1	24.85	26.46	27.95	29.33	30.62	31.83	32.97	34.05	35.08	36.06	37	37
36	15.7	18.13	20.27	22.2	23.94	25.54	27.01	28.38	29.66	30.86	32	33.08	34.1	35.07	36	36
35	14.84	17.25	19.38	21.29	23.02	24.61	26.07	27.43	28.71	29.9	31.03	32.1	33.11	34.08	35	35
34	13.98	16.38	18.49	20.39	22.11	23.68	25.14	26.49	27.75	28.94	30.06	31.12	32.12	33.08	34	34
33	13.12	15.5	17.6	19.48	21.19	22.75	24.2	25.54	26.79	27.97	29.08	30.14	31.14	32.09	33	33
32	12.25	14.62	16.71	18.58	20.27	21.83	23.26	24.59	25.84	27.01	28.11	29.16	30.15	31.1	32	32
31	11.39	13.74	15.82	17.67	19.36	20.9	22.32	23.65	24.88	26.05	27.14	28.18	29.16	30.1	31	31
30	10.53	12.87	14.93	16.77	18.44	19.97	21.39	22.7	23.93	25.08	26.17	27.2	28.18	29.11	30	30
29	9.67	11.99	14.03	15.86	17.52	19.04	20.45	21.75	22.97	24.12	25.2	26.22	27.19	28.12	29	29
28	8.8	11.11	13.14	14.96	16.61	18.12	19.51	20.8	22.01	23.15	24.22	25.24	26.2	27.12	28	28
27	7.94	10.23	12.25	14.05	15.69	17.19	18.57	19.86	21.06	22.19	23.25	24.26	25.22	26.13	27	27
26	7.08	9.35	11.35	13.14	14.77	16.26	17.63	18.91	20.1	21.22	22.28	23.28	24.23	25.14	26	26
25	6.21	8.47	10.46	12.24	13.85	15.33	16.69	17.96	19.15	20.26	21.31	22.3	23.24	24.14	25	25
24	5.35	7.59	9.56	11.33	12.93	14.4	15.75	17.01	18.19	19.29	20.33	21.32	22.26	23.15	24	24
23	4.48	6.71	8.67	10.42	12.01	13.47	14.81	16.06	17.23	18.33	19.36	20.34	21.27	22.15	23	23
22	3.62	5.83	7.77	9.52	11.09	12.54	13.88	15.12	16.27	17.36	18.39	19.36	20.28	21.16	22	22
21	2.75	4.94	6.88	8.61	10.18	11.61	12.94	14.17	15.32	16.4	17.42	18.38	19.3	20.17	21	21
20	1.88	4.06	5.98	7.7	9.26	10.68	12	13.22	14.36	15.43	16.44	17.4	18.31	19.17	20	20
19	1.01	3.18	5.08	6.79	8.34	9.75	11.06	12.27	13.4	14.47	15.47	16.42	17.32	18.18	19	19
18	0.15	2.3	4.19	5.88	7.41	8.82	10.11	11.32	12.44	13.5	14.5	15.44	16.33	17.19	18	18
17	-0.72	1.41	3.29	4.97	6.49	7.89	9.17	10.37	11.49	12.53	13.52	14.46	15.35	16.19	17	17
16	-1.59	0.53	2.39	4.06	5.57	6.96	8.23	9.42	10.53	11.57	12.55	13.48	14.36	15.2	16	16
15	-2.46	-0.36	1.49	3.15	4.65	6.03	7.29	8.47	9.57	10.6	11.58	12.5	13.37	14.2	15	15
14	-3.33	-1.24	0.6	2.24	3.73	5.09	6.35	7.52	8.61	9.64	10.6	11.52	12.38	13.21	14	14

Relative Humidity %

Dry · Comfortable · Alright · Uncomfortable · Very Uncomfortable

Fig. 13 Temperature, Relative Humidity

fork/rewrite of ESP32-mqtt-room.[7] ESPresense could also connect some sensors like Temperature & Humidity module like DHT22 out of the box.

Steps:

a. Install firmware to esp32 devices via usb (web-serial).
b. Configure Wifi.
c. Set a name for the station.
d. Calliberate the maximum distance and rssi expectation.
e. Setup beacon (e.g., smart phone or esp32 board) for tracking in Home Assistant.
f. Add automation & test.

Dashboard of Home Assistant

As ESPresense is still intensively under developing, it has some issues with the RISC-V esp32-c3 board. The enroll UI to get the IRK for your iOS device is missing on the M5 Stamp C3 board, while it is functioning properly with the old standard esp32 dev board. And ESPresense could not setup AP (Access Point) on esp-C3-32s-Kit with 2m, which is related to the Arduino library for esp32-c3 chips.

3.6 AR Integration

Augument Reality is a great way to interact with IoT devices intuitively.

“It is where augmented reality is the perfect solution. You can take your phone and point at any building, room or appliance to call an action. For example, I have a sauna in my garden that has to get to a certain temperature level before people get in. AR enables me to

skip multiple steps to get information. I no longer have to open the Home Assistant app and select the right building and the function I need. I can point my phone camera at the sauna and see if it is hot enough to enjoy.”[8]

3.7 Matter

When you touch the smart home topic, you would probably find so many different lot. Now comes Matter at the end of 2022, a protocol that would integrate with almost any smart home device in the future.

“Matter is a common language for smart home devices. It’s designed to simplify everything about the smart home, from purchase to setup and everyday use. Its biggest promise is making smart devices work with each other across platforms and ecosystems, no *matter* who made them.”[9]

protocols (e.g., Wifi, Zigbee, Bluetooth 4.2/5/5.1, BLE, Lora etc.) that confuse you a

Across the Different Protocols Supported by Matter. Image: Thread Group[9]

Benefits of matter[10]:

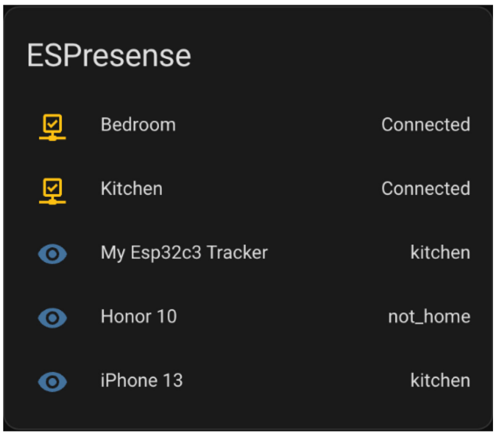

Fig. 14 Dashboard for ESPresense

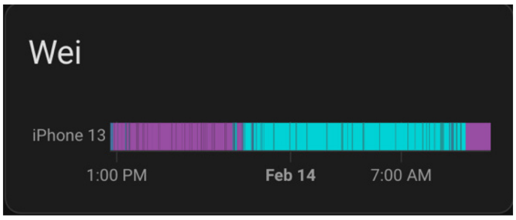

Fig. 15 History for iBeacon device (iPhone)

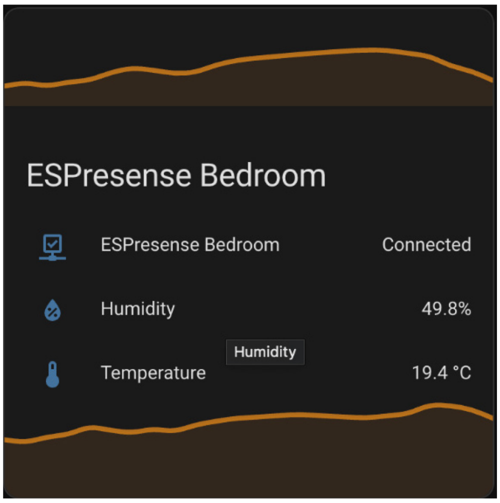

Fig. 16 Integration with Temperature and Humidity sensor (DHT22)

a. local connection – Internet is optional
b. the radio protocol thread – mesh network
c. easy setup – QR code
d. security and privacy – encryption, device certificates and blockchain technology

Home Assistant supports Matter with a beta addon Matter-server. For esp32 chips, Espressif has esp-matter sdk[11], so that you could turn an esp32 dev board into a matter device.

4. Discussion

4.1 Complexity

During our experiment, we came across many issues that is not stated in the guidelines or official documents. Some issue need expert knowledge and time to resolve. We also realized that the interdisciplinary knowledge sharing is quite difficult. The terms and methods for IT-expert & non-IT-expert are so different, which requires much effort and time to understand and have enough confidence to handle by general people. When someone asks for help in the forum or posts an issue on GitHub, contributors and other people need more special details (OS, version, steps, errors, log, screenshots, etc.) to understand the problem, and they also need to describe it in an easy way to help tackle the problem.

Compared to Tuya TRV603 Wifi Thermostat[1], our solution seems more complex to setup, less stable and costs more (without include the cost of a Raspberry Pi). Through this unsuccessful experiment of smart home, we do learn a lot and have a better understanding about the IoT devices and it prepares better us for the digitalization of traditional construction industry.

4.2 Customization

Home Assistant has a community store for add-ons to add more features to integrate into smart home automation.

4.3 Multi-Platform Support

As matter comes as an interoperate protocol, new products could easily support multi-platform, which is great for customers.

4.4 Cost & Saving Potentials

According to nest energy saving white paper[12], smart thermostats could save 10-15% of cost for heating. While the smart devices are quite expensive, it may not be so attractive for a small single apartment to invest such automation if the rent is short. In the long run, however, they could save a very considerable amount of money and energy.

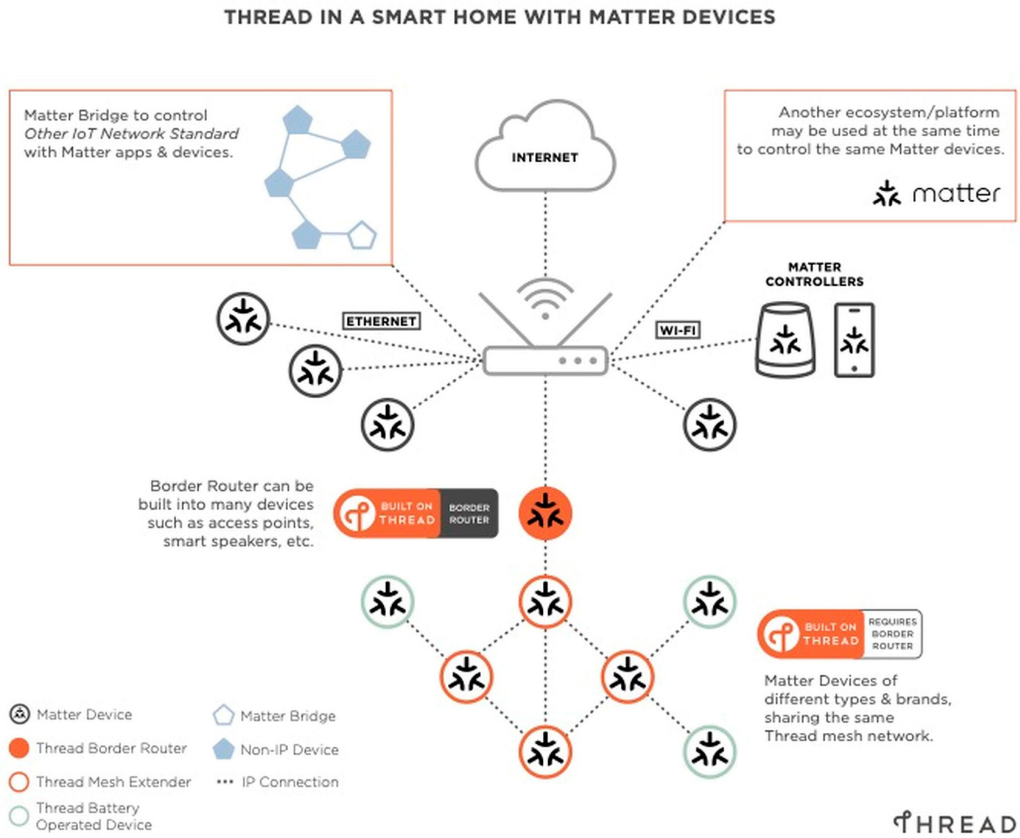

Fig. 17 How Devices Will Communicate Across the Different Protocols Supported by Matter. Image: Thread Group[9]

4.5 Security

The prospect of automation could be interesting and enjoyable, provided that smart devices are protected from potential malicious users.

Smart Home Security Tips for Customers [13] :

- Use the screen lock on your smartphone.
- Ensure all your computers and smartphones are password protected (consider using a password manager, e.g., Bitwarden).
- Ensure your main computer account is not at an administrator or root level.
- Change the default username and password on your router.
- Use firewalls on any computers and on your router (consider setting up a guest network for smart home devices).
- If your existing router doesn't offer you good security features, replace it.
- Use a strong security software on your computers and smartphone.
- Always run security patches and updates and keep your software up to date.

For smart home developers, rewriting/implementing a software with rust language could also reduce risks of exploits and many security issues. TockOS is a promising alternative for Free-RTOS. A good start could be the Book *Getting Started with Secure Embedded Systems: Developing IoT Systems for micro:bit and Raspberry Pi Pico Using Rust and Tock*[14].

4.6 Inspirations for Construction

Although customers could setup smart home to an existing building, there could be a lot of benefits to consider fundmental smart hubs and sensors in the stage of design and install during the construcion stage. For example:

- Extra plugs/power supply, for micro stations/wifi mesh
- Smart plugs, which could control and collect eletricity comsuption, for non-smart devices
- Smart bulbs, with an IR sensor, which could be used for room level presence
- Extra space for smart curtain motor
- Smart sensors to provide maintenance information
- BIM data for AR/ Digital Twins applications

5. Conclusion

5.1 Challenge & Trend

Setting up smart home system is still a complex task even for experts. With matter coming to production, smart home automation could be easier and easier for new customers and hobbyists. We learned a lot through spending a lot of effort experimenting and researching for so many hours, whether individually or together. Even though this was unfortunately an unsuccessful experiment, we believe that it would be a benefit for us in some sort. We are pretty sure that it would give us a head start when the automation and application of smart homes would become easier and more popular in the very near future.

5.2 Community & Open-Source

As smart home is so complex and not mature, community support is a good way to get help from experienced experts and other customers. Open-source community is great for customization to get the devices smart for your need.

5.3 AR & AI

AR application for smart home might become a must feature for future smart home, espcially when AR glasses come to daily life. As smart home collects so much data about your daily acitivities, AI companies would have great interests to help you find a better solution to build more automation for your smart home.

5.4 Construction

If smart home fundamentals could be considered during the construction processing, the residents could enjoy a better life.

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