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How can visual programing be used to aid the development of a structural scheme design process utilising geometric data within an Architectural Revit model?

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Abstract - The early-stage structural scheme design of a building is a complex task requiring the collection of multiple information categories such as geometry, loading and materials. The collection and review of this information is traditionally conducted in a 2D environment. This is inefficient, time-consuming, and tedious. This paper provides a review of how structural engineers' understanding and implementation of BIM has evolved significantly in recent years, validated by extant literature in areas such as BIM automation, visual programming, and structural optimisation in the structural engineering sector. Structural engineers are growing more aware that BIM provides a vast repository of data to be used in their design processes, the author presents solutions through action-based research to demonstrate how visual programming can be used to aid the development of an early-stage structural scheme design by utilising the geometric data within an architectural Revit model. A focus group of industry professionals reviewed and tested the proposed solutions and found them to add value and efficiency to the process. While the proposed solutions are in basic form, they can be developed further to gain additional efficiencies. It was noted that due to their design responsibility, structural engineers felt the need to manually validate the results of the automated process, potentially nullifying efficiencies gained.

Keywords– BIM, Structural Engineering, Visual Programming, BIM Automation, Structural Optimization

I Introduction

Well before the turning of the 21st century Structural Engineers (SEs) had already embraced the digital world. As SEs use of Computer-Aided Design (CAD) expanded, and coupled with the ever-increasing availability of computer hardware, the market for bespoke programming and commercial software products became more commonplace (Raphael and Smith, 2003). The use of Structural analysis packages provided speed and efficiency of repetitive calculations and tasks, giving the ability to adjust parameters and observe the effect on the results.

With the growing demand for more complex projects, the requirement for SEs to embrace and adopt digital technologies in their everyday business has become a necessity, as is the need to keep informed of the latest innovation and future technologies (Eastman et al., 2018). This was apparent following the BIM mandate by the UK government in 2011 (Cabinet office, 2011), which caused substantial growth of BIM adoption in the sector (Vilutiene et al., 2019).

While at that time BIM was considered to be a 3D parametric modelling application, it is now widely considered to be a process that integrates the information involved in a construction project to facilitate planning, design, analysis, construction and maintenance (NBS, 2020).

The increased level of knowledge and understanding of the BIM process in the sector drives a curiosity which in turn inspires innovation. Research shows that engineers were investigating ways to improve efficiencies within BIM by using the vast amounts of relevant information available to them in relation to a construction project. Research topics in areas such as efficiency, object detection and BIM automation are becoming more prominent in structural engineering (Vilutiene et al., 2019), however, it is noted in the literature that the research in these areas is still in its infancy and many papers state the need for further studies to be conducted.

a) *Research Background*

The early-stage structural scheme design of a building is a complex task requiring the collection of multiple information categories such as geometry, loading and materials. How these elements interact causes an effect on the proposed structure. As discovered in a recent questionnaire conducted by the author with industry professionals detailed later in the paper, the collection and analysis of this information is conducted in two separate processes and is very often conducted in a 2D environment. This is inefficient, time-consuming, and tedious.

The primary objective of this paper is to investigate if visual programming can be utilised to automate processes within a BIM environment to aid the development of an early-stage structural scheme design, hence, transferring traditional practices from a 2D to a data rich 3D environment, realising the efficiencies made available by the vast quantities of data held within an architectural Revit model.

To achieve the author's objective, this paper is structured as follows. **Section II** is a review of relative literature examining BIM in relation to its evolution and application within the structural engineering sector. **Section III** provides an analysis of the initial questionnaire undertaken to establish current practices used. **Section IV** details the action research and its development in building the automated process. **Section V** details an evaluation of the solutions and **Section VI** provides the author's conclusion under the sub-sections: summary of findings, suitability of methodology, prerequisites for successful application, relevance to the sector, further refinement, implications for other sectors and areas of potential future research.

II Literature Review

The literature review was undertaken to determine the evolution of BIM in structural engineering and examine workflows and frameworks in relation to the development of automated processes in structural design. Research was sourced from multiple areas such as books, journals, conference papers, educational institutions. Prominent search terms used were, "BIM," "BIM Optimisation," "BIM Structural Engineer," "Visual programming."

a) BIM

Building Information Modelling (BIM) is accredited to originate from Charles M. Eastman's article titled *"The Use of Computers Instead of Drawings In Building Design"* where he details a *"Building Description System"* published in the *AIA Journal in March 1975*. It has since been the topic of vast development, investment, and research. In more recent times, a study conducted by (Manzoor et al., 2021), BIM was discovered to be the most important digital technology in the AEC industry.

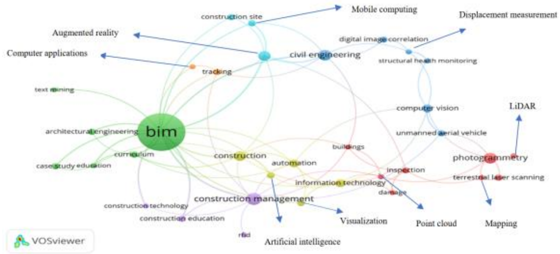

Figure 1. Research interests on DTs in the AEC industry (keywords co-occurrence). (Manzoor et al., 2021)

The National BIM report 2020, the latest at time of writing, states that respondents, when asked what their organizations overall approach to BIM was, the majority described BIM as a standardized process (NBS, 2020), a view which is also supported by (Banfi et al., 2017) in their article where they conclude that BIM is not the use of 3D applications, but is a process that integrates the information relevant to a construction project for design, analysis, planning maintenance and management.

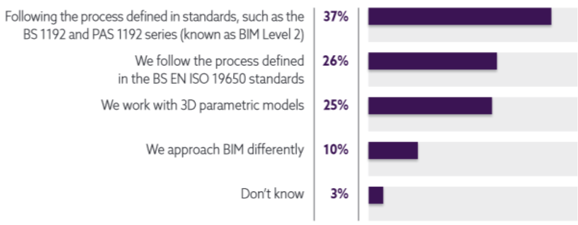

Figure 2: Graph showing the view of respondent's organisation's approach to BIM. (NBS, 2020)

BIM creates an environment to simulate the virtual construction of a project, allowing experimentation and adjustment to the design prior to physical construction (Grilo and Jardim-Goncalves, 2010) resulting in a data rich model of a building or infrastructure (Sampaio, 2017).

Research shows that there is a gain in productivity realised by the visualisation of the model. This Leads to the elimination of conflicts on site and a reduction in labour due to the clarity of installations as the process has been coordinated in the model. These factors also contribute to a reduction in time spent to construct the building (Fan et al., 2014).

As there is a demand from industry for more complex projects and given the associated difficulty to manage them (Alshawi and Ingirige, 2003), BIM is placed centrally in the future development of the construction industry’s processes. A study conducted by (Fan et al., 2014) noted that BIM provides a leaner and more effective method of communication between project stakeholders which in turn enhanced and inspired innovative solutions derived from a more informed design. However, it is worth noting that the free movement of information between stakeholders that may have competing or conflicting interests can be a challenge (Hamidavi et al., 2020a).

Further barriers in BIM implementation in a study by (Liu et al., 2015) were found to be, lack of skilled personnel, lack of national standards and the high cost of application. Although, in the case of structural engineers, price is the least considered factor when ranking structural analysis packages, functionality and reliability are the top two factors (Jarrah et al., 2021).

Factor	Analysis Set (CR = 0.014)	Validation Set (CR = 0.025)	AHP-Shannon
Standardization	12%	11%	11%
Reliability	24%	24%	17%
Longevity	15%	16%	19%
Usability	14%	16%	15%
Price	6%	6%	3%
Functionality	29%	27%	35%

Figure 3: Calculated factor weights using score averages, source (Jarrah et al., 2021).

Despite the barriers, the 2020 NBS BIM report shows that BIM adoption has grown dramatically. In 2011 43% of respondents had not heard of BIM and only 13% were using it, yet today awareness is at 99% and 73% are now using BIM.

The benefits of using BIM are recognised as:

- Improved Coordination.
- Better Productivity.
- Reduced Risk.
- Increased profitability. (NBS, 2020)

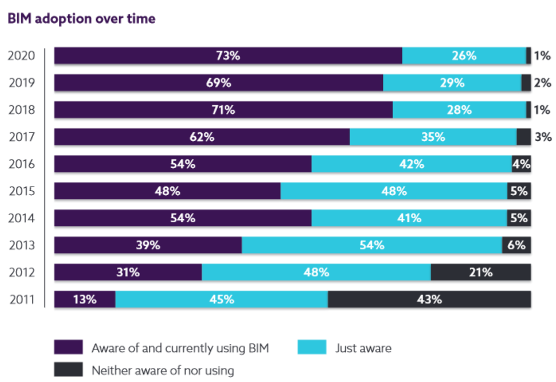

Figure 4: Graph showing the BIM adoption over time. (NBS, 2020)

b) The Structural Engineer and BIM

The role of a Structural engineer on a construction project incorporates a wide range of complex tasks including, structural analysis, geometric design of structural elements for efficiency, monitoring of on-site works and value engineering (Vilutiene et al., 2019). In developing and providing solutions for these tasks, the engineer will require integration of information provided by the Architect, M+E engineer, Landscape architect and other design team members.

BIM facilitates the coordination of design team information with the ability to model data rich elements containing information on the three key properties required for structural design, geometry, material, and loading (Vilutiene et al., 2019). However, while structural engineers have increased their knowledge and use of BIM, there is a need for training to keep pace with the increasing demands of projects with ever-growing complexities (Eastman et al., 2018).

A bibliometric analysis of literature on BIM for structural engineers showed the relevance of BIM for structural engineers has increased significantly since 2014 and attributed the increase from 2012 onwards to the 2011 UK mandate for the use of BIM Level 2 on all public projects by 2016 (Vilutiene et al., 2019, p. 5).

Figure 5: Graph showing the number of publications in the area of Structural Engineering over time. (Vilutiene et al., 2019)

The study also showed the evolution of the areas of interest across the period 2003 to 2018. Below are some of the prominent keywords noted in papers during the period 2010-2018:

2010-2012 - Three-dimensional, computer aided design, and software.

2013-2015 – Information Management, Lifecycle, and interoperability.

2016-2018 – Automation, object detection, and efficiency.

The evolution mapped in the keywords noted above show an increase in complexity of the research questions, and a deepening understanding toward the potential benefits available within the BIM process. However, the author noted that BIM has a large unexplored capacity for solving complex technical issues in structural engineering and concluded that BIM applications for structural engineering is in its infancy and further research is needed (Vilutiene et al., 2019).

In more recent times, generative design methodologies are being used to solve complex problems in BIM. Generative design is described by (Nagy et al., 2017) as a design process between computers and humans, whereby the computer generates promising design options based on criteria for further analysis by the designer. The solution evolves iteratively based on the result of the preceding study, following feedback from the designer. The results are then graded on how they meet the designers initial requirements, and the final result is selected and incorporated into the project design. The stages of generative design as noted by (Bohnacker et al., 2012) are, generate, analyse, rank, evolve, explore, and integrate.

In a study conducted by (Díaz et al., 2021) regarding generative design, 65% of engineers surveyed admitted to not knowing or having little knowledge of it, 25% didn't know what it was and only 8% have used it. This recent study validates (Vilutiene et al., 2019) and the purpose of the research set out in this paper.

b) *Structural Design Optimisation (SDO)*

Design optimization is defined as the pursuit of better solutions to minimise cost function while meeting the design criteria (Farkas and Jármai, 1997). The conceptual structural design of a building has implications on its cost, performance and constructability (Fenves et al., 2000). It is a dynamic and complex process whereby the behaviour of a building must be analysed to understand the effect experienced under various loads (Liu et al., 2016). Considerations given at this early stage can have an enormous effect throughout the lifecycle of the project. The decisions made at the outset can prove more costly and difficult to adjust as the process develops (Tofigh Hamidavi et al., 2018).

The British Standards institute notes the four main considerations for structural optimization as: design constraints, fabrication constraints, cost function and mathematical methods (bSi, 2002). Traditionally, with these considerations in mind, engineers are required to rely on their knowledge and experience to develop a conceptual design and optimize the design in a time-consuming iterative process manually. Getting the initial design correct can yield a reasonable design that meets the architect's requirements simultaneously (Larsen, 2016).

Given that the design process has layers of complex multi-criteria problems requiring clear definition and exploration, the BIM process and its associated technologies can provide the solution by means of a detailed digital model of a building throughout the complete design phases. The structural model forms a vital component (Liu et al., 2016) in this process and can play an important role at conceptual design stage as it can hold a repository of information for harvesting that can be utilised to undertake the design.

Extant literature shows that many researchers have developed methods that employ automated processes in favour of the engineer in the conceptual design stage (Tofigh Hamidavi et al., 2018). In an article published in the Journal of Information Technology in Construction by (Saad Travassos do Carmo and Dominguez Sotelino, 2022) the authors set out to develop a framework to demonstrate the synergy between BIM and structural optimization (SO) with the main objective of developing an understanding of how SO could be incorporated in a BIM project and what it can provide. They concluded with two main findings. Firstly, by the mapping of information and structuring the processes a SO process can be incorporated in the early design stages. Secondly, synergy between structural engineer and architect promotes a better solution and improves collaboration between both parties, which is a core principle of BIM.

c) *BIM Automation*

As noted earlier, structural engineers are posing an increasing number of questions around the subjects of automation and efficiencies within BIM (Vilutiene et al., 2019), an article published in Construction Innovation conducted an online questionnaire with 354 accredited structural engineers with the aim of developing a framework for an optimised structural design in BIM. The framework uses the data within an architectural model to build a parametric structural model in Autodesk Robot structural analysis package. This is completed using visual programming language Dynamo through an automated process. Dynamo was selected to mitigate interoperability issues between the architectural and structural models. The proposed framework was developed and tested via a proof-of-concept prototype. The authors believe they have developed a potential solution to the lack of BIM integrated frameworks relating to automated structural design processes within the BIM platform (Hamidavi et al., 2020).

Further exploration studies conducted also show many areas in which automation can be utilised, for efficiency in architectural design (McNally, 2019), structural optimisation (Hamidavi et al., 2020b) and compliance checking (Reinhardt and Matthews, 2017). Commonalities are noted in these papers: the requirement for the use of multiple software applications and visual programming to complete an automated process; the automated process had positive outcomes; clearly defined workflows are required, and action research and experiments were used as the process was developed.

A BIM-based automated optimisation framework in the design of steel reinforcement for concrete framed buildings was developed by (Mangal and Cheng, 2018), the framework was constructed with four main modules, BIM model extraction, Structural analysis, Steel reinforcement calculation, and steel reinforcement optimisation. The authors used a genetic algorithm and summarised that the framework was successful in optimising steel reinforcement design, however they cautioned the framework was only applied with regular shaped elements and required more development and validation for complex shaped irregular elements.

Progressing to the application of automated processes in the real world, a case study published in the BIM handbook detailed how the structural engineer developed in-house custom application to use the architect's parametric model to extract geometry and build the structural analysis parametric model from the information gathered. This was a lean process and allowed for the ease of collaboration between both parties, validating the article by (Saad Travassos do Carmo and Dominguez Sotelino, 2022) mentioned earlier. The authors concluded that many advantages were realised in the use of BIM and the parametric models. However, they also noted limitations, that the complexity of the modelling reduced the number of staff with the ability to work on the project (Eastman et al., 2018).

This creates a dilemma for BIM professionals as to the level of detail and complexity to develop models beyond the minimum requirements of the client. In a study on the effects of BIM during construction, (Fan et al., 2014) found that too little modelling could be a cause for a drop in field productivity and increase waste, but too much modelling had no negative impact on field activities.

It is shown in the research that Structural optimisation frameworks and BIM automation provide lean and productive processes in the early-stage conceptual design in structural engineering. Although research in the area is in it's early stages, there is a growing awareness of the benefits that can be realised, a high level of automation within BIM yields innovative, accurate and rapidly generated solutions to the problems of modelling practices. (Banfi et al., 2017).

III Initial Questionnaire

Following the findings of the literature review, a questionnaire was compiled and distributed to the staff of an award winning Civil and Structural engineering company. The company has offices in Dublin, London, and Sofia with extensive experience in public and private projects across a wide range of sectors including high rise, commercial, residential, education, healthcare, hotel & leisure, conservation, and Civil & Infrastructure. The level and broad range of experience within this company provided a solid base for valuable input, however, as there is only a single company included in the questionnaire there may be set practices and preconceived ingrained processes that gives rise to the potential of inhibiting outcomes.

a) Initial Questionnaire

The purpose of the questionnaire was to build on the knowledge gathered in the literature review and gain an insight to current real-world attitude and practices in the development of early-stage structural scheme design and the use of an automated process to aid the task.

The questionnaire was structured to gain information in the following areas:

- Current practices in developing schemes
- The benefit of an automated process.
- The extent of use of the automated process.
- Demographic of respondents.
- The development of structural schemes in relation to process and regularity.
- Willingness to partake in the focus group.

The questionnaire was sent out to fifty staff including structural technicians, engineers, and directors. Of the fifty, thirteen responded and the results below are based of the thirteen responses.

b) Analysis of questionnaire results

To assist the development of the new automated process it was imperative to gain an understanding of the current practices being used. The first section of the questionnaire posed questions giving response options to choose from and the second section required a detailed description of the process taken.

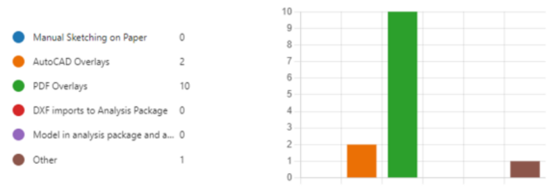

Figure 6: Methodology used in scheming buildings.

All respondents stated that there would be a benefit in the use of an automated process. This would indicate that they felt their current practices could be streamlined and this validated the findings within the literature that there is growing awareness of the benefit of automation of processes among structural engineers.

The demographic of the respondents, noted in figure 7 below, displayed a higher level of interest in the automated process amongst associates, project engineers and design engineers. This aligns with the roles that would predominantly prepare structural schemes.

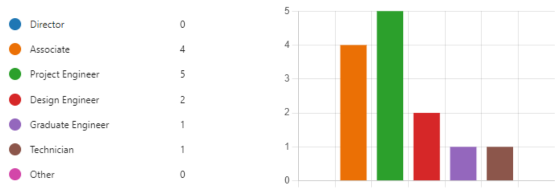

Figure 7: Demographic of respondents by role.

There were multiple questions posed in relation to the extent of use of the utility. These were regarding the regularity a respondent undertook the task of scheming a building, regularity they would use the utility, if they foresaw multiple use of the utility on the same project, and if they would use it as a check of existing projects.

Figure 8: Regularity of development of schemes.

Figure 9: Estimated regularity of use of the automated process.

The results as shown in the graphic in figure 9 above indicate that there is a desire within the office to use such a utility, and that it would be used on a regular basis.

The final question put to the respondents was to query their willingness to take part in a focus group to aid the development of the automated process. There was a high level of interest, with 77% of respondents willing to take part. The findings of the focus group are detailed in part d of this section.

c) Summary of results

The respondents in their current practices, have adopted electronic processes. Overlaying architect's plans in a 2D format by use of pdfs or AutoCAD files to establish structural zones. This is then supplemented by a preliminary review and basic supporting calculations to establish spans / scheme options. Some respondents have developed excel files to run supporting calculations.

The results also show that there is an appetite for an automated utility, and a need for a more standardised and streamlined process to be developed. There would be regular use of the utility, and the high level of willingness to assist in its development. This shows a positive reaction to the possibility of having the utility available.

d) Focus Group - Initial Stage

The focus group was comprised of six members selected from the group of ten that in the final question of the questionnaire indicated willingness to take part. The selection criteria for the six was based primarily on ensuring that members were from different working groups within the office, secondly, they were members that would regularly scheme buildings.

The aim of the focus group was to aid in development of a practical, easy to use utility that is accessible to all. The group forms an integral part of the action-based research as feedback from the participants as future users provides direction and confirmation of the processes under examination.

While the group concurred with the findings of the questionnaire, concerns were raised. Primarily, that an automated process extracting geometry from an architectural model at the initial design stage would inhibit the SE from having an intimate knowledge of the building that is required for further development of the design. Another concern was that an architectural model is not always available at the early design stage.

IV Action Based Research

a) Selection of Software tools

As noted in the NBS National BIM report 2020, the most used modelling design tools are Autodesk Revit, Graphisoft ArchiCAD, AutoCAD, AutoCAD LT, and Vectorworks. Of those surveyed, 50% stated they are using Autodesk Revit as their primary design tool (NBS, 2020). The author has selected Revit to ensure this study provides more relevance to industry.

In selection of the codification tool, as noted earlier in the paper, visual programming was widely used to develop successful automated processes in multiple aspects within BIM. However, it is not without its deficiencies; in the case of generative design, scripts tend to be bespoke in their nature requiring specific design metrics to meet particular performance criteria which limits repeatability (Lamon and Behan, 2019).

The deficiencies noted are not seen as an inhibitor for this study as visual programming has the potential of writing all data types to BIM models (Lakhera O'Shea, 2021). Therefore, it provides suitability in a structural engineering design process where multiple data types are required and the mundane manual tasks are eliminated, allowing designers to focus on more complex challenges (Reinhardt and Matthews, 2017).

For the purpose of this study, the author has selected visual programming application Dynamo. Dynamo was developed as a data manipulation tool for Autodesk Revit (McNally, 2019), . There is a Dynamo plugin for Revit, that integrates directly to the Revit model.

Therefore, the applications selected for use in the research are:

1. Autodesk Revit 2023 23.0.0.318
2. Dynamo Revit 2.13.1.3891

Using Autodesk Revit, a basic architectural model was developed by the author. The building is over four storeys with a flat roof, there are a total of thirty-two residential units, eight per floor that are set out around a central corridor. Doors are placed on the central corridor walls and windows around the perimeter of the building. No stair cores, furniture or internal layouts were developed as the primary purpose for the model was the testing and development of the dynamo script.

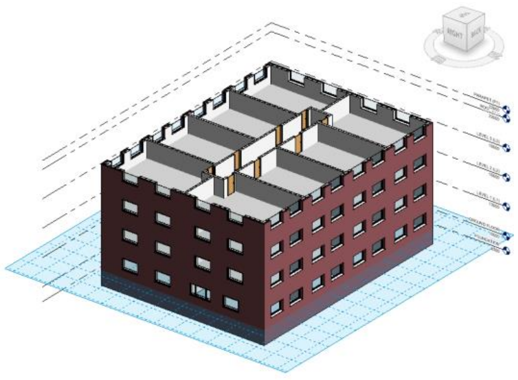

Figure 10: The Basic Architectural Model used for testing.

b) Automated actions

The automated actions for this research were developed to mimic the work practices found to be used by the industry professionals who took part in the questionnaire. The findings from subsequent focus group detailed earlier were also considered. The commonality noted by the respondent's processes was that they:

1. Reviewed 2D drawings to assess the horizontal and vertical geometry of the building.
2. Used information gained in point 1 to identify locations to place vertical structural elements unhindered by openings.
3. Once there is a clear understanding of the locations available for vertical structure, span distances were assessed, and the early-stage scheme options that can meet the criteria found is assessed and applied.

Below are the automated actions required to bring the 2D process into a data rich 3D environment.

- Extraction of relevant geometric data from the architectural Revit model.
- Identification of the zones available for vertical structure / column locations.
- Develop a scheme grid system.
- Propose available valid scheme options.

c) *Development of the process*

The initial operation required from the script was to extract the geometry of the relevant elements from the architectural Revit model. Figure 11 shows the Dynamo console and how this can be achieved. Firstly, the node *Categories* is used to define the category of Revit element, then the node *All elements of category* creates a list of all elements of the defined category, and from that list the *Element.Geometry* node creates a list of the geometry of those elements.

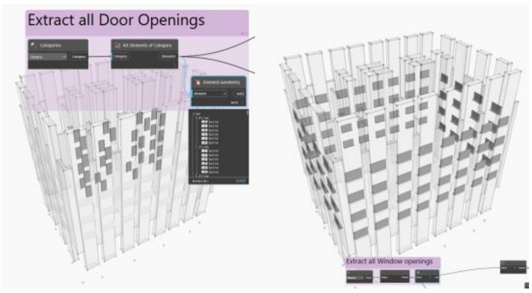

Figure 11: The Dynamo console showing all window and door geometry extracted from the model.

This procedure was repeated for all the relevant elements to be extracted. The relevant elements for this study were walls, floors, and openings such as windows, doors, and shafts. As per figure 11, the 3D graphical representation of the model within the dynamo console has the ability to highlight the contents of a list, in this case doors, allowing the user to monitor the script results as it is developed.

The next operation required of the script was to utilise the geometric data extracted to define the areas of structural interest within the building. For the purpose of this study, the areas in which vertical structure cannot transverse the building from top to bottom has been defined as the "red zone." The red zone is an area that must be excluded for consideration for positions at which columns can be located. The inverse of this is the "green zone," an area where columns can be located.

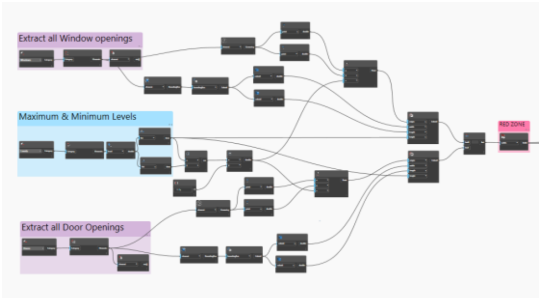

Figure 12: The nodes used to define the "red zone".

Using the geometry of the openings extracted, the *Element.BoundingBox* node was used to identify the extent of all openings, the bounding box list was input to *BoundingBox.ToCuboid* to create a series of cuboids at all opening locations. The height of the cuboids were then increased to span the full height of the building to form the red zone. Under testing, it was found that bounding boxes were not fit for purpose as they are axis aligned and not element aligned. A further section of script was inserted to rotate the bounding boxes to match their associated element.

The green zone was then defined by firstly joining the geometry of all the walls to a single solid using the *Solid.ByUnion* node. Then by using the resulting solid and getting the *Solid.Difference* of its geometry and the red zone geometry, the green zone geometry was created. The zone available to place vertical structure has now been established.

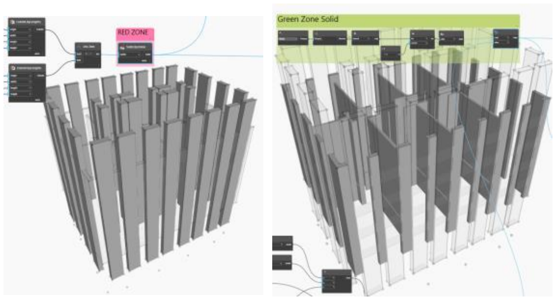

Figure 13: The Dynamo console showing the red zone and subsequently created green zone.

At this stage in the process, the task of overlaying plans in a 2D environment has been successfully transferred to a 3D environment. The output for review by the engineer is developed in a plan view clearly delimiting the green and red zones.

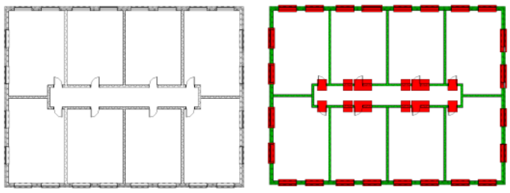

Figure 14: The original layout and green / red zone layout plan developed by the Dynamo script.

Following the development of the green zone, the proposed solution is branched into two experimental avenues. Solution A would be a scheme identifier which would identify column locations within all solids of the green area for assessment by the engineer as to the appropriate scheme, and solution B, starting with the preferred scheme and inputting specified spans to achieve it by placing columns along the slab edges for assessment by the project engineer.

d) *Solution A*

In Solution A, the green zone solid geometry was separated into individual solids by using the *Solid.Seperate* node. The resulting solids were then passed through the *Solid.Centriod* node which returned the centroid of each individual solid. The Z coordinate value of each centroid point was then set to the lowest level listed in the model.

Using the coordinates of these points a grid system was developed by filtering points with matching x-axis values and establishing the maximum and minimum y-axis value for that line. The two resulting points were deemed to be the start and end point of each grid line and as such were input to the *Grid.ByStartPointEndPoint* node to model the gridlines. The process was repeated for the y axis points. A further refinement was required to edit a parameter on the gridlines to associate them with a scope box related to the building. This was achieved by using the *Element.SetParameterByName* node.

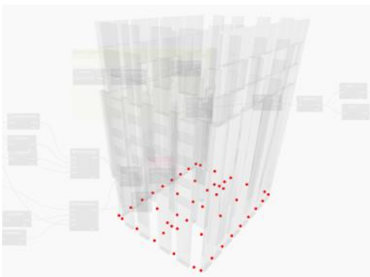

Figure 15: A view of the Dynamo model showing location of proposed valid column locations.

e) *Solution B*

Solution B required input from the user for column size and span. The script identified the perimeter of the slab arrangement, offset the perimeter line by half the column dimension and placed points at the defined span as input within the dynamo console. The script identified a start point on the slab perimeter using the *Curve.StartPoint* node. From this, the points were set out along the perimeter (curve in Dynamo) at the span spacing. Columns were then placed at identified points and assessed if they lay within the red zone. A grid was then applied using the same method as solution A.

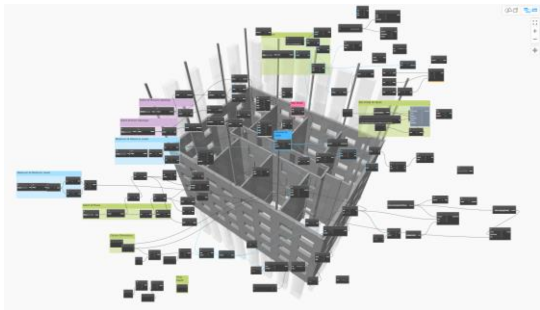

Figure 16: Solution B script showing column positions identified.

V Evaluation of the Solutions

a) *Focus group – Evaluation stage*

Solutions A and B were presented to the focus group to obtain feedback. Volunteers were also requested from the group to test the solutions against their traditional methods. The group had prior knowledge of the research from their participation in the earlier questionnaire and subsequent meeting, therefore the evaluation group meeting was structured as follows:

- An overview of the research.
- An overview of Dynamo / Revit interaction.
- A demonstration of solutions A and B.
- Questions and open discussion in relation to the proposed solutions.
- Request for testing volunteers.

Six members of the focus group attended the meeting. The group members were presented with the research followed by an overview of the Revit / Dynamo interaction, and then were given a synopsis and demonstration of the proposed solutions. Following this, the author initiated an open discussion for comment and feedback.

The red/green zone concept was received positively, and the group stated that the visual representation of the areas available to place structure not only aided in their development of a structural scheme, but also would provide clients and architects with a clear understanding of the difficulties faced in placing structure within the proposed design. Overbearing red zones would lead to a more complex structural solution, which is likely to lead to a more costly construction.

Within the group there was a preference for Solution A. The iterative process of having all potential column locations identified, then allowing the engineer to select the suitable locations to assess and apply the most efficient. This human-machine design experience aligns with (Lamon and Behan, 2019), where the author conclude that through the human-machine cooperative process the designer gains a greater appreciation of their design challenges.

In contrast, the group had concerns regarding over-reliance on automated the processes. There was a fear that the scripting would prevent a professional conducting due diligence on their work, and this would lead to a manual check being carried out, hence eliminating the efficiencies gained.

This represents an ethical dilemma for the engineers, as the members were very much aware that the responsibility of the final design lay with them. Therefore, for any automated process developed, their manual verification would be required. This in turn formed the opinion that the solution could only be used as be an aid, and in that context, it fulfilled its purpose.

b) Final Questionnaire

At the end of the focus group meeting, a questionnaire was issued to allow the members to respond individually and add any further comment. The questions were based on their perceived future use of the script, positives and negatives of the script and future research and enhancements. Four of the six members of the group completed the questionnaire.

All four stated that the script would save time and added value to the scheming process, and they would use it on their projects. However, they all stated they would do a manual verification of the results. The reasons for manual verification were, "it is good practice to verify results," "to get a further understanding of how the script works," "to ensure the script is running correctly" and "no errors are reported, and results can be backed up." When asked if they would trust the script if it were successful over time, 75% stated that they would trust it over time.

When asked about the positives and negatives of the script, the positives noted were the identification of the red/green zones and the speed at which this can be done. This was a common positive to all. Another positive noted was the ability to illustrate the zones to the client and Architect at early design stage. The negatives noted were an over reliance on the script, and the need for awareness of it's limitations.

c) Traditional process Vs Script

In the final question of the questionnaire, all respondents agreed to take part in a timed experiment to compare the traditional process with the new solution. The respondents were provided with layout plans of the test building at each level, in pdf and AutoCAD dwg format. They were then asked to develop a plan with the red/green zones indicated. The time to complete this was recorded and the results of the four participants were averaged and compared with the time taken to run the script are noted in table 1 below.

User 1	**User 2**	**User 3**	**User 4**
2700 sec	810 sec	835 sec	1800 sec

User Average	**Script**
1,536 sec	22.4 sec

Table 1: Participants Average Vs the Script time.

As shown in table 1 the average time taken for the participants was 1,536 seconds, compared to the time taken to run the script, which was 22.4 seconds. This constitutes a 6,857% efficiency in using the script.

VI Conclusion

a) *Summary of Findings*

Traditional methods of preparing an early-stage structural scheme are time consuming and tedious. This research presents solutions that aid the process of automating the development of an early-stage structural scheme.

In the first operations of the action research, visual programming is utilised to develop the structural red and green zones. This automated action is successful in transferring the traditional practice of overlaying plans in a 2D environment into a 3D environment. The script also provides a visual representation of the zones. This gives the ability to communicate the complexities faced in determining an efficient structural design solution.

The further operations executed within Solutions A and B were focused on structural scheme development. Both solutions aided the development and selection of the early-stage structural scheme. Structural column locations and grid systems were identified and visualised for further assessment by the engineer.

b) *Suitability of methodology*

The solutions were tested and verified by a focus group of industry professionals. The visual representation of the red and green zones was noted by the focus group as adding high value to the process. Under testing the process showed an efficiency of 6,587%. The findings of this research coupled with the volume of supporting evidence in the literature, show that the methodology of visual programming can be utilised to aid the development of an early-stage structural scheme design.

c) *Prerequisites for successful application*

The results from script are derived from the geometric data extracted from an architectural model. In most cases the engineer will have no input in how the model is developed. Prior to running the script, the architectural model must be reviewed in relation to modelling practices that may affect the results. For example, the improper or ambiguous use of categories could lead to the script misinterpreting or ignoring opportunities where structure could be placed.

d) *Relevance to the sector*

While the benefits of automation in BIM clearly exist, it must be noted that structural engineers are contractually and legally responsible for their designs. They need to ensure they can execute their design with confidence and comfort that they have fulfilled their duty without risk to others and, themselves. This creates the need for a form of verification of the automated processes on their part. The validation then risks the elimination of the efficiencies gained and the automated process in turn becomes a checking mechanism.

As noted in the literature, large parts of BIM for structural engineers remain unexplored and is in its infancy (Vilutiene et al., 2019). It could be said that the engineer's need for manual validation inhibits their exploration as they are reluctant to risk their reputation on processes that are outside their full control.

e) *Further Refinement*

Limitations of this research should be noted, the dynamo script was tested and assessed with a simplified architectural model developed by the author. All walls had vertical alignment and the arrangement was also orthogonal in nature. While the script can deal with more complex architectural models, the time constraints of the research did not permit testing on other models. In addition, the scripts were developed to the level of function to suit time allocated.

The additional development of the scripts would allow it to identify and suggest potential scheme options. By linking it to excel, pre-set criteria could be specified by the designer. The script could then return a pass/fail on each scheme option. This coupled with the inclusion of a generative design process would go further to aid the application of automated processes in BIM in relation to structural engineering.

f) *Implications for other areas*

By using the solutions presented in this study, complexities in the building's arrangement can be solved. Thus, allowing simplified and more efficient structural solutions to be applied. Simplified structural solutions such as, the avoidance of transfer structures, the use of modular construction, and the use of an offsite construction processes. The benefits of offsite construction are noted as increased potential for recycling, reduction in noise and dust, lower levels of community disruption and improved levels of energy and water consumption which promotes a sustainable construction approach (Zhai et al., 2014). Which goes toward the construction industry playing its part in the Irish Government's Climate Action Plan 2023 (Government of Ireland, 2023), where the Government aspires to halve emissions by 2030 and be carbon neutral by 2050.

g) Further Research.

It has been shown that structural engineers understand the value and timesaving factors of automated processes. However, to ensure they are carrying out due diligence and protect themselves and their businesses, they feel the need to validate the automated processes. An area of further research arising out of this study, is in relation to the attitude of structural engineers toward the use and adoption of automated processes. This further research would have high value as it would address a gap and identify if their need for validation presents as a contributor to the fact the large areas of BIM remain unexplored by the sector.

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