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THE USE OF BIM FOR ROBOTIC 3D CONCRETE PRINTING

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Abstract: Digitization has proven its added value to the construction industry, particularly through Building Information Modeling (BIM). This digital shift addresses all phases and aspects of construction projects. Additive manufacturing (AM) through 3D Concrete Printing (3DCP), is one of the most remarkable technologies which development has accelerated in recent years. BIM and 3DCP are evolving in parallel, though, and the potential for their integrated use or convergence has not yet been sufficiently studied. Indeed, the association of these two systems faces challenges in terms of interoperability. This concept is not only limited to the ability to exchange information between two software, but also concerns the procedural, organizational and contextual aspects of these systems. Nevertheless, design process has evolved with the help of computational design tools and recent developments such as Rhino.Inside.Revit and Speckle. This study aims to streamline the use of BIM in the 3DCP process. An overview of the technological interoperability between these two systems is presented. The necessary approaches to be used in concrete additive manufacturing applied to construction are defined. Finally, this research suggests the optimal approach for the application of BIM to 3DCP and identifies the obstacles encountered through a case study. Possible development paths for a better adoption of BIM in 3D concrete printing are identified.

1 INTRODUCTION

The construction industry is facing serious problems due to low productivity and lack of skilled workers. Digital transformation can be an effective solution to overcome these challenges (Poirier et al. 2018) especially with digital design. BIM and Virtual Design and Construction (VDC) are commonly used for coordination, project management, quality control and project handover. Digital tools offer a variety of functionalities that facilitate the design of innovative structures, but this capacity remains largely underutilized due to the complexity of nonconventional architectures (Hack et al. 2020). Concrete construction through additive manufacturing has a strong capability to unlock this innovative potential (Mechtcherine et al. 2019). This methodology has been proven, in various studies, to offer architecturally attractive projects with economically and environmentally efficient results compared to projects carried out using conventional construction methods (Weng et al. 2020). Many of these research projects are limited to studying the material properties and use workflows specific to the field of additive manufacturing. As a result, the adoption of this technology in construction remains ambiguous for designers. In this context, through the visualization of construction data. The use of BIM represents the core of digital transformation in construction since it provides the technological environment necessary for project modeling (Poirier et al. 2018). Many researchers have assessed that BIM processes contribute significantly to improving productivity throughout the building's life cycle, from design to operation and maintenance (O&M). It is a collaborative process that allows users to work in a BIM environment and exchange information through open file formats. Therefore, the integration of BIM-based construction activities with 3DCP can improve the performance of the construction workflow and contribute to the development of the industry.

This research project aims to integrate the two concepts to facilitate the digital shift of the construction industry, but this association faces several interoperability challenges. Interoperability is defined as the ability to exchange information between all software or platforms used by the construction team throughout the project lifecycle (Wegner 1996). According to Gallaher et al. (2004, 107), "$15.8 billion in interoperability costs were quantified for the U.S. capital facilities supply chain in 2002". This concept should not be limited to the technological dimension alone since it also includes an organizational, procedural and contextual dimension (Poirier et al. 2014). The use of 3D concrete printing within a construction company provokes changes in its organization since this technology implies drastic alterations in work methods (Wu et al. 2018). These interoperability challenges persist in both the industry and the academic field. There are few examples of any research that integrates the concepts of BIM and robotic 3DCP in any depth. Thus, this project seeks to clarify the main links between these two technologies, including parametric design.

2 LITERATURE REVIEW

To identify the processes used for applying BIM to robotic 3DCP, a bibliometric analysis is carried out. This analysis uses the systematic literature review (SLR) method to summarize the most relevant articles for the analysis (Kitchenham 2004). In addition, the backward and forward snowballing method is used as a support for the SLR to be able to identify articles addressing the subject directly. This analysis is mapped using the VOSviewer software, which visualizes bibliometric maps (Van Eck and Waltman 2010). The generated map is based on bibliographical data of the SLR output, it has a co-occurrence as a type of analysis and the authors' keywords as a unit of analysis. The minimum number of co-occurrences is set at two, resulting in 34 co-occurring keywords grouped under eight clusters. Figure 1 shows the authors' co-occurring keywords in the literature review articles. Terms with a higher number of occurrences are displayed in larger font, and the line thickness represents the number of items in which all related terms appear simultaneously.

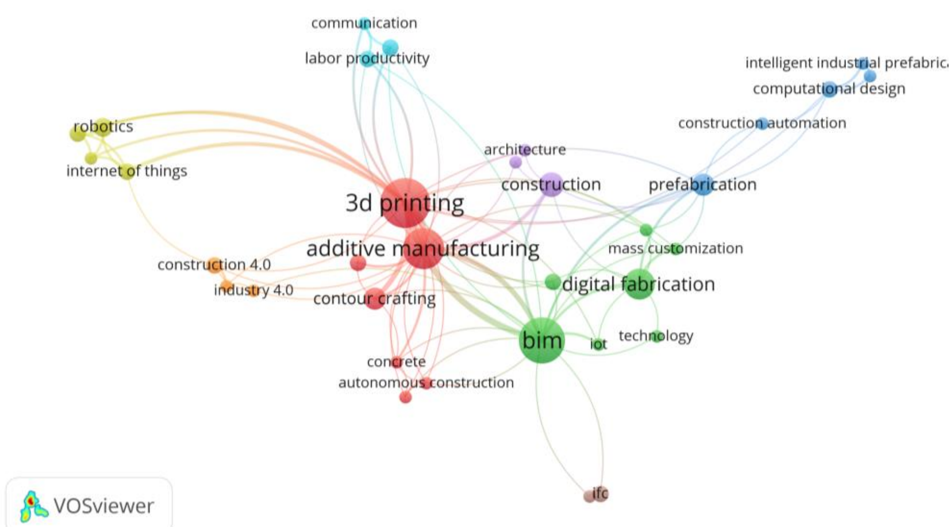

Figure 1: Co-occurrence of authors' keywords in the literature review

Figure 1 reveals the lack of research on the relationship between BIM and 3DCP, as there is no connection between them. This reflects the limited number of citations of these two concepts in the same document. Indeed, this literature review is characterized by a scarcity of articles that directly address the topic. It also demonstrates the lack of investigation into the interoperability between BIM and robotic arms. Thus, confirming the problematic of the parallel evolution between BIM and robotic 3DCP.

3 METHODOLOGY

BIM and additive manufacturing represent two very broad domains that are evolving in parallel. It is not possible to summarize the totality of the processes used in BIM that could be applied to additive manufacturing. This is the case since the technological tools of the two fields are quite diverse. Therefore, only workflows involving 3D printing with a robotic arm are addressed. This method allows the realization of complex architecture and can be carried out with modeling tools allowing to control simultaneously the trajectory of the extruder and the model parameters (Gosselin et al. 2016). This document focuses on concrete printing as the material used in this method is the most widely used in construction (Bos et al. 2016). It identifies the various scenarios where BIM and 3DCP are used collectively and aims to develop a seamless integration between them.

To explore the issue of interoperability identified in the literature review, the state of its technological dimension between BIM and 3DCP with a robotic arm is defined. The approaches involving this association are then categorized according to the classification of Janssen (2015) which addresses only the workflows characterizing parametric BIM modeling. Indeed, Janssen's methodology divides parametric BIM modeling between an embedded and coupled approach. The embedded approach is about using the software built-in functionalities. The coupled approach is subdivided to tightly coupled which associates two systems through the modeling software application programming interface (API), and loosely coupled, which involves a model exchange through the transfer of file formats. Adapting this methodology, our research categorizes the different approaches found in the literature review for using 3DCP in construction. It proposes two new approaches to apply BIM to this method. Finally, it suggests the most efficient approach by comparing the data transfers it involves and the functionalities it offers.

4 TECHNOLOGICAL INTEROPERABILITY BETWEEN BIM AND 3D CONCRETE PRINTING IN CONSTRUCTION

Technological interoperability is the exchange of data and information in a digital environment. In construction, this aspect has been recognized as one of the significant barriers to the adoption of BIM in the industry due to the paradigm shift it brings (Poirier et al. 2014). Nevertheless, the use of BIM is currently expanding in the construction industry thanks to the potential of centralized information and facilitated collaboration. This level of adoption has not yet been reached in 3D concrete printing. The integration of BIM design activities into 3DCP offers the potential to significantly increase productivity by reducing implementation time and improving product quality. However, this integration still encounters critical challenges with respect to the transfer of information between BIM tools and automated construction systems. BIM is well known for its design of open file formats such as IFC. It is an open format that is in constant development and the reputation of this exchange technology is now well established since many of its aspects have reached maturity (Froese 2003). IFC is a file format based on objects rich in information to represent building data. Janssen et al. (2016, 2) states that “the use of an open standardized file format ensures that the approach remains workflow agnostic.” This has contributed to its growing popularity in the industry and most CAD systems include it in their export formats (Fu et al. 2006). However, IFC is not the most common format for 3D printing as there are other well-known file formats such as OBJ, AMF or 3MF. Yet the most common import format used by 3D printers remains the STL or STEP format depending on the type of information to be transmitted (Mechtcherine et al. 2019). This highlights the parallel evolution of

BIM design and 3D concrete printing tools. This project is part of the effort to propose an optimized approach that will support technological interoperability in the adoption of 3DCP in construction.

5 APPROACHES FOR THE USE OF BIM FOR ROBOTIC 3D CONCRETE PRINTING

5.1 Loosely coupled approach

According to Hager et al. (2016), the workflow involving additive manufacturing begins with a model that is prepared in a 3D modeling application. It is then exported in a 3D data exchange format, often STL. This model is then sliced to constitute the successive deposited material layers. These layers define the control commands to position the extrusion head and start the printing of the model. This approach is defined by (Janssen 2015) as loosely coupled because it involves an exchange of models between different software programs, typically a 3D modeling software and a digital fabrication software. However, the transfer of data throughout this process involves the risk of information loss. For example, the STL format only transmits geometric data and neglects information related to the component properties, such as the material properties or surface conditions. Moreover, the data processing in the slicing software is not always optimal (Mechtcherine et al. 2019). As a result, a fragmented process occurs, losing critical information for the integration of the 3D printed project into a construction environment. This also concerns the BIM application's alternative to the workflow since the 3D model will be exported in a format accessible by BIM engines. Figure 2 is realized in order to explain the loosely coupled approach associating BIM. This workflow is considered the least efficient due to the amount of format conversion it requires and the number of modeling and fabrication tools that it involves. This demonstrates the importance of integrated processes as once the model export is done, all the parameters related to the model are lost. With this, the user ends up with a bare model that is hard to modify depending on the printing parameters. In fact, the printing process is not always optimal from the very first attempt, thus requiring modifications to the model according to the challenges encountered during the fabrication process. With such a method, all the steps related to 3D printing will have to be repeated from the beginning without any possibility of rewinding. This will not be efficient within the time constraints incurred during construction. Data for O&M and 3DCP requirements are illustrated in this figure and all subsequent figures as dotted lines since it is not the focus of this study, which is primarily aimed at the realization of the project.

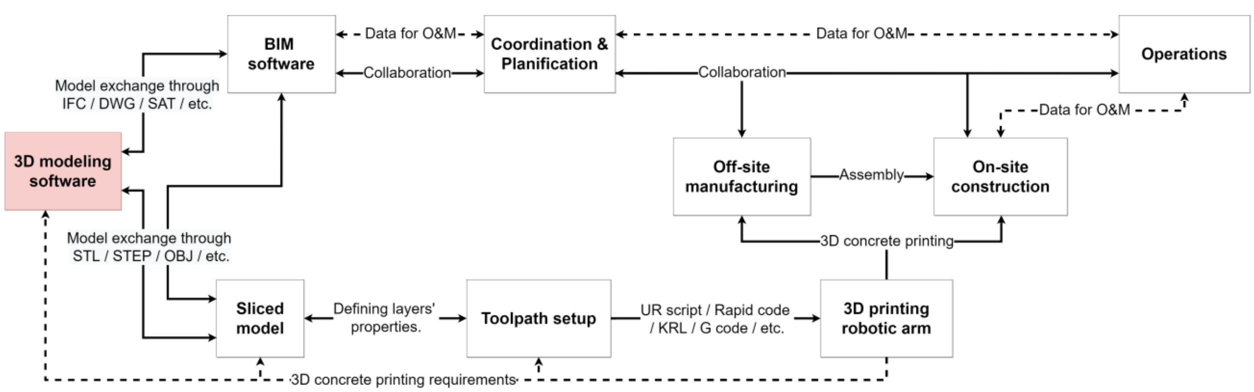

Figure 2: Loosely coupled approach for applying robotic 3DCP in construction

In order to contribute to the evolution of robotic 3D concrete printing in construction, the integration of BIM in its development represent an appealing alternative. BIM has a lot of potential to offer from the perspective of its adaptability, the collaborative opportunity it offers and its ability to reduce costs (Poirier 2015).

Research has already been conducted to apply BIM to the loosely coupled type of approach (Davtalab et al. 2018; Sakin and Kiroglu 2017). Yet most have not mentioned the parametric workflow and have been content with a simple export of the BIM model for printing. These studies have been focusing on the advantages of using BIM functionalities and neglecting the optimization of 3D printing. The benefit of this approach is illustrated in Figure 3. Taking advantage of BIM will lead to better integration in construction and allow better management of the 3D printed component throughout its lifecycle. It enables the use of BIM tools to predict clash detections and exploit the data collected for collaborative purposes.

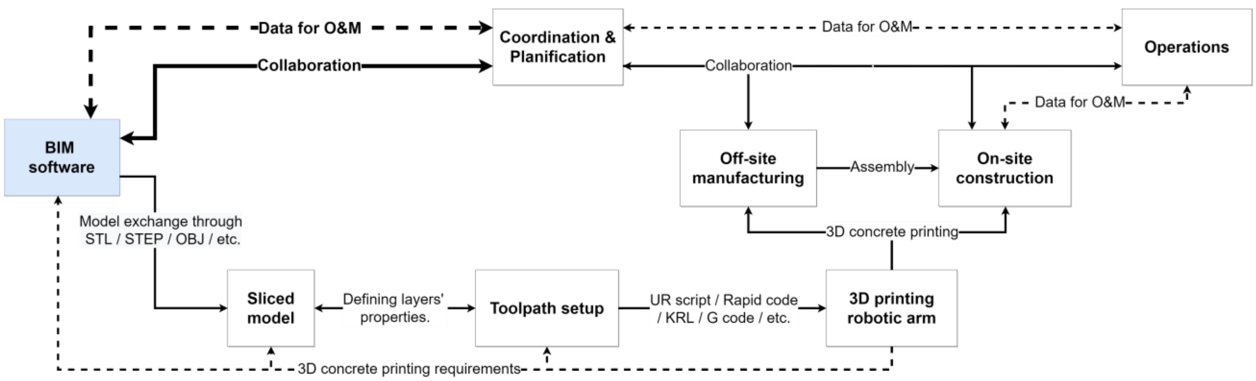

Figure 3: Loosely coupled approach for applying robotic 3DCP in construction starting with a BIM software

In the context of this study, this process still presents a parallel evolution of BIM and robotic 3DCP. The use of a BIM software at the beginning of the process offers a considerable advantage. It allows a direct use of the information generated from the model and facilitates its integration into the construction environment. But this approach remains loosely coupled with 3D printing because it loses all the advantages of the embedded approach using BIM. By transmitting the model to the digital manufacturing tools, a discontinuity in the process is created, and a loss of information is possible.

5.2 Moderately coupled approach

In the context of this study, it was necessary to include another type of coupled approach other than those developed by Janssen (2015). The moderately coupled approach consists of adopting a tightly coupled approach on the one hand and a loosely coupled approach on the other. Examples of this approach can be identified through the use of parametric modeling tools such as Grasshopper. This methodology allows the application of visual programming for the control of the 3D printing robotic arm using rapid iterations. That enables the user to modify both geometry and toolpaths as well as machine parameters, and then simulate the results in a single environment (Braumann and Brell-Cokcan 2015). It is a methodology that has been widely used in research projects such as the work of Lim et al. (2016). These tools will generate a script that will be transferred to the robotic arm to print the model and will be combined with a modeling software to produce a 3D printing simulation. This process is not only dependent on visual programming tools, as it can also be adopted with a modeling software integrating a programming and robotic simulation plugin.

According to the literature review, BIM integration has not been thoroughly investigated in this approach. This integration can be explained in other research that addresses specifically parametric design. For example, the study by Janssen (2015) discussed the possibility of transferring information using other plugins of visual programming like GeometryGym. But these tools only offer a means of exporting to IFC which implies a model exchange. Figure 4 illustrates that the process of applying BIM remains parallel to the 3D concrete printing process and is recognized as a moderately coupled approach. It involves model exchange on the one hand, and the use of parametric design tools using the modeling software API on the other.

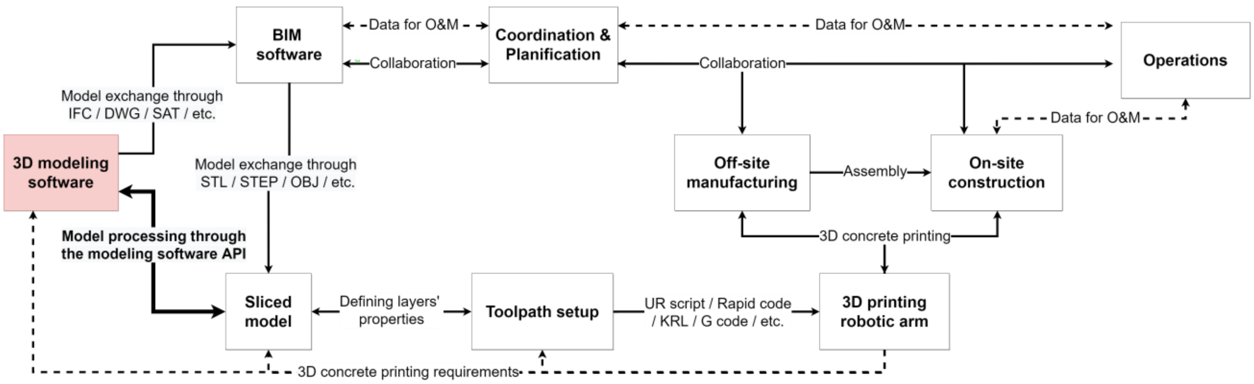

Figure 4: Moderately coupled approach for applying robotic 3DCP in construction

5.3 Proposed tightly coupled approach

This study presents two alternatives to improve the efficiency of the application of BIM to robotic 3D concrete printing. With the first alternative, it is possible to avoid the need for a model exchange format by using representational state transfer (REST) APIs. For example, this can be available with Speckle, which allows the transfer of 3D models between various design and analysis tools (Revit, Rhinoceros, Unity, Blender, etc.). Figure 5 illustrates this workflow which starts with a 3D modeling software like Rhinoceros. The model developed is then transferred to Revit (as a BIM software) in almost real time with Speckle. This workflow offers several opportunities for collaboration between the project participants and allows to collect a database of the 3D model evolution. In fact, it permits a parametric control of the 3D model and the printing mechanism in a simultaneous way. It allows the model to be transferred to a Web viewer enabling cloud-based collaboration and uses an object-based version control system to design and structure the data (Poinet et al. 2020). However, Speckle's performance is dependent on the volume of data to be transferred. It is not yet possible to transfer voluminous models instantly with Speckle, which raises the importance of data management.

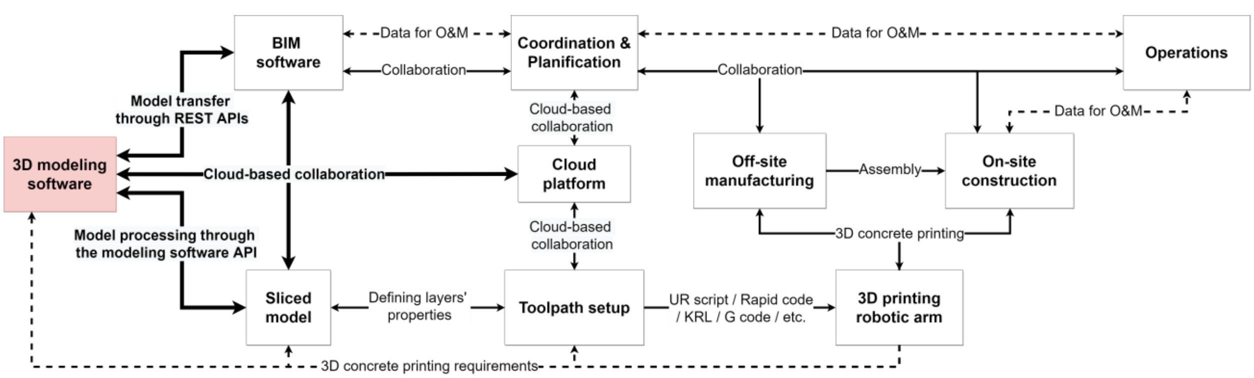

Figure 5: Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a 3D modeling software

To achieve a better adoption in construction and as demonstrated by the application of BIM to the loosely coupled approach. It is necessary to initiate the process with a BIM software for a smoother adoption in construction. In contrast to the moderately coupled approach, the second alternative illustrated in Figure 6 proposes to start with a model developed with visual programming tools. This provides the advantage of having a tightly coupled BIM approach since these tools are directly linked to the BIM software API (Dynamo for its connection with Revit, Rhino.Inside.Revit for the Grasshopper/Revit combination or Live connection for the Grasshopper/Archicad combination, etc.). The quality and the number of plugins intended for digital fabrication vary between visual programming tools. For example, this approach is possible with Rhino.inside.Revit as it offers the necessary functionality to create 3D printing simulations. It allows to instantly generate printing scripts that can be transmitted to the robotic arm. This process offers design flexibility with centralized information, it reinforces the role of BIM as a facilitator of the adoption of robotic 3DCP. It provides both a model with the information required for its realization on the site or off-site, and also the simulation of its printing process.

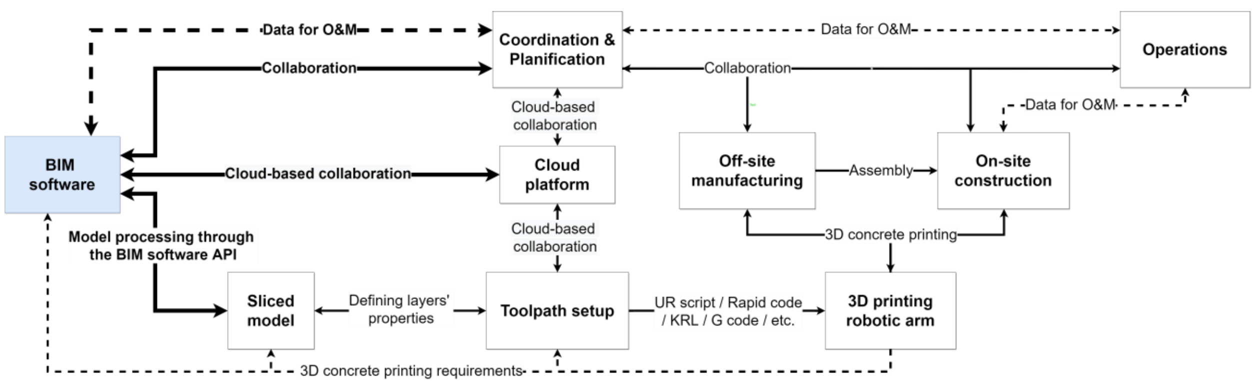

Figure 6: Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software

Compared to the first alternative, the advantage of this workflow consists in its structured information since it starts with a BIM software. In addition, cloud-based collaboration is better supported by this process given the range of platforms available through the BIM processes. This approach presents the fewest steps in the information flow with no model exchange format. It limits the loss of information during model transitions and transforms transfer challenges through format conversion into transfer challenges through the API provided by the system used.

6 SUGGESTED APPROACH

In this step, the suggested approach consists in the tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software. Revit is taken as an example of BIM-modeling software and this approach is realized using the Rhino.Inside.Revit plugin. Therefore, the script for robotic printing is developed in Rhinoceros. Grasshopper is suggested since it is much more used in the digital fabrication environment compared to Dynamo. The case study focuses on the prefabrication of an observatory realized with robotic 3DCP. This observatory will be placed on the roof of a building inspired by the Morpheus hotel in Macau. The modeling process is developed in Grasshopper with the BIM schema provided by Rhino.Inside.Revit. The additive manufacturing script is also prepared in the same environment. As a result, the printing simulation and command lines are instantly generated. With Rhino.inside.Revit, it is Rhino running inside the Revit memory space. This means they can share all available data, saving considerable time and accuracy compared to loosely coupled approaches. No information transfer takes place through model exports and imports since the entire process is prepared in one environment. This combination will allow the use of all the advantages of both tools to have a multifunctional result. For example, the Speckle plugin can be used for collaboration between the various stakeholders of a project. It will be employed to transmit geometry information and exchange printing data in real time between the software it supports. It will allow the visualization of the model through a web viewer which will guarantee an efficient collaboration. Cloud-based collaboration can also be executed with Forge, BIM360 or Unity reflect for information management and collaboration. Fologram could be used for the augmented reality representation of the 3DCP simulation and the model used. Ladybug and Honeybee could also be used for the sustainable development aspect through the different analyses that these plugins offer. BIM tools can be used for clash detection when integrating into construction environments and all dimensions of BIM including project documentation. The result of this process is shown in Figure 7, which illustrates the simultaneous visualization of the developed model and 3DCP simulation. This visualization is represented in four columns from left to right, in Rhinoceros, Revit, Speckle web viewer and in augmented reality through Fologram.

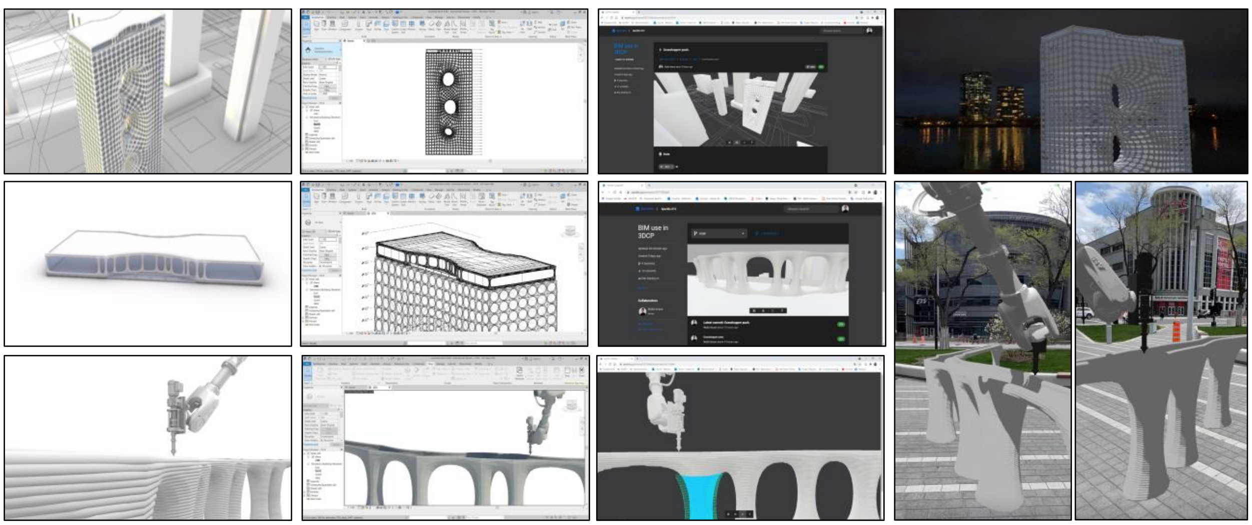

Figure 7: Simultaneous visualization of the suggested
process result in Rhinoceros, Revit, Speckle and Fologram

However, this approach has some limitations. 3D printing is based on meshes, and since Revit and Rhinoceros use different geometry engines, the use of Grasshopper models in Revit will not always result in perfect meshes. Moreover, meshes are often voluminous in data. Without reduction, they can cause limitations in their transfer to the cloud. This combination of tools gives a much more stable result in the management of boundary representations (Brep). In the case of 3D printing simulations, there are no good ways to embed an object animation in Revit as this software is not designed for this functionality. Nevertheless, these simulations can be supported in any other tightly coupled software such as Rhinoceros or Unity, which highlights the importance of information management. In spite of these limitations, the process remains more efficient than the loosely coupled approach. It keeps all the parameters of the design and printing process, and enables the modeling to be adjusted according to the printing tool. Rhino.Inside.Revit development defines a significant evolution of the technological interoperability between

Revit and Rhinoceros. It offers a multitude of possible application tracks, such as the one addressed in this approach which is robotic 3D concrete printing.

7 CONCLUSION

BIM and robotic 3D concrete printing have evolved in parallel in the industry and this is due to the lack of interoperability between these two systems, among other reasons. This research focuses on the aspect of technological interoperability by comparing the different possible approaches for the application of BIM to robotic 3DCP. Based on the various scenarios evaluated, we suggest that the most efficient process consists in the tightly coupled approach starting with a BIM software. By using this approach, the need for exchange formats is avoided. The risk of information loss is reduced and technological interoperability between the two systems is improved. This study constitutes a step towards clarifying the advantage of integrating BIM into the workflow. Indeed, the application of BIM to robotic 3DCP is a very interesting alternative for off-site manufacturing and the standardization of printed objects. It improves collaboration between the various stakeholders of a construction project, especially on the MEP side. This will certainly influence the other dimensions of interoperability defined by Poirier et al. (2014), i.e. the procedural, organizational and contextual dimensions of the two systems, which constitute future avenues for development.

The proposed methodology can apply not only to additive manufacturing, but also to the case of subtractive manufacturing or robotic manipulations. Fabrication of wood, for example, would constitute a quite promising development path since it requires both manufacturing and data. In this context, many other research directions can be explored, which reveals the potential of BIM's application to digital fabrication in construction.

8 Acknowledgements

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9 REFERENCES

Bos, F. Wolfs, R. Ahmed, Z. and Salet, T. 2016. “Additive Manufacturing of Concrete in Construction: Potentials and Challenges of 3D Concrete Printing.” *Virtual and Physical Prototyping* **11** (3): 209–25. doi:10.1080/17452759.2016.1209867.

Braumann, J. and Sigrid, B.C. 2015. “New Parametric Workflows Directly from Design to KUKA Robots,” 8.

Davtalab, O. Kazemian, A. and Khoshnevis, B. 2018. “Perspectives on a BIM-Integrated Software Platform for Robotic Construction through Contour Crafting.” *Automation in Construction* **89** (May): 13–23. doi:10.1016/j.autcon.2018.01.006.

Froese, T. 2003. “Future Directions for IFC-Based Interoperability,” 16.

Fu, C. Aouad, G. Lee, A. Mashall-Ponting, A. and Wu, S. 2006. “IFC Model Viewer to Support ND Model Application.” *Automation in Construction* **15** (2): 178–85. doi:10.1016/j.autcon.2005.04.002.

Gallaher, M.P. O’Connor, A.C. Dettbarn, Jr, J.L. and Gilday, L.T. 2004. “Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry.” NIST GCR 04-867. National Institute of Standards and Technology. doi:10.6028/NIST.GCR.04-867.

Gosselin, C. Duballet, R. Roux, P. Gaudillière, N. Dirrenberger, J. and Morel, P. 2016. “Large-Scale 3D Printing of Ultra-High Performance Concrete – a New Processing Route for Architects and Builders.” *Materials & Design* **100** (June): 102–9. doi:10.1016/j.matdes.2016.03.097.

Hack, N. Dörfler, K. Walzer, A.N. Wangler, T. Mata-Falcón, J. Kumar, N. Buchli, J. et al. 2020. “Structural Stay-in-Place Formwork for Robotic in Situ Fabrication of Non-Standard Concrete Structures: A

Real Scale Architectural Demonstrator." *Automation in Construction* **115** (July): 103197. doi:10.1016/j.autcon.2020.103197.

Hager, I. Golonka, A. and Putanowicz, R. 2016. "3D Printing of Buildings and Building Components as the Future of Sustainable Construction?" *Procedia Engineering* **151**: 292–99. doi:10.1016/j.proeng.2016.07.357.

Janssen, P. 2015. "PARAMETRIC BIM WORKFLOWS," 10.

Janssen, P. Chen, K.W. and Mohanty, A. 2016. "Automated Generation of BIM Models," 8.

Kitchenham, B. 2004. "Procedures for Performing Systematic Reviews," 33.

Lim, S. Buswell, R.A. Valentine, P.J. Piker, D. Austin, S.A. and De Kestelier, X. 2016. "Modelling Curved-Layered Printing Paths for Fabricating Large-Scale Construction Components." *Additive Manufacturing* **12** (October): 216–30. doi:10.1016/j.addma.2016.06.004.

Mechtcherine, V. Nerella, V.N. Will, F. Näther, M. Otto, J. and Krause, M. 2019. "Large-Scale Digital Concrete Construction – CONPrint3D Concept for on-Site, Monolithic 3D-Printing." *Automation in Construction* **107** (November): 102933. doi:10.1016/j.autcon.2019.102933.

Poinet, P. Stefanescu, D. and Papadonikolaki, E. 2020. "WEB-BASED DISTRIBUTED DESIGN TO FABRICATION WORKFLOWS," 10.

Poirier, E.A. Forgues, D. and Staub-French, S. 2014. "Dimensions of Interoperability in the AEC Industry." In *Construction Research Congress 2014*, 1987–96. Atlanta, Georgia: American Society of Civil Engineers. doi:10.1061/9780784413517.203.

Poirier, E.A. 2015. "Investigating the Impact of Building Information Modeling on Collaboration in the Architecture, Engineering, Construction and Operations Industry." Montréal: École de technologie supérieure. https://espace.etsmtl.ca/id/eprint/1600/.

Poirier, E.A. Frénette, S. Carignan, V. Paris, H. and Forgues, D. 2018. "Accroître la performance de la filière québécoise de la construction par le virage numérique." Canada: BIM Québec. https://www.bimquebec.org/ressources.

Sakin, M. and Kiroglu, Y.C. 2017. "3D Printing of Buildings: Construction of the Sustainable Houses of the Future by BIM." *Energy Procedia* **134** (October): 702–11. doi:10.1016/j.egypro.2017.09.562.

Van Eck, N.J. and Waltman, L. 2010. "Software Survey: VOSviewer, a Computer Program for Bibliometric Mapping." *Scientometrics* **84** (2): 523–38. doi:10.1007/s11192-009-0146-3.

Wegner, P. 1996. "Interoperability." *ACM Computing Surveys* **28** (1): 3.

Weng, Y. Li, M. Ruan, S. Wong, T.N. Tan, M.J. Ow Yeong, K.L. and Qian, S. 2020. "Comparative Economic, Environmental and Productivity Assessment of a Concrete Bathroom Unit Fabricated through 3D Printing and a Precast Approach." *Journal of Cleaner Production* **261** (July): 121245. doi:10.1016/j.jclepro.2020.121245.

Wu, P. Zhao, X. Baller, J.H. and Wang, X. 2018. "Developing a Conceptual Framework to Improve the Implementation of 3D Printing Technology in the Construction Industry." *Architectural Science Review* **61** (3): 133–42. doi:10.1080/00038628.2018.1450727.