A Critical Analysis of the Application of Visual Programming to Increase Efficiency in BIM Object Metadata Delivery Workflows During the Delivery Phase of an Asset

Kieran Lakhera O'Shea
Technological University Dublin, kieran.lakheraoshea@tudublin.ie

Davitt Lamon
Technological University Dublin, davitt.lamon@tudublin.ie

Recommended Citation

Lakhera O'Shea, K., & Lamon, D. (2021). A Critical Analysis of the Application of Visual Programming to Increase Efficiency in BIM Object Metadata Delivery Workflows During the Delivery Phase of an Asset. Technological University Dublin. DOI: 10.21427/W73K-9531

A Critical Analysis of the Application of Visual Programming to Increase Efficiency in BIM Object Metadata Delivery Workflows During the Delivery Phase of an Asset

Kieran Lakhera O'Shea[1] and David Lamon[2]

School of Multidisciplinary Technologies

Technological University Dublin, Co. Dublin, Ireland.

E-mail: [1] D19128456@mytudublin.ie [2] Davitt.Lamon@tudublin.ie

---

Abstract – Uniclass 2015 data generally seems to be overlooked in favour of the more valuable COBie data when discussion begins about BIM model metadata and, at present, few studies are devoted to it and its delivery through automated methodologies. Classification is a key part of the BIM process – without the ability to distinguish one object from another a BIM model lacks the definition required for implementing downstream applications such as functional simulations, compliance checking and other automated technologies. The use of classification data is, of course, not the only way of identifying objects but it is currently the only standardised way and compliance opens the way for the smoother adoption of 4D, 5D and 6D technologies. Despite the important nature of this data, existing methodologies for delivering it tend to be mostly manual in nature and prone to risk. This paper examined the delivery of classification metadata with the aid of visual programming. The author has shown such a methodology can deliver consistent deliverables that save time, increase accuracy and are repeatable across multiple projects. A literature review appraised the value of applying visual programming methodologies to project BIM deliverables. The author then critically evaluated current classification data methodologies identifying their inherent risks and proposed a bespoke visual programming methodology to mitigate these. The research has shown visual programming can be very effective in the delivery of Uniclass 2015 metadata. With a relatively small amount of time invested, Dynamo scripting is shown to be a cost effective, accurate and repeatable tool in BIM data delivery. The findings also show that despite barriers to adoption, automated visual programming methodologies can save significant amounts of time in BIM data delivery and thereby add considerable value too. A relatively modest goal, such as adding model object data, can also serve as a gateway for practices and practitioners to develop more ambitious goals in relation to visual programming and computational design.

Keywords – Uniclass, Visual Programming, Dynamo, BIM.

I INTRODUCTION

a) Data in AEC Industry

Leading consultancies are beginning to provide separate information management services to clients, who realise the importance of getting the data and digital processes right, to reduce risk and ensure they get the deliverables they intended [1]. This development highlights both the increasing importance of the "I", or information, in BIM to clients and also the need for the AEC industry to provide high quality consistent data deliverables. The statement also suggests that currently clients usually expect consultants to provide that data and that consultancies do not always get it right.

b) Classification Data

A significant part of the data required in a BIM project is object classification. Classification metadata provides a consistent and systematic way of identifying information containers. This helps both people and technology to locate information containers because their identity becomes largely predictable. It also establishes a means of aligning information containers in various information management resources [2]. For example, the adoption of 5D BIM methodologies requires the correct classification of elements in a model. This enables automated methodologies to correctly interpret model objects despite the current challenges around naming conventions [3].

The preeminent classification system in the UK is Uniclass 2015 [4] and although a classification system is still required in Ireland under ISO19650-2:2018 there is currently no system specified in the National Annex [5]. The author is currently employed by a UK-based consultancy so this study will focus on the provision of Uniclass metadata. Uniclass 2015 is a consistent classification structure for all disciplines in the construction industry. It contains tables classifying items of any scale and is an essential way of identifying and managing the vast amount of information that's involved in a project [6].

c) Visual Programming

Programming is increasingly common for engineers [7] as it allows designers to focus on more complex compliance and design challenges [8]. The development and successful use of visual programming tools on projects like Foster + Partners' Swiss Re (aka The Gerkin), London 2003, is well documented [9] and have helped highlight its value. With 70% of respondents to the 2020 NBS BIM Report using Autodesk products as their primary design tool [10] the focus of this report will be on Autodesk Dynamo as its primary visual programming tool, though there are others available. Dynamo reduces the need to understand programming languages [8] and it is this accessibility that makes it an ideal first step into programming.

d) Dynamo and Uniclass 2015

This research sets out to explore the use of Autodesk Dynamo in streamlining object metadata workflows (in this case classification, but it should be applicable to other forms of data). The purpose of this study is to incorporate its findings into day-to-day practices while also using the opportunity to champion the investment in, and adoption of, visual programming tools.

It begins with a review of the benefits of utilising visual programming in BIM workflows, followed by examining current methodologies for delivering BIM metadata. Finally, I will propose a methodology for delivering Uniclass 2015 metadata using Autodesk Dynamo.

II LITERATURE REVIEW 1

a) Benefits of visual programming in BIM workflows

Parametric modelling tools are key enablers of data-driven design. Generative Components, a pioneering application, is still in use but Grasshopper for Rhinoceros and Dynamo for Revit are newer and more commonly used visual-coding parametric tools [11]. Their benefits have been the subject of numerous studies over the last few years.

Visual programming has been shown to be beneficial during design development for faster delivery of residential buildings in Ireland [12]. The authors proposed that by adopting BIM methodologies early in design development the design team has the potential to automate design optioneering with significant gains on collaboration and coordination. They also propose using computation design tools, namely Dynamo, to enhance delivery – it is used at feasibility study stage to explore site feasibility and context modelling with Open Street Mapping files. Scripts were also used to create different but related instances of the same design solution to quickly generate options by experimenting with different parameter values thus helping to streamline the early stages of the design process [12].

Another generative design workflow, which included the use of Autodesk Dynamo and Python, was developed for the architectural space planning of an office floor located in Dublin, Ireland with promising results [13]. The authors suggest a methodology for linking generative design, model evaluation and business intelligence in the optioneering of generative design models. When put to a research group, the benefits of a computation design approach include the ability to evaluate many more design options in comparison with a more traditional approach and the capability of developing tools to resolve unique problems. The research group ranked a reduction in time spent as the most significant benefit and noted the ability to meet the clients brief more effectively and a reduction in human error as other benefits [13].

Generative design methodologies also have benefits for structural engineers. Research from the University of Portsmouth, UK, focuses on the optimisation of structural design in a BIM environment through visual programming automation [14]. The research proposes a prototype that provides a wide range of alternative optimised structural design options for the same architectural design. By introducing design optimisation at an early stage, the engineers can evaluate a larger number of designs to identify the optimum solution. Visual programming is used to synchronise parametric data between the structural model and the architectural model ensuring any change of design by the architect to be identified and the structural model to be redesigned to suit. Automation in this case can help to mitigate the risk of expensive design changes late in the design stage of an asset [14].

Visual programming has also been used to show Blockchain technology can have a place in BIM [15]. Dynamo is used to capture energy readings from within a custom family and then feeds the data through a Blockchain. The author created a script to select a specific category within a BIM model, in this case data sensors and energy readings are then captured from within the Revit family. The data is then passed into a custom node creating a genesis block, the first block of a Blockchain. The script then adds a timestamp, assigned a hash number and then connected to the previous block via their unique hash number – the basic workings of a Blockchain. The script then combines the blockchain data with the energy reading and feeds the combined information into a bar chart for visual representation[15].

Dynamo has been used in an automated workflow to provide the current output requirements of a fire certificate application under the Building Control Act of 1990 [16]. The authors show that drawing production and specifications can be automated to allow the designer to achieve compliance with fire codes. With the use of a previously constructed open-source script [17] exit path analysis can be run and evacuation route path plans can be produced to show compliance. Scripting is also employed in the calculation of maximum occupancy [16].

Another study looks at the use of automated methodologies for building regulation compliance. This time the study attempts to mirror the automated BIM systems currently in use in Singapore, Norway, USA and Australia for building regulation compliance by developing an automated Dynamo solution for potential application within the Irish Planning and Building Control system [8]. Dynamo was used to extract floor area data from a Revit model and save it to and excel spreadsheet. The floor area data was then linked to a standards table for code compliance checking. User feedback reported that automation had a profound impact on current work practices in offices and to individuals e.g., floor areas could now be checked and updated automatically. Dynamo was also found to provide a link between software and workflows where it was not previous possible with manual processes [8].

In another study looking at compliance automation, researchers in Denmark have shown that visual programming tools can be used to transfer data from Revit to environmental quality assessment applications [18]. Dynamo is used to validate existing Revit model data against exchange requirements to verify the model's suitability for energy simulation before linking model objects to a bespoke environmental assessment tool. The Revit-dynamo-excel workflow is shown to reduce transfer process complexity, target specific parameters and establish data extraction parameters [18].

The provision of COBie data requirements is another area where Dynamo has been shown to be effective [19]. The research goes beyond current recommendations for delivering COBie of having advanced knowledge of Revit scheduling and COBie parameters and proposes a dynamo workflow that aims to eliminate human error and rework. The authors propose a visual programming workflow that cuts the execution time of populating some COBie data parameters by 95% (from 98 minutes to 4.5 minutes). Survey results following a workshop presentation of the proposed workflows showed positive results 67% felt it would help produce better deliverables and 87% said they would recommend it to others. The proposed solution was also considered to be repeatable across separate projects [19]. This study mirrors the authors own research in proposing a dynamo workflow that seeks to eliminate human error in the provision of Uniclass 2015 data and the author was unable to identify any existing studies with similar aims.

Dynamo has been used to automate the transfer of data between BIM models and facilities management systems demonstrating significant potential for the improvement of adoption of BIM by facilities management teams [20]. The study proposes a methodology for managing data transfer between the Computer-Aided Facilities Management System and the BIM model when it is used as a Common Data Environment. This study finds that Dynamo provides a simple, scalable approach to extracting data from spreadsheets and then updating model parameters with a variety of data. The study also finds significant reductions in cost and time required for an FM team to maintain a BIM model [20].

Another case study relating to facility management looks to establish a BIM-based building handover workflow to capture and retrieve facility information to help deliver integrated handover deliverables [21] showed that Dynamo can significantly improve interoperability during implementation of models during handover and operation and maintenance. The methodology involved creating Revit parameters to capture and develop each model element to handover information and then use Revit Dynamo to capture, validate, retrieve, and document this data as per the client's handover requirements. The study provides AEC and FM teams with a practical framework towards establishing an integrated process for the development of deliverables that maintains its value from the construction phase through to FM handover and operations and maintenance [21].

In an effort to overcome barriers within the AEC industry as a result of the introduction of BIM technologies, visual programming is found to help as part of a solution that allows for the formation, creation, verification and validation of project information in a model [22]. The study proposes an automated taxonomy that is used to accurately create BIM model elements, validate them later, and then pushing the results into a single source dataset. The solution is critically appraised through stakeholder interviews with results finding it could be of significant benefit to the AEC industry in overcoming barriers [22].

b) Drawbacks

The perceived drawbacks of visual programming methodologies very much mirror those of BIM adoption.

An obvious drawback of the use of visual programming in generative design is that the time associated with developing the generative model can be quite substantial [13], and there is a steep learning curve when transitioning from manual workflows [8].

The bespoke nature of dynamo scripting is seen as another restriction of the visual programming approach. All projects have a unique set of performance criteria and design metrics therefore the repeatability of developed solutions can be limited. [13, 16, 18]

If a high level of automation is desired across multiple projects, thorough modelling and calculation standards need to be implemented across project stakeholders [18]

Blind reliance on others, in this case, the results of scripting, takes away from a professional’s obligation to do due diligence in the production of their work [22].

Though the drawbacks listed are all significant, none need be a cause for the adoption of visual programming to be avoided.

III Literature Review 2

a) Critically evaluate manual data entry as a methodology for delivering Uniclass 2015 data.

During manual data entry the user types the appropriate Uniclass 2015 code and description directly into the model object parameter fields – in data entry terms this is commonly referred to as single entry [23]. In the authors experience, single entry is by far the most common form of Revit model object data entry, therefore this methodology will be the focus for the manual delivery of Uniclass 2015 object data.

Task teams are required to undertake quality assurance checks prior to sharing models within the common data environment [24]. In the field of manual data entry, there are two common methods of identifying data entry errors: visual checking and double entry. In single entry with visual checking, the user enters the data once and the same user then visually compares that entry against the original intent. When discrepancies are found, as single entry with visual checking rarely results in perfect accuracy [23], the user manually corrects the errors. In double entry, the user enters the data twice and the computer compares these entries to identify any discrepancies [23]. In the authors experience, visual checking is commonly used in drawing offices for verifying data entry whereas double entry is not used at all.

Although the most common methodology, there are many problems associated with manual data entry and they are well documented.

One study concludes that errors during manual data entry are caused by a poor intention of the data producers to appropriately enter the data and/or by a low degree of fit between the data entry task, the technology and the data producer [25]. In the context of the AEC industry this would point to factors such as lack of training, inadequate resources or even a poor working environment as contributing to poor quality data sets.

Similar conclusions are drawn in another study investigating to what extent the data producers’ intention to enter data without error explains the degree to which they actually enter data without error [26]. Unsurprisingly the authors find that the amount of data errors decrease when the data producer undergo behavioural intervention aimed at increasing their intention to enter data correctly. They also find that data producers’ ability to enter data is based on them having the required knowledge to do this correctly [25].

b) Manual data entry with Revit schedules for delivering Uniclass 2015 data.

Having manually entered the correct data into a model element once, the user can utilise material take-off schedules to help reduce risk and the time required by populating similar elements with the same data. The user must set up a schedule with the following fields: family name, type name, classification name, classification code. Once the schedule is set up, the classification data is copied from one element to another (or group of elements) by selecting the element(s) with the missing data and selecting the required classification data from the fields drop-down menu.

The success of this methodology is still based on the same factors as manual data entry; user knowledge, intention and resources [23] [25] [26]. The advantage of this methodology is that once the initial data set is entered correctly, it can then be copied to all other elements of the same type, producing a correct classification data set.

c) Critically evaluate Autodesk Classification Manager as a methodology for delivering Uniclass 2015 data.

Classification Manager is provided as part of the Autodesk BIM Interoperability Tools for Revit add-in and is available as a free download from the Autodesk website. It was developed out of a need to organise and manage classification data across multiple Revit models and is flexible enough to be used with multiple classification databases.

We will evaluate the step by step methodology on how to use Classification Manager as provided by Autodesk [27]. For this paper, the methodology examined will be a simplified one based on the application of Uniclass 2015 data and will just looking at providing this for a single element type. Customisable settings for databases will also not be explored as part of this evaluation.

1. The first step in using the Classification Manager is to select a classification database. After clicking on Setup from the Classification Manager panel, the user is then required to select the required database for their project from the list provided (UK, US, or custom database).
2. To assign classification data, the element(s) must first be selected followed by the Assign Classification icon in the Classification Manager panel.
3. The user is then presented with a filtered selection of classifications available based on the type of element selected. The user is then required to navigate the selection presented and select the appropriate Uniclass 2015 classification [27].

At each step, the user is required to make choices with varying degrees of risk that affect the accuracy of the classification data to be added to the model:

1. Choose the correct classification database.
2. No risk if adding data to only one element but if multiple elements are selected, they must all be of one type only.
3. Choose the correct Uniclass 2015 classification data.

At this point it becomes clear that the challenges facing the use of Autodesk Classification Manager are the same issues people or organisations deploying a manual data entry methodology might face. Although the workflow is more refined, knowledge of the correct data required and intent to enter the correct data are still factors contributing to the quality or correctness of the data set. Any attempted improvement of this workflow must seek to mitigate these factors while not compromising on the reduced time required by Classification Manager.

IV Action Research

For the purposes of this paper the author will focus on using the visual programming tool Dynamo to add Uniclass 2015 data to a Revit model containing two different wall types only. The wall types are:

1. Reinforced concrete wall
2. Brickwork wall

The software applications used in this research are as follows:

1. Autodesk Revit 2020.2
2. Dynamo Revit 2.3.0.8352

b) Areas for automation

To mitigate the risks discussed in the previous section, the three tasks requiring automation in the processes detailed are as follows:

1. Choosing the required classification standard.
2. Selecting the correct model objects.
3. Adding the correct object metadata.

c) Uniclass 2015 data parameters in a Revit Model

For Uniclass 2015 data to be entered into a model, the appropriate model object parameters must first be created.

There are two types of parameter available in a Revit model, type, and instance. For the purposes of this paper the author has chosen to create Uniclass 2015 Code and Title data fields as instance parameters. This allows model authors greater freedom and flexibility in how they construct their model. i.e., steel beams may be required to be modelled as part of a staircase – this situation would require they be classified as stairs rather than steel beams. The parameters will also be present for all objects modelled-in-place as long as they are created under the correct category.

d) Choosing the required classification standard

The correct classification standard should be set in the individual projects BIM Execution Plan and as discussed earlier, in the UK it will be, and in Ireland it is likely to be, Uniclass 2015.

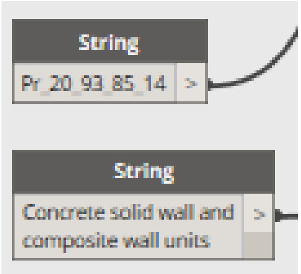

Fig.1: Uniclass 2015 code (top) and title (bottom) data

Figure 1 shows Uniclass 2015 Title and Code data already entered into Dynamo string nodes. A string is a sequence of characters representing a literal constant or some type of variable. Informally, string is programming terminology for text [28]. In this case they are used as a means of listing Uniclass 2015 text data ready to be added to the model by running the script.

Data from Uniclass 2015 tables are written into the Dynamo script(s) ruling out the possibility an uninformed user might select an incorrect classification standard to populate the model object parameters. In the event the standard changes or an alternative is required, the Dynamo script can be updated to suit.

e) Selecting the correct model objects

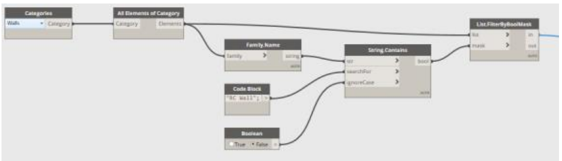

Fig.2: Selecting and filtering the walls

Figure 2 shows the portion of the script responsible for selecting the correct model objects. The note marked *All Elements of Category* selects all elements selected by the proceeding node *Categories*. Given that the drop-down menu in the *Categories* node has Walls selected, all walls in the model are selected by the first two nodes in the script.

The remainder of this portion of the script filters the selection. The chosen filter criteria are by element name. The names of all selected elements are read by the *Family Name* node and each name or string is searched to determine if it contains *RC Wall* by the *String.Contains* node. Setting the *Boolean* node to False means that the *String.Contains* node is looking for Family names without *RC Wall*. When these are fed into the *List.FilterByBoolMask* node the resulting selection is all elements with *RC Wall* in their name.

This part of the script automatically isolates of the appropriate set of elements to receive the aforementioned RC wall Uniclass Title and Code.

f) Adding the correct object metadata

Fig.3: Setting the parameter values

Figure 3 shows the current selection (all wall elements containing RC Wall in their name) being fed into a series of two *Element.SetParameterByName* nodes. The first node takes all elements fed into it and adds the value *Pr_20_93_83_14* into the Uniclass Code parameter. The same elements are fed into the second node in the series which adds the text *Concrete solid wall and composite wall units* into the Uniclass Title parameter.

This part of the script adds the correct data to the appropriate set of model elements automatically and without any input necessary from the user.

g) The finished script

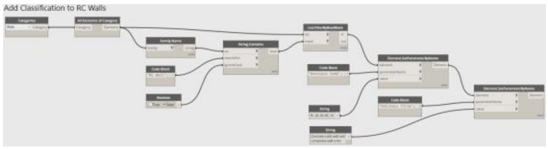

Fig.4: The finished script

Figure 4 shows the complete script for successfully isolating all wall elements in the model with *RC Wall* in their name and adding the correct Uniclass 2015 data for a reinforced concrete wall into the appropriate parameter. This script means no data input or selection is required from the user and their only task is to open and run the script.

g) Revising and reusing the same script

To add Uniclass 2015 data to a brickwork wall and complete the action research a copy of the same script is to be utilised but with crucial changes to node input data.

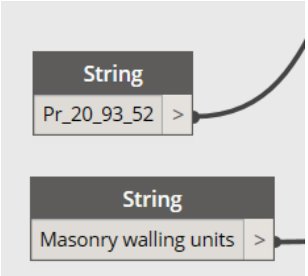

Fig.5: Uniclass 2015 data for a brickwork wall

Figure 5 shows that the Uniclass Code and Title have been updated to show the correct Uniclass 2015 data for a brickwork wall.

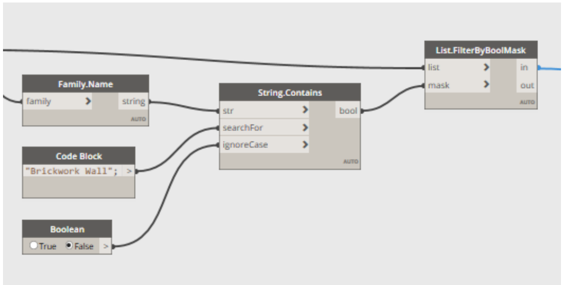

Fig.6: Filtering the selected elements

Figure 6 shows that all selected wall elements are being filtered based on the presence of the text *Brickwork Wall* in the element name.

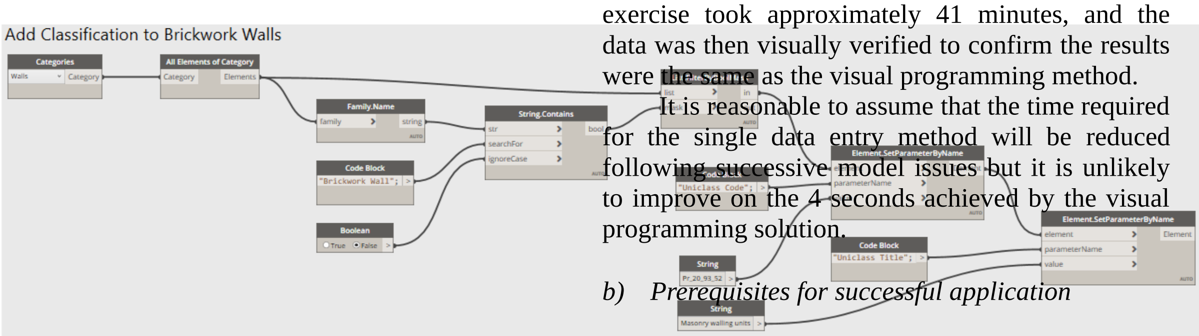

Fig.7: Brickwork wall script

Figure 7 shows a copy of the original script revised to now isolate all wall elements in the model with *Brickwork Wall* in their name and add the correct Uniclass 2015 data for a brickwork wall into the appropriate parameter. As before, no data input or selection is required from the user and their only task is to open and run the script.

Finally, both scripts are to be saved in the same script file. This allows the user to run both scripts at the same time and is more efficient than running both as separate files thus ruling out the possibility of forgetting to add a section of model data.

V CONCLUSION

a) *Suitability?*

The author tested the script on an existing Revit model to establish if it was fit for purpose and also to examine the advantages, if any, it might bring to a live project.

The test model was an 7-storey residential building predominantly concrete frame in construction, on piled foundations, with steelwork balconies and supporting structure. There are also two annex buildings in the same model file with brick/blockwork external walls, suspended timber floors and timber framing to the roof. The model consisted of 1125 elements that translated into 18 Uniclass 2015 categories. The proposed script was copied 17 times within the same Dynamo file and the separate scripts were amended to fulfil all 18 Uniclass 2015 categories required.

Once run, the script took approximately 4 seconds to complete. The data was then verified visually using material take-off schedules customised to display the relevant parameter fields. In a professional environment, software solutions like Navisworks or Solibri can be used to automate the verification of the required data, increasing the efficiency of the process even more.

The author also completed the same task through the single data entry method with the use of schedules as described in Literature Review 2. This exercise took approximately 41 minutes, and the data was then visually verified to confirm the results were the same as the visual programming method.

It is reasonable to assume that the time required for the single data entry method will be reduced following successive model issues but it is unlikely to improve on the 4 seconds achieved by the visual programming solution.

b) *Prerequisites for successful application*

The script relies on one clear prerequisite for a successful application: the user must have a clearly defined attribute that allows model objects to be filtered and grouped before writing the appropriate Uniclass 2015 data. In the authors proposed solution filtering is done by element name but it can be done by other criteria such as category, element type, or material.

c) *Further refinement*

The proposed script is a simple solution to the provision of Uniclass 2015 data which can be further refined to improve the user experience. For instance, instead of hard writing the Uniclass data into the script it could be read from a spreadsheet along with corresponding filter conditions and values. This would mean that there is no longer a need to copy the script when a new classification is required, it would be controlled directly from the spreadsheet.

d) Relevance to other sectors

The addition of classification data is significant to all AEC sectors both inside and outside of the project design team. Once added, it allows data in the model to be accurately identified and interrogated by all potential users, from the design team, to contractors, suppliers, the client team, facilities management team and even future design teams planning for refurbishment or even demolition.

However, the potential of the proposed visual programming script goes far beyond Uniclass 2015 data. Visual programming has the potential to write all data types to BIM models and as data becomes a more valuable commodity in today's construction industry, the ability to create that data becomes a valuable skill.

e) Relevance in Ireland

The script was developed to incorporate Uniclass 2015 data into a Revit model and while this directly satisfies the needs of practitioners working to the ISO19650 UK National Annex it is assumed it will also satisfy those working to ISO19650 Irish National Annex. Given the close ties between the UK and Ireland, geographical proximity and cross-pollination of workforce and skills it is only assumed Uniclass 2015 data will be used in Ireland. However, should another classification system be required, the script is easily adapted to suit and indeed, BIM practitioners around the world can easily adapt the script to suit their regional preference.

f) Future research

An area of possible future research could be adapting and expanding the script to write COBie data. In the authors experience, the delivery of COBie data is usually priced for separately by the design team so any methodology that can deliver COBie data more efficiently is likely to show a clear increase in profits for that task. This avenue of future research therefore has the potential to be of high value if it can achieve a successful outcome.

g) Summary of findings

Following the script test and the weight of evidence supporting the use of visual programming on BIM projects, it can be concluded that the proposed methodology can improve the efficiency of Uniclass 2015 data delivery. It can easily be integrated into existing AEC practices for model sharing workflows and allow design professionals to devote more time for coordination and other aspects of design delivery. With digitisation, there comes a need for a shift in mindset and if the construction industry is going to continue its transformation it will do so by taking advantage of more automated production and processes [1].

References

[1] M. Winfield. "Overcoming the Challenges and Obstacles to Successfully Implement Technology, Digitisation and Digitalisation." https://www.futurebuild.co.uk/. https://www.futurebuild.co.uk/2021/03/11/overcoming-the-challenges-and-obstacles-to-successfully-implement-technology-digitisation-and-digitalisation/?utm_source=linkedin&utm_medium=social&utm_campaign=Webinar&utm_term=&utm_content= (accessed 01/01/2021, 2021).

[2] "UK BIM Framework Guidance Part 2," UK BIM Framework, 2021. [Online]. Available: https://www.ukbimframework.org/wp-content/uploads/2021/02/Guidance-Part-2_Parties-teams-and-processes-for-the-delivery-phase-of-assets_Edition-6.pdf

[3] T. Moses, D. Heesom, D. Oloke, and M. Crouch, "Exploring the Benefits of Early Contractor Involvement (ECI) and the Mechanism for Automated 5D BIM Quantification Process in Offsite Modular Construction," *Modular and Offsite Construction (MOC) Summit Proceedings*, 09/29 2016, doi: 10.29173/mocs6.

[4] *UK National Annex to BS EN ISO 19650-2:2018*, 2021.

[5] *Irish National Annex NA:2021 TO I.S. EN ISO 19650-2:2018*, 2021.

[6] "NBS." https://www.thenbs.com/ (accessed 01/05/2021, 2021).

[7] P. Debney, *Computational Engineering*. The Institution of Structural Engineers, 2021.

[8] J. Reinhardt and M. Mathhews "The Automation of BIM for Compliance Checking: a Visual Programming Approach," presented at the CITA BIM Gathering 2017, Croke Park, Dublin, Ireland., 2017. [Online]. Available: https://arrow.tudublin.ie/bescharcon/29/.

[9] M. Day, "The generation game - AEC Magazine," 2019-10-09 2019.

[10] "10th Annual BIM Report," NBS, 2020.

[11] R. Sacks, P. M. Teicholz, C. Eastman, and G. Lee, *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers, contractors and facility managers*, Third ed. (no. Book, Whole). Hoboken, New Jersey: Wiley, 2018.

[12] J. McNally and A. Behan, "The potential impact of BIM on early design stages of Residential Apartment Construction in Ireland: A Computational Design Approach," Capstone Report 2019. [Online]. Available: https://arrow.tudublin.ie/schmuldistcap/17/

[13] D. Lamon and A. Behan, "A critical examination of the use of business intelligence (BI) in the optioneering of generative design models: a case study.," presented at the CITA BIM Gathering 2019, 2019.

[14] T. Hamidavi, S. Abrishami, P. Ponterosso, D. Begg, and N. Nanos, "OSD: A framework for the early stage parametric optimisation of the structural design in BIM-based platform," *Construction Innovation,* vol. 20, no. 2, pp. 149-169, 2020, doi: 10.1108/CI-11-2019-0126.

[15] A. O'Reilly, "Incentivising multidisciplinary teams with new methods of procurement using BIM + Blockchain " presented at the CITA BIM Gathering 2019, 2019. [Online]. Available: https://arrow.tudublin.ie/schmuldistcap/8/.

[16] R. Harrell and M. Mathews, "Could Autodesk Revit 2018 Be Automated for Code Compliance Checking and Demonstration with A Focus on Fire Safety Regulations?," 2018. [Online]. Available: https://arrow.tudublin.ie/bescharcrep/3/

[17] D. Vermeulen. "Evacuation Path Analysis with Dynamo. ." https://revitbeyondbim.wordpress.com /2016/04/22/evacuation-path-analysiswith-dynamo/ (accessed 28/03/21, 2021).

[18] A. Piaskowski, R. W. Petersons, Simon Petrova, Ekaterina, and K. Svidt, "Automation of data transfer between a BIM model and an environmental quality assessment application," presented at the 36th CIB W78 2019 Conference: ICT in Design, Construction and Management in Architecture, Engineering, Construction and Operations (AECO), Northumbria University, Newcastle, United Kingdom, 2019. [Online]. Available: https://www.researchgate.net/publication/337008516_Automation_of_data_transfer_between_a_BIM_model_and_an_environmental_quality_assessment_application.

[19] R. Kenna and B. TUDublin, "Can the Application of the Visual Programme Tool Dynamo Assist in Streamlining Current COBie Requirements for Design Professionals," *Capstone Reports* . 2., 2018. [Online]. Available: https://arrow.tudublin.ie/schmuldistcap/2/

[20] M. Khaja, J. D. Seo, and J. J. McArthur, "Optimizing BIM Metadata Manipulation Using Parametric Tools," *Procedia Engineering,* vol. 145, pp. 259-266, 2016/01/01/ 2016, doi: https://doi.org/10.1016/j.proeng.2016.04.072.

[21] M. Sadeghi, W. Elliott Jonathan, N. Porro, and K. Strong, "Developing building information models (BIM) for building handover, operation and maintenance," *Journal of Facilities Management,* vol. 17, no. 3, pp. 301-316, 2019, doi: 10.1108/JFM-04-2018-0029.

[22] S. Colley and B. TUDublin, "The Automation of BIM for Project Information Formation, Creation, Verification and Validation: a Visual Programming Approach.," ed, 2019.

[23] K. A. Barchard and L. A. Pace, "Preventing human error: The impact of data entry methods on data accuracy and statistical results," *Computers in Human Behavior,* vol. 27, no. 5, pp. 1834-1839, 2011/09/01/ 2011, doi: https://doi.org/10.1016/j.chb.2011.04.004.

[24] *BS EN ISO 19650-2:2018*, B. S. Institution, 2021.

[25] T. Haegemans, M. Snoeck, W. Lemahieu, F. Stumpe, and A. Goderis, "Towards a theoretical framework to explain root causes of errors in manually acquired data," 2016: MIT Information Quality Program, pp. 15-15.

[26] T. Haegemans, M. Snoeck, and W. Lemahieu, "Entering data correctly: An empirical evaluation of the theory of planned behaviour in the context of manual data acquisition," *Reliability Engineering & System Safety,* vol. 178, pp. 12-30, 2018/10/01/ 2018, doi: https://doi.org/10.1016/j.ress.2018.05.009.

[27] Autodesk, "Whitepaper: Classification Systems and Their Use in Autodesk Revit," ed, 2018.

[28] "Learn - Dynamo BIM." Autodesk. https://dynamobim.org/ (accessed 01/01/2021, 2021).