BUILDING INFORMATION MODELLING BASED ON-SITE 3D PRINTER POSITION OPTIMIZATION FOR DIGITAL FABRICATION

A Thesis

by

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Submitted to the

Graduate School of Sciences and Engineering
In Partial Fulfillment of the Requirements for
the Degree of

Master of Science

in the
Department of Civil Engineering

Özyeğin University
December 2022

BUILDING INFORMATION MODELLING BASED ON-SITE 3D PRINTER POSITION OPTIMIZATION FOR DIGITAL FABRICATION

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To

All academic researchers

who dedicate their lives to contribute to future generations.

ABSTRACT

Digital fabrication, Additive Manufacturing (AM), and Building Information Modeling (BIM) has recently been advancing in the Architecture, Engineering, and Construction (AEC) industry and have been leading to increasing number of applications of digital fabrication technologies for three-dimensional (3D) printed structures such as tiny houses, shelters, or even bridges. The 3D printing processes of structures provide advantages in terms of time, cost, and energy efficiencies, as well as health, safety, and environment (HSE) aspects. The on-site integration of 3D printing and Building Information Modeling (BIM) has shown potential to improve the production processes of digital fabrication with concrete. So far, the utilization of building models by 3D printers has been the focus of this integration for more effective digital fabrication applications. BIM can be used in the site planning and optimization of the digital fabrication process by optimally positioning the 3D printers on the construction site.

In this work, a BIM-based 3D printer position optimization tool was developed using the Dynamo plugin of the Autodesk Revit software. Similar to the optimization of the site layout with BIM for major construction equipment (e.g., cranes); this tool looks at the design and geometry of the elements to be printed as well as the fresh and hardened state properties of the concrete mix. This tool considers the physical properties of a 3D printer, such as its dimensions and printing range, the geometry and location of the elements to be printed on-site, and the properties of printable concrete mixture, such as initial setting time. In the case study, the tool significantly reduced the number of steps required for printing the walls of a single-floor office building with a robotic arm 3D printer. The main objective of this research is creating an algorithm examining relocation

step counts of a robotic arm 3D printer in a real case office building construction and decreasing this relocation counts from 20 to lower values with determining optimal places over the slab. The outcome of this research will enable decreasing the relocation step counts for printer to 7 from 20 and unnecessary 13 steps are eliminated. As a result of this optimization work, 65% yield is gained in terms of labor force, time and energy consumption for relocation process of the printer.

ÖZETÇE

Dijital fabrikasyon, katmanlı üretim ve Yapı Bilgi Modellemesi (YBM) son zamanlarda Mimarlık, Mühendislik ve İnşaat (MMİ) endüstrisinde hızlıca gelişmekte ve küçük evler, sığınaklar ve hatta köprüler gibi üç boyutlu (3B) baskılı yapılar için dijital fabrikasyon teknolojilerinin artan sayıda uygulamasına yol açmaktadır. Yapıların 3 boyutlu baskı süreçleri, zaman, maliyet ve enerji verimliliği ile sağlık, emniyet ve çevre (SEÇ) yaklaşımları açılarından avantajlar sağlar. 3 boyutlu baskı ve Yapı Bilgi Modellemesinin (YBM) sahadaki entegrasyonu, beton ile dijital fabrikasyon üretim süreçlerini iyileştirme potansiyeli göstermiştir. Şimdiye kadar, 3 boyutlu yazıcılar tarafından sürekli kontrol edilen bina modellerinin kullanılması, daha etkili dijital üretim uygulamaları için bu entegrasyonun odak noktası olmuştur. BIM, 3 boyutlu yazıcıları şantiyede en uygun şekilde konumlandırarak, saha planlamasında ve dijital imalat sürecinin optimizasyonunda kullanılabilir.

Bu çalışmada, Autodesk Revit yazılımının Dynamo eklentisi kullanılarak bir 3 boyutlu yazıcının YBM tabanlı konum optimizasyonu aracı geliştirilmiştir. Tasarlanan bu algoritma, vinçler gibi büyük inşaat ekipmanları için yapılan BIM ile saha optimizasyonu çalışmalarına benzer şekilde; yazdırılacak elemanların tasarımı ve geometrisini dikkate almakta ve bunun yanı sıra beton karışımının sertleşme süresini de değişken olarak inceleyebilmektedir. Bu araç, bir 3 boyutlu yazıcının boyutları ve baskı aralığı gibi fiziksel özelliklerini, sahada yazdırılacak elemanların geometrisi ve konumu ile yazdırılabilir beton karışımının ilk priz alma süresi özelliklerini dikkate alır. Örnek proje incelemesinde optimizasyon aracı, tek katlı bir ofis binasının duvarlarını robot kollu bir 3 boyutlu yazıcıyla basmak için gereken adım sayısını önemli ölçüde

azaltabilmektedir. Bu araştırmanın temel amacı, gerçek bir ofis binası inşaatında robot kollu bir 3D yazıcının yer değiştirme adım sayılarını inceleyen bir algoritma oluşturmak ve döşeme üzerinde en uygun yerleri belirleyerek bu yer değiştirme sayılarını 20'den daha düşük değerlere indirmektir. Oluşturulan bu algoritma sayesinde yazıcı için yer değiştirme adım sayısı 20'den 7'ye düşürülerek gereksiz 13 adım ortadan kaldırılmıştır. Bu optimizasyon çalışması sonucunda yazıcının taşınma işlemi için iş gücü, zaman ve enerji tüketimi açısından %65 verim elde edilmiştir.

ACKNOWLEDGMENTS

I want to express my thankfulness to my advisor, Asst. Prof. Dr. Zeynep Başaran Bundur for her encouragement, support, and beneficial advice during my M.Sc. education process. I have been so happy and lucky to share my master's years with an advisor who believed in my ideas about interdisciplinary work for my project and allowed me to work freely.

I would also like to express my gratitude to my co-advisor, Asst. Prof. Dr. Gürşans Güven Işın for her planned working approach, new teachings about different disciplines, current new ideas for improving my thesis project, and also high motivation during all processes of this thesis work.

I would also like to thank my thesis committee members Asst. Prof. Dr. Bekir Oğuz Bartın, Asst. Prof. Dr. Senem Seyis and Prof. Dr. Esin Ergen Pehlevan for their attention and advice.

This research was conducted with financial assistance from the Scientific and Technical Research Council (TUBITAK) of Turkey Project: MAG-119N246. I want to acknowledge TUBITAK for the financial support.

I would also like to extend my special thanks to ISTON Corporation A.S., Emre Örtemiz, and Halit Dilşad Yilmaz for their collaboration and for sharing the project-related information and documents on the case study office building, which made this research possible.

Special thanks to my dear friends Muratcan Özçelik, Arda Üzümcü, Tolga Çağlar, İnanç Telci, Kerem Yavuz, Ebru Gelen, Murat Fazla, Yağmur Çınar, Sefer Gül and

Ramiscan Özel for their friendships, motivation, and support. I want to acknowledge my friends and colleagues Ozan Eray Aydın and Ilgın Sandalcı for their guidance and contribution to my study. I want to thank all the members of the OZU SAM research group.

Finally, I would like to express my deepest thanks to my mother Dilek Baş, my father, Mustafa Baş; my dear sister Nazem Baş and my uncle Hüseyin Barbaros Dicle for supporting my every decision; for their encouragement, for supporting me financially and tolerating me in every condition.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Over the last decade, the use of Building Information Modeling (BIM) in the construction industry is significantly increased. A similar trend can also be observed for integrating digital manufacturing in terms of additive manufacturing (AM) of concrete. There is great potential in integrating BIM and AM for increasing the efficiency of construction processes. BIM can be described as the digital representation of a facility's physical and functional characteristics and is used to store and manage all the information generated throughout the project's life cycle [1]. BIM applications in construction projects provide crucial information related to the life cycle of projects and enable visualization of the design and construction of building elements or simulations based on the performance and physical properties of buildings [2]. One of the primary uses of BIM is for planning the operation stages of a construction project well before the project starts. It has been proven to be a powerful tool for the optimization and planning of the site layout based on the characteristics of sites [3] and the location of large equipment (e.g., tower cranes) [4]. BIM-based visualization and optimization examples have been applied to the different applications on the construction sites, such as operating and planning lifting works of the cranes or their locating processes during construction periods [5] Site layout optimization aims to decrease project costs while increasing productivity and safety of working conditions [6] and BIM-based applications can help with identifying the optimal construction site layouts by creating realistic models that provide spatial data and dynamic navigation, as well as a continuous understanding of the indoor and outdoor spaces [7]. Object mapping applications can also be done with optimization algorithms by BIM tools for the Architecture, Engineering, and Construction (AEC) objects such as walls, footings, slabs, beams, or columns in a construction project. These applications will remarkably improve the energy consumption ratio [8]. Especially, BIM applications should be done with wide range of AM methods as 3D printing construction projects because the lack of applications such as life cycle assessments, large-scale implementations, or continuous controlling systems are creating disadvantageous limitations against the potential of the technologies [9].

On the other hand, AM provides several significant benefits to the industry by providing new and innovative design approaches by eliminating the formwork and optimizing the consumption of raw materials and labor requirements [10], [11]. American Society for Testing and Materials (ASTM) defines AM as "a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining" [12]. Compared to conventional casting methods, AM provides more design flexibility, and the application will improve the use of resources and reduce waste generation [13]. The initial purpose of AM methods for all industries was to produce conceptual product models for aesthetics and ergonomic purposes, determining the design flaws of products and testing them during this designing process [14]. The use of AM in the construction industry can provide significant advantages in reducing the need for additional equipment, total production costs, and time. Additionally, on-site AM applications can enable rapid design changes, improved optimization for the changing functions of projects, and a potentially more straightforward supply chain, shorter lead times, and lower inventories [15].

AM in the construction industry is generally obtained by 3D-printing of cement-based systems. The most used 3D printers in the fieldwork through the layer-by-layer production method in a fixed coordinate system [16], [17]. The first one is the gantry-type extra-large 3D printer systems that work on large-scale steel cage truss systems that are set up around the construction site before construction starts. A movable part placing the top of the fixed truss system carries the nozzle of the printer and changes the location according to the printing data for each printable element of the structure [18]. These gantry-type printers comprise an easily programmable and operable Computer Numerical Control (CNC)-controlled printing head with three-chain driven tubular steel beams that move in the direction of X, Y, and Z directions according to the coordinate system [19]. If the printed raw material can be provided constantly to the printer, this type of 3D printer system can complete a small structure, such as a shelter or a small-sized house, as fast as 24 hours [20]. However, the installation and operation processes of this type of printer create new problems requiring long times to install or dismantle the 3D printer systems on the construction site [18]. Also, when gantry-type printers are compared with robotic arm printers, 3 or 4 degrees of freedom of the gantry printer is likely making the gantry system less efficient and less flexible than the robotic arm printer system because of its 6-axis movement mechanism [21]. Besides, the printer occupies a relatively large, fixed space that cannot be changed easily. Therefore, the second type of printing system, robotic arms, have been more frequently preferred in field applications due to their flexible mobility properties [18].

The robotic arm 3D printers focus on the coordinate system with an arm that can move along the x, y, and z directions and is connected to a portable robotic system [22]. The pumping system of the concrete mixing tank feeds this mobile robot and based on the provided structural data. The printer can extrude the concrete mixture by moving along different directions to construct an element of structure [23]. The robotic arm 3D printer systems work with printheads mounted over the system and these printheads can inject concrete ink along with the robot's movement [24]. The relevance of robotic arm

3D printer usage on construction sites has been increasing because of their improved mobility and working conditions compared to the gantry-chart printers [25]. Physical properties of the printer system, such as the maximum working height and maximum opening angle of the robotic arm, are used to determine the printable area according to the printer's location. The operating range of these printers is within the dimensional limits of the robotic arm, which might lead to logistic disadvantages in accessing the elements printed on the worksite.

Integration of BIM with AM has the potential to provide better workflows and efficient planning for the 3D printing processes on construction sites [26]. During the last year, very recent research have started to investigate the usage of BIM for 3D concrete printing with robots in terms of not only for designing or architectural concerns but also conceptual, procedural, productional, organizational, and operating processual aspects [27], [28]. Moreover, a recent research completed last year has shown that some gaps between BIM applications and 3D printing in the construction industry prevent critical advantages and disadvantages of 3D printing operations for AEC [29]. For AM applications, detailed information such as the performance of the materials, spatial relationships of system and project elements, or manufacturing information can be obtained from BIM rather than just the geometry information [30]. By bringing together AM and BIM applications, designers can change the design of the building or design of the printable elements during different stages of the project, or operators can analyze the building's printability and constructability before initiating the printing process [9]. BIM can also assist in the visualization of the construction project and the worksite, as well as in the planning and optimization of the 3D printing workflow. Although BIM has been significantly used in the computerized design and off-site prefabrication of industrial elements, the relationship between BIM and AM in terms of the detailed modeling, designing, and 3D printing processes of projects have yet to be investigated in detail [2].

Goals and Objectives

To further explore the integration of BIM and AM for on-site digital fabrication applications, the objective of this study is to develop a BIM-based tool for optimizing the position of robotic arm 3D printer systems on a construction site for digitally fabricated projects. This tool can be used to determine the optimum positioning of a 3D printer at a construction site and provide an optimum working plan for the 3D printer. The goal is to enable completing the printing operation of all printable building elements through an optimized operation scenario. This study is the first known BIM-based optimization study for positioning robotic arm 3D printers for digitally fabricated construction projects.

The significant contributions of this study include the following:

1. The development of a BIM-based optimization tool that calculates the optimum printing path for projects built with robotic arm printers
2. Effective placement and usage of robotic arm 3D printers in projects by considering the printer dimensions and project design and characteristics (e.g., dimensions and locations of walls),
3. Ability to consider in the planning of optimum printing sequencing the properties of the concrete mix used in the fabrication of the project to ensure proper thermal insulation.

CHAPTER II

LITERATURE REVIEW

2.1 The use of Building Information Modelling (BIM) in construction projects

BIM can be described as a digital representation of a building, an object-oriented three-dimensional model, or a repository of project information to facilitate interoperability and exchange of information with related software applications, and also BIM software or applications authorize new levels of spatial visualization, simulation of the behavior of the building thanks to providing more effective project management [31].

Eastman et al. [1] described the BIM as one of the most promising development in the architecture, engineering, and construction (AEC) industry. They mentioned that one or more accurate virtual models of a construction project supporting design phases, allowing better analysis and controlling manual processes are created [1]thanks to digitally enabled BIM tools digitally. New collaborations between construction processes, facility management and maintenance of the project, and design processes can be provided by correct application instances of BIM [31].

Previous research and applications about BIM applications in the construction industry clearly showed and proved that BIM technology could improve productivity and efficiency, enhance constructability, minimize errors, and save time and cost [32]. These new BIM approaches and applications are widely used in the construction industry, such as bridge projects, water conservancies, port constructions, and transportation constructions [33].

Although BIM applications in the construction industry pretend to include very beneficial factors for different variables of projects, Bernstein et al. [34] mentioned that many barriers to the adoption of BIM applications in the construction industry have occurred due to technological improvements of 21'th century because critical points for BIM approaches was not only based on learning new software applications but also reinforming the workflow of the project, training staff or correct way of the modeling the construction according to new technological improvements [34]

S. Kim et al. [35] gave an example about integration problems of new technological improvements for the construction industry such as adopting robots on the construction sites in terms of task planning and mentioned that highly detailed schemas, elemental motions, or schedules can be planned with correct implementations of BIM software and applications.

2.2 Additive Manufacturing (AM) applications in construction industry

AM is a new technological approach for the construction industry and is generally defined by the ASTM as: "the process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [12].

An AM approach was applied in traditional construction methods during the construction industry history such as masonry buildings or brick wall applications. Technological improvements and mechanization for the construction industry provided new manufacturing methods for building or structure production processes such as 3D printers or robots leading additive manufacturing methods in recent years [25].

Thanks to different application methods of Additive Manufacturing (AM), the advancement of AM technology is increasing the range of on-site or off-site implementations for the projects such as paragoned and notably irregular design examples of constructions [35]. On the other hand, designing flexibility resulting from AM implementations provides trying to implement aesthetic characteristics over the project or element designs, which is impossible with traditional methods [36].

M. S. Khan et al. [22] examined crucially improved AM methods and mechanization in their research: gantry type 3D printers, robotic arm concrete printers, crane cable type 3D printers, and D-shaped printers for construction. According to the research, these 3D printing systems have some benefits for construction sites, such as economic and social impacts for the project, energy efficiency, exact time and cost planning, or skilled labor. On the other hand, these systems are procuring critical computational models to help optimize conditions for implementing 3D printed objects with high dimensional accuracy.

Huang S. et al. [24] have investigated mobile 3D printing systems for in-situ construction projects in research. Robotic arm 3D printers for construction sites have many crucial advantages, such as having small dimensions, being easily compacted, and working with multi-axis systems. Researchers mentioned that thanks to the improved flexibility properties of robotic arm printers and as a result of their 6 degrees of freedom working systems, these types of printers could be located easily in different locations on the construction site; they can easily reach to very difficult places of the printable elements such as close corner points, they can be fed with concrete mixtures by regular and smooth pumping systems and also they can be controlled and operated by the operator. However, as mentioned, this flexibility property of the robotic arm printers will only be favourable when the correct site and path planning are applied to the project [37].

Adapting robots and 3D printers in AM provide many crucial contributions and innovations from an industrial point of view. Robots are assisting in making the process rapid, creating complicated and detailed parts with an easier approach, building a part with high accuracy and precision, and being adaptable to new design changes, less waste, etc., compared to the existing system in industries. Also, correctly designated toolpaths for robots in the construction industry will be beneficial in reducing construction time and collisions for process thinking and planning [38].

2.3 Benefits of integrating BIM and AM

In a study, F. Craveiro et al. [14] have focused on the controlling processes of AM applications in the construction site with new technological approaches such as BIM, Internet of Things (IoT), or construction 4.0. Construction 4.0 and IoT are improved technological systems implemented for collecting data from the project, controlling construction processes and phases, and monitoring examined properties and variables of the project [39], [40]. In this study, these new online monitoring applications have tried on ingoing developed construction systems which new AM methods such as contour crafting systems, robotic arm systems, 3D printers, or d-shape applications for examining printing processes of building. During this examination, some critical properties of these AM construction operations, such as the printing time of the project, multi-material deposition property, deposition process, and flow rate properties, real-time feedback of the printer, have been evaluated with BIM or other controlling approaches to increase construction productivity, quality, cost, and resource-efficiency [14].

J. Zhang, H. Luo, and J. Xu [42] describe the necessity of the BIM and robotic construction systems each other with this definition: “The architecture, engineering, and construction (AEC) industry have seen continuous growth in the application of Building Information Modelling (BIM) over the last two decades while building automation and robotics is also gaining ground in the meantime. With more joint applications of both BIM and robotics being exposed, the compatibility of BIM for robotic building construction and maintenance is fundamentally key to further practical implementations”. According to the study, BIM information flows during designing and implementing processes has been growing in terms of the complexity of higher automation developments in the construction industry. Besides, robotic and automation work for the construction industry should support with more expanded BIM information frameworks to gain interoperation and synchronization between BIM and external applications.

Olsson et al. [26] have focused the BIM integration for new technological AM methods for different industries, especially the construction industry. The research mentioned that many current projects in the construction industry from various companies such as 3D printing applications, automation, robotics, or geographic information systems, have been conducted with BIM integrations. These collaboration systems of BIM with AM provide very-high quality building components and proper production applications thanks to collecting data from the project regularly and efficiently with computer aided designs. Procured BIM data from the projects ensures necessary information workflows to carry out innovation efforts for construction process thinking and standardization application. Also, the construction of complex parts or efficient designs and site plans, such as modularization applications which are non-applicable with the traditional methods, occurs thanks to digital drawings and captured data with BIM tools.

2.4 *The importance of site planning in construction projects*

In construction site planning, when an optimal construction site layout is created before projects has started, time and cost estimation analysis will be done effectively, and redundant time and cost consumption can be prevented. On the other hand, productivity and safety of working conditions can be enhanced by the BIM-based planning tools and optimizations. The project schedule or prioritization of the planning works in terms of equipment distribution on the construction site will be monitored thanks to created BIM site planning optimization and current data flow from the algorithms. They can be arranged according to efficient scenarios [41].

The importance of effective site planning for construction projects is mentioned in research completed by R. Bartolini et al. [42]. This research has completely focused on the unnecessary energy consumption resulting from wrong or lack of site planning applications in a real-life construction site. To extinguish this ineffectiveness on the project, a 4D BIM modeling was created and applied to the project. The application of BIM application has provided logistic planning and controlling for different phases of the construction project, and a remarkable increase in terms of time and energy saving has been observed. When the project was compared in different conditions before and after the site planning BIM approach applied, correct site planning showed 38% gain from time consumption and 88% gain from energy consumption for laborers [42]. A. Jalali Yazdi, et al.[43] describe the importance of correct site and operation planning for a portable equipment in the construction area such as lift car because they have mentioned that very different variables like resource dimension, capacity of the removable equipment, movement path of the equipment and also time variable are existing on the construction process. Therefore, correct planning of these all equipment will provide higher yield and the performance for the construction projects and projects can be accelerated with this planning. On the other hand, correct layout on the construction sites can minimize total cost induced by material transport, equipment rental, and layout modification [44]. This yield can be gained from not only optimization of the equipment on the construction sites such as tower cranes but also from planned areas such as ware houses, service roads or mobilization areas.

Research Gap

The main and the first purpose of the additive material application methods on the construction site is actually decreasing the construction time. When the additive manufacturing methods was applied with gantry type systems, establishing process of the systems come out with too many loss of time and cost. Besides, robotic arm 3D printers seems have too much advantages according to other systems thanks to easy operational processes but when location of the printer should be changed for printing other equipment on the site, it tooks to much time and robotic arm printer usage approach AM system goes beyond the purpose of application. Therefore, optimization of the construction sites that have been planned with the AM methods is very crucial to gaining main purpose of the applications from projects. However, there is not any example or research in the literature about site planning for the new technological applications of AM methods. Site optimization for construction projects in the literature have been done generally for conventional methods and conventional equipments and also they have been done with old techniques such as mathematical or manual approaches. This is the very novel and first application in terms of site planning with BIM applications on the AM methods.

CHAPTER III

METHODOLOGY

A real-world 3D-printed construction project was used as a case study in this research for the development of the BIM-based optimization tool. The case study building is a single-story office building (Figure 1a) that was printed with a KUKA robotic arm 3D printer by ISTON Corporation A.S. in Istanbul, Turkey, in 2021 (Figure 1b). Information related to the case study building project, such as the two-dimensional (2D) floor plans, the schedule, and progress reports, were obtained. The 3D-printed case study building is approximately 150 m^2 and consists of 20 unique 3D-printed walls, which are 3m in height and at lengths ranging between 3 to 5 m. During the construction of the project, the planning of the 3D printing was done intuitively by the project engineers, who determined 20 different points in the front of mid-points of each wall for positioning the robotic arm 3D printer for printing every element. The printing process was completed in 20 steps by placing the robotic arm printer at these points individually for each wall. All printing processes were completed in 20 workdays by working 8 hours a day. When the printer located over on a point, it starts to printing process according to the coordinate information of the location and the printable element. Printing process of an element take a specific time according to dimension of the printable wall and then location of the printer should be changed for new printable element. This relocating operation of the printer approximately take 4 hours and this time loss very conflicting with the purpose of robotic arm 3D printer usage on the construction site. Through using the developed BIM-based optimization tool, this study aimed to optimize the 3D printing process of the case study building by decreasing the number of times the printer needs to be carried from one location to another during the construction, and therefore, improve the efficiency of the printing process by saving time and energy.

(a) (b)

Figure 1: (a) The case study building, (b) KUKA robotic arm 3D printer.

Based on the obtained 2D floor plans, the BIM of the case study building was modeled in Autodesk Revit (version 20.0.0.377) (Figure 2). This was followed by the coding of the position optimization tool using Revit's visual programming plug-in Dynamo (version 2.1.1.7733). With its open-source, built-in node library, Dynamo enables industry professionals to perform design optimization, apply certain functions on lists of building elements and model additional elements outside of Revit [45].

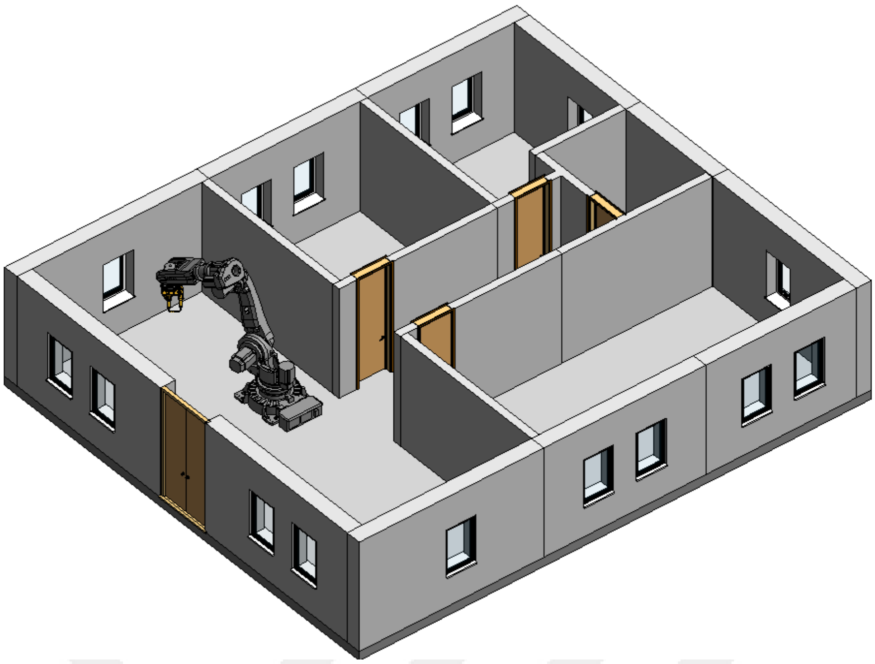

Figure 2: A general 3D view of the BIM of the 3D-printed single-story office building (Autodesk Revit)

This section provides the development details of the BIM-based site layout optimization tool for robotic arm 3D printer systems (Figure 3). The three main steps of the development process are as follows: (1) determining the possible points for placing the printer within the project boundaries, (2) finding how many times the printer needs to be relocated to complete all the printing in the project, and lastly, (3) determining the most effective route for the 3D printer considering the distances between the relocating points determined in the previous step. This third step also considers the properties of the concrete mix and the effects of material properties on the thermal insulation of the walls if needed.

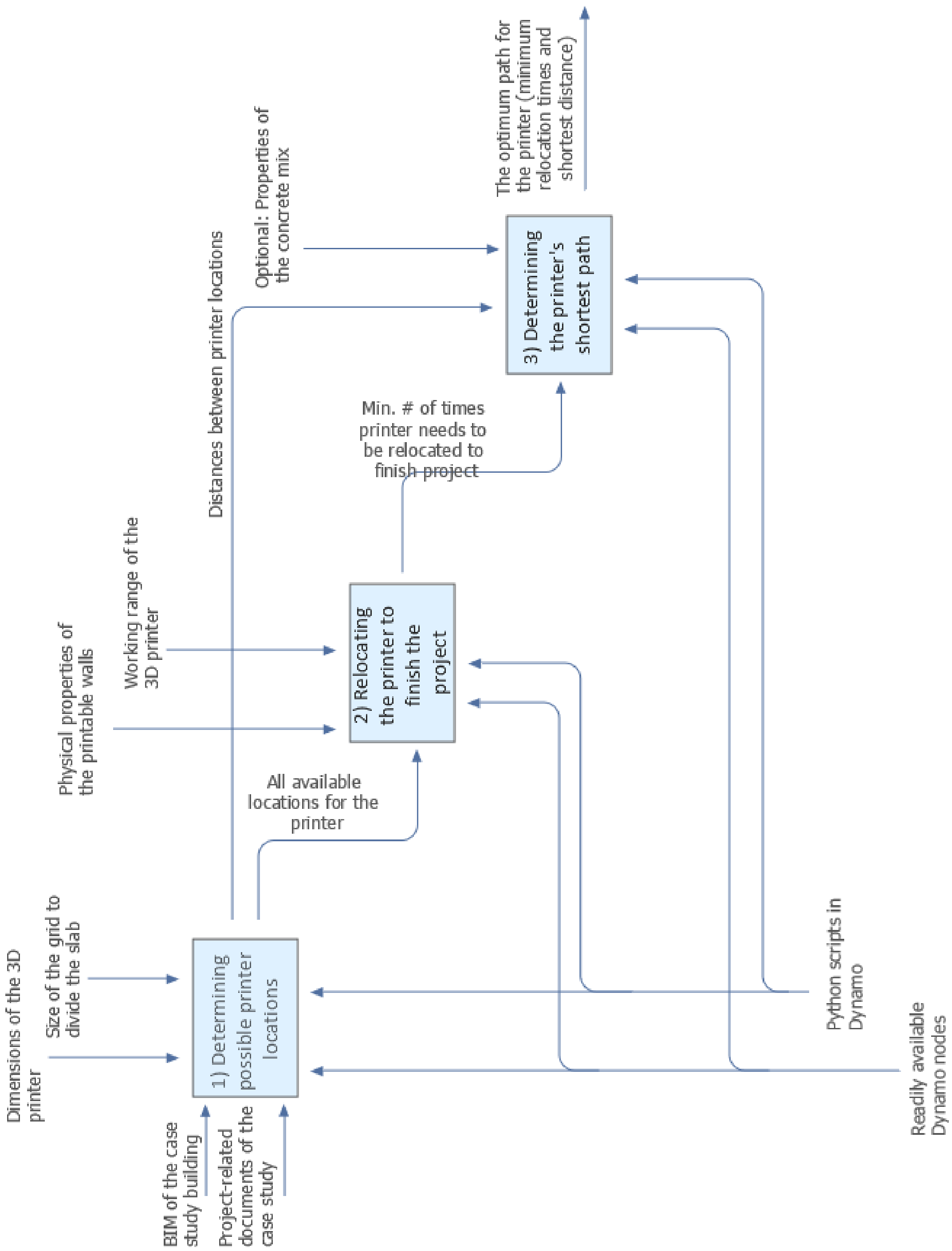

Figure 3: The main steps for BIM-based site layout optimization for robotic arm 3D printer systems

3.1 Determining the possible points for locating the printer within the project boundaries

In this first step, all available locations for placing the robotic arm 3D printer on site are determined (Figure 3.1)). The slab area that defines the project boundaries for the printing operation is obtained from the BIM of the case study and used as a basis for locating the printer on-site. The slab area is divided with a virtual grid to obtain points on the project surface where the printer can be found. A certain number of points are created based on the sizing of the grid (e.g., 100 points for a 10 x 10 grid). The sizing of the grid is critically important as it affects the optimization algorithm's performance in calculating the minimum number of times the printer will be relocated in the project. The possible printer locations are the ones that are confirmed to have no interference between the printer and the building elements to be printed, and this is determined by considering the dimensions of the printer. By combining a number of built-in Dynamo nodes and newly coded Python scripts, all possible points in the project where the printer can be placed are determined.

3.2 Finding how many times the printer needs to be relocated for completing all the printing in the project

All available points determined in the previous step as possible locations for the 3D printer to be placed are used to detect the minimum number of times the printer needs to be relocated to complete the whole project (Figure 3.2)). This step detects the locations where the printer can print more than one wall. The purpose of this is to avoid the need for moving the printer to a different point each time when a wall will be printed (i.e., 20 different printing points for the 20 walls in the case study project). In this step, the printability of every wall is evaluated from every single point on the project. This step considers the operating range of the robotic arm 3D printer and the properties of the walls, such as wall dimensions, and identifies the number of walls that can be printed at each point. Based on the number of walls that can be printed at each point, the minimum number of times the printer needs to be relocated to complete the project is calculated.

3.3 Determining the most effective route for the 3D printer considering the distance between printer locations

In this final step, the purpose is to ensure that the printer will travel on the most effective route to finish the printing of the project. Based on the distances between the determined relocation points on the slab, this step orders the previously determined printer locations to calculate the shortest path for the printer to travel. Also, in this step, the user can incorporate the properties of the concrete mix into the sequencing of the printing process if needed. When the concrete mix has a short setting time, the user might want to ensure the proper thermal insulation of the project by printing adjacent exterior walls at the same time.

CHAPTER IV

IMPLEMENTATIONS

This section describes in detail the implementation steps for calculating the minimum number of times the printer needs to be relocated to complete the printing of the entire case study building. The developed optimization tool starts with determining the possible working points for the 3D printer that do not overlap with the other elements on site. Then, the printability of all walls from all available points is evaluated to decide where the robotic arm 3D printer should be placed. Based on this, a score list is created for all points to show which walls can be printed by the printer when located at a particular point. These score lists are then checked one by one, and the order in which the robotic arm 3D printer should be relocated at these points to complete the project is identified. In this section, the utilized ready-built nodes and commands in Dynamo, the newly coded scripts and algorithms that are applied for optimization are explained in a step-by-step fashion:

Step 1: Determine the possible printer locations by checking for interference between the element surfaces of the project in BIM and all points (Section 4.1) and checking for clashes between the walls in the project and the footprint of the printer (Section 4.2).

Step 2: Calculate the minimum number of repositioning for the printer (Section 4.3) by first identifying which wall can be printed from which point (Section 4.3.1), then creating a list of printable wall IDs from the possible points (Section 4.3.2), followed by assigning scores based on how many walls can be printed at a point (Section 4.3.3) and finally based on these steps, creating the optimization algorithm for finding the minimum number of printer repositioning that is needed (Section 4.3.4).

Step 3: Calculate the shortest path for the final printer locations identified on the project in the previous steps (Section 4.4).

All these steps have been carried out as an example with a small grid sizing assignment of just 10 to 10 to be able to understand the lists, nodes, and algorithms created by Dynamo more simply, to observe them easily, and to transfer them to the reader in an understandable way. At the end of the research, it was determined that the minimum grid sizing for this project was 32 to 32 according to the dimensions of the working area for the printer, the dimensions of the printable walls, and the working diameter range of the printer. Then the final optimization results were obtained by assigning the grid sizing size to 32.

4.1 Comparing the possible printer points with wall locations in 2D

The first step determines the possible working points for the robotic arm 3D printer based on the geometry, layout, and dimensions of the given design. The case study building is divided into a virtual grid, and points are created on the slab where the printer can be located. For simplicity, the steps in this section are explained for a 10x10 grid on the slab (and 100 possible points for the printer). The actual sizing of the grid for the case study is determined as 32x32 based on the dimensions of the slab and the printer, and this process is explained in detail in Section 5. The ready-built Dynamo node **"Surface.PointAtParameter"** creates the necessary number of points on the slab based on the grid size, as shown in Figure 4. These points are stored in a Dynamo list and another list created by calling in the 20 walls in the project.

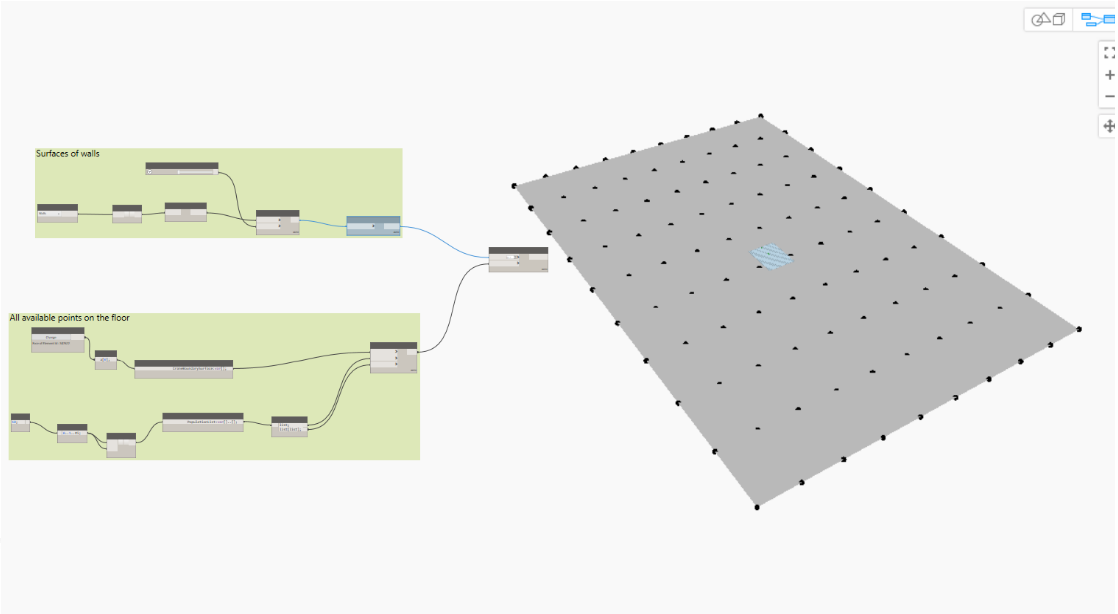

Figure 4: 100 possible printing points on the slab created by the 10x10 grid in Dynamo

Next, a generated code block is used to check the intersection between these two lists to determine each point that is overlapping with the location of a wall. This code block compares every element in the two lists by using the **"Geometry.Intersect"** node in Dynamo and eliminates the points that are determined to be intersecting with the wall surfaces as the printer cannot be located on these points. Out of 100 points, 35 were determined to be intersecting with wall surfaces, and the remaining 65 possible points were defined as possible printer positions.

4.2 Comparing the printer points based on the dimensions of the 3D printer

In the previous step, the list of potential printer points was compared with the location of the walls, and points determined to overlap with the walls were eliminated. In this step, the three dimensions of the printer (width x height x depth) are taken into account to determine the points where the printer is clashing with the walls in the project. These points are then eliminated from the list of possible printer points. The actual robotic arm printer used in the case study project would fit inside a 1m x 1m x 1m cube; therefore, a cube of this size that represents the 3D printer is placed on all the remaining possible points coming from the previous step. A ready-built Dynamo node block called **“Geometry.DoesIntersect”** is used to determine which of these cubes interfere with an element (i.e., wall) and which does not, and the points where the cubes are determined to be clashing with the walls are eliminated. Out of the 100 initial points, the number of possible points that were determined in the previous step decreased to 42 from 65 as it was determined that 23 points were interfering with the walls in the project due to the space that the 3D printer takes up.

4.3 Optimal printer position distribution check for minimum relocation process

Python scripting with the **“Python.Script”** node in Dynamo was used to determine the optimal printer positions to print all the printable elements. The available points for robotic arm 3D printer positioning were determined in the previous steps. The optimization algorithm takes that list of final available points as input. In addition to that, the wall coordinates and positions are needed to check which walls can be printed entirely at each printer position. The following sections describe these steps in the coding process in detail.

4.3.1 Controlling the printability of walls from available printer positions:

In this step, all walls in the project are checked from the available printer positions to ensure they can be fully printed from a specific location. The **"Topology.Edges"** and **"Geometry.Intersect"** ready-built Dynamo nodes are used to determine the most distant points of all walls and create a list of corner points of the walls. When the robotic arm printer is located at an available point on the slab and can reach all the corner points of a wall (most distant points to the printer), it means that the wall is entirely printable from this specific printer positioning point. Once all walls are checked against all the possible printer points, the total number and IDs of walls that can be printed from each position are determined.

The **"Geometry.DistanceTo"** node is used to cross-check the corner points list of all walls against the final point list by measuring the distance between two points in the x-y-z coordinate system. For this step, the arm length of the robotic arm printer is defined as the upper limit, and the distance between the printer and a wall to be printed is checked to be smaller than this value. For example, in the case study project, the diameter of the working range of the KUKA KR210 L100 2-K type robotic arm printer was 3.6 m for a 3 m height wall when it is located in the middle point of a wall (1.5 meters above the ground). Therefore, the upper limit of the robotic arm to reach from a specific point was assigned as 360 cm for the case study. A Python script is used to check that this distance criterion is met, and a list called **"Printable Wall ID in Points (True/False)"** is created. It consists of a master list of all the possible points, and in addition, 20 sub-lists (for each wall) are assigned for every list one by one. If all elements of a sub-list within the 20-wall sub-list are marked as "True", this means that a wall is printable from the specific possible points.

An example is given in Figure 5 for Point 0 and Wall 9 in the project. "0 List" in the master list represents the possible point ID "0" from the final point list, and "9 List" in the 20-wall sub-list of "0 List" in the master list represents the wall ID "9" from the general wall list. Since all elements (i.e., edge points) in the “9 List” are listed as “True”; this means that Wall 9 can be printed entirely from the possible Point 0.

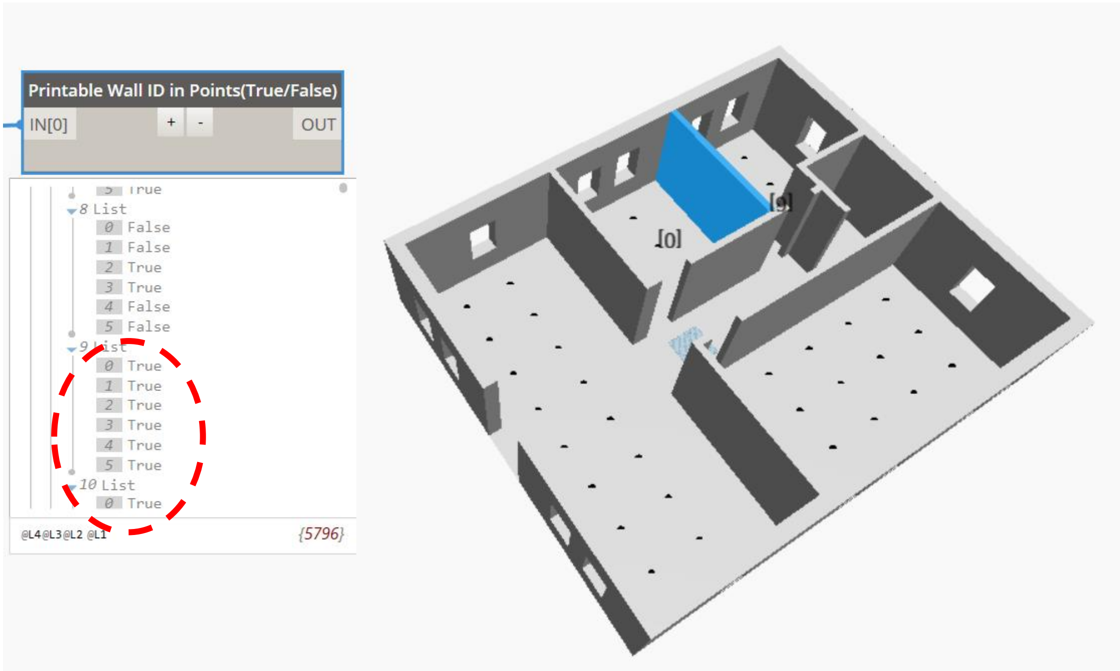

Figure 5: Example: The **“Printable Wall ID in points (True/False)”** script calculates that Wall 9 can be printed from Point 0

4.3.2 Determining printable wall IDs for every possible printer position:

The “True-False” list obtained from the previous step is used for determining the printability of every wall from each specific available printer location. A new script was created for checking every sub-list from the previous step. If these sub-lists include “True” strings for every edge point related to that wall; the script appends these walls in another list as “printable” from the specific point. This script also creates a new master list called **“Printable Wall ID from the Point”** and includes as many elements as the list of final available points. For instance, when 10x0 grid sizing was applied to the slab area, this script creates 42 different lists for a master list to represent available printer position points. Script turns back to the “**Printable Wall ID in Points(True/False)”** list for checking all the sub-lists. When the script sees a sub-list involving all “True” strings for every edge point of the related wall; the script appends the wall ID to the point list in this new master list. If any sub-list includes one or more “False” strings, this means that the wall cannot be printed from this point. As shown in Figure 6, among the 42 points, the “0 List” in the master list represents the possible Point 0, and the sub-lists that have all ”True” strings as “9 List”, “10 list” and “14 List” represent walls 9, 10, and 14. And this way, it is identified that walls 9, 10 and 14 can be printed from Point 0. The script repeats this process one by one by checking every point from 0 to 41 (a total of 42 points) until to finish all possible point options and appends every printable wall ID from the precise point to its list. When the distance check is completed if a point cannot print any walls, in other words, if all sub-lists for a point includes one or more “False” string; the script appends the “-” string to that point list to indicate that there is no printable wall from this specific point.

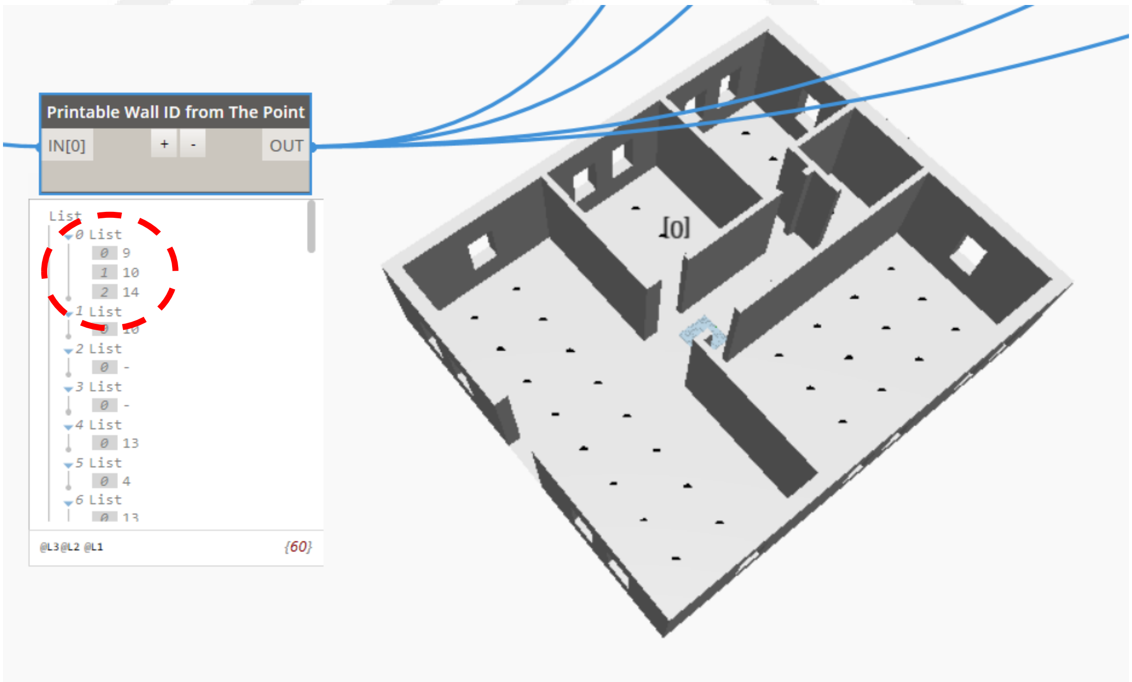

Figure 6: Example: **“Printable Wall ID from The Point”** script at Point 0 for Walls 9, 10, and 14

4.3.3 Assigning a score to possible printer positions in terms of the number of printable walls:

In this step, a score list is created for finding out the number of walls the printer can print at a possible position. This is obtained by using the "**Printable Wall ID from The Point"**. A new script was created for counting the number of printable walls at every possible printer point that is included in the master list. This script focuses on calculating the size of every sub-list of every point-related list in the "**Printable Wall ID from The Point"**. These size values of sub-lists are directly related to the scores of the points. When this new script counts the scores of all points from the sub-list size, it appends the printable wall score of an investigated point in a new master list as a first element, and also appends the ID of the investigated point again in this new master list as a second element. The algorithm script repeats this process one by one for every possible point until there are no possible printer position lefts that are not investigated. Then the list is sorted in the descending order by checking the first element of every created new list.

For instance, when the slab area was divided with a grid sizing 10x10, point ID 36 from all possible 42 points gave the best score result with the ability to print 5 walls. The script appended the "5" string as the first element in a new sub-list and the "36" string was added to this sub-list as the second element (Figure 7). For the points at which the printer cannot print any walls; a "0" string is appended for the first element of the related point's list to indicate that the wall printing score is 0 for this point. The node and list of this script are called "**Printable Wall Scores for Points"**, as shown in Figure 7.

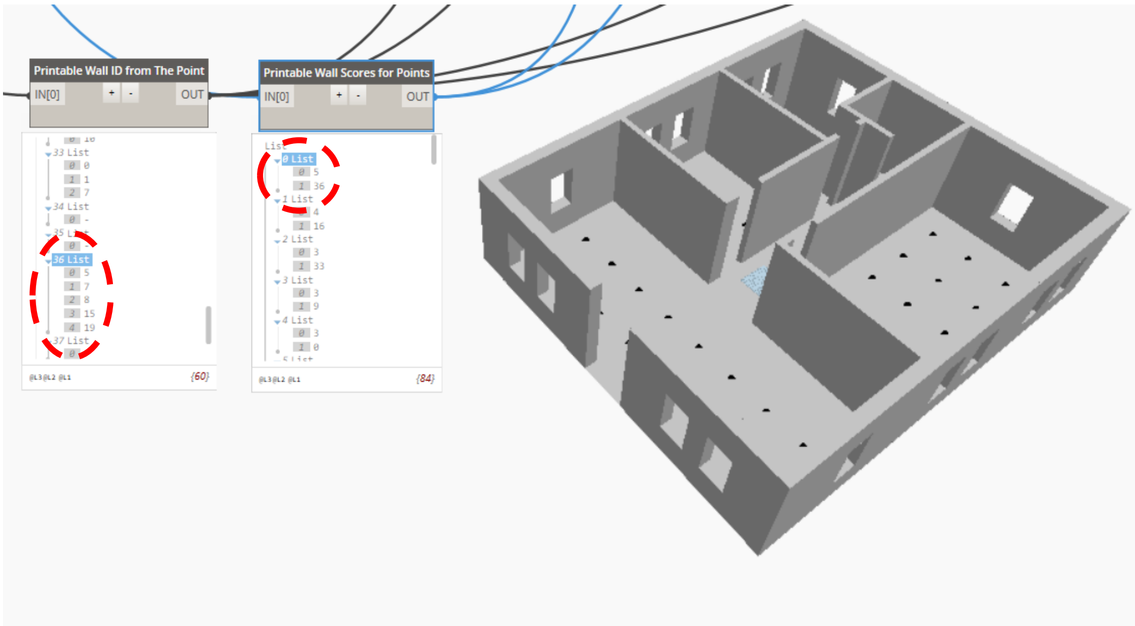

Figure 7: Example: **“Printable Wall Scores for Points”** script Point 36 with a score of 5 (meaning 5 walls can be printed when the printer is located on Point 36)

4.3.4 Minimum number of times the printer to be relocated to complete the entire project:

The goal here is to identify how many steps are required for printing all the walls in the project and what the minimum number of times the robotic arm printer needs to be relocated to complete the project. The algorithm here uses three different lists as inputs: The first one is the wall IDs that comes from the “**Printable Wall ID from The Point”** list that shows which wall can be printed at which specific point. The second input is the point scores that comes from the “**Printable Wall Scores for Points”** list for determining which specific point is more efficient according to others in terms of its ability to print more walls. Finally, the third input is a general wall ID list for removing the printed walls from the list and checking how many walls remain or if the project is completed or not.

The algorithm starts with the point that has which has the highest score in the score list. Then the algorithm adds this point to a path list as the first location of the printer. For designating the second step of the printer, the algorithm this time should check the next highest score point from the score list and add this point to again path list as the second step of the printer. This iterative process could be repeated for all points until no walls are left to be printed, however, but this way it does not take into account the common walls that appear in multiple lists at the same time. Instead, once the point with the highest score is assigned as the first step of the printer; the score list is then updated by evaluating the remaining non-printed walls right before the next point with the second highest score in the score list is checked. According to the newly updated score list, the algorithm visits again the first point with the highest score and assigns it as the second step for the printer. This iterative process is repeated for each point until the all the printing process is completed (Figure 8.). The "Pseudocode" of this optimization tool can be found on the appendix to undesrstanding the approach clearly (Figure A.16).

Final Points w/Updating Score List

```
# Load the Python Standard and DesignScript Libraries
import sys
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *

# The inputs to this node will be stored as a list in the IN variables.
WallList = IN[0]
ScoreList = IN[1]
PrintableList = IN[2]
FinalPoints =[]
tempNewScore = []
# Place your code below this line
#while len(ScoreList) != 0:
DeleteList = []
x = 0
while len(WallList) != 0:
    NewScoreList = []
    x = x+1
    if x == 1000:
        break
    k = ScoreList[0][1]
    for i in range(len(PrintableList[k])):
        DeleteList.append(PrintableList[k][i])
        for value in DeleteList:
            if value in WallList:
                WallList.remove(value)
    FinalPoints.append(k)
    for j in range(len(PrintableList)):
        count = 0
        for l in range(len(PrintableList[j])):
            if PrintableList[j][l] in WallList:
                count+=1
            else:
                continue
        NewScoreList.append([count,j])
        NewScoreList.sort(reverse=True)
    tempNewScore.append(NewScoreList[0])
    ScoreList = NewScoreList

```

Run Save Changes Revert

Figure 8: The **"Final Points w/ Updating Score List"** algorithm to determine minimum number of times the printer to be relocated

An example for determining the final printer points is given for the 10x10 grid in Figure 9. When the printability check was completed, Point 36 was the highest printable wall score (five walls) and these wall IDs were 5, 7, 8, 15, and 19. The second point in the highest score list was 16, with printability of four walls and these wall IDs were 7, 8, 9, and 19. When the algorithm chooses point 36 as the first step; it removes walls 5, 7, 8, 15, and 19 from the general wall list and updates the score list as a new score list according to the remaining 15 walls. In that case, the score of point 16 decreases from four to just one because the walls 7, 8, and 19 were common and they are now printed and therefore deleted from the general wall list in the previous step. After this, Point 0 became the point with the highest score (three walls) with walls 9, 10, and 14, and moved to the top of the score list. The algorithm takes Point 0 as the second position of the printer and repeats this until there are no walls remaining in the general wall list (Figure 9). Algorithm shows that in final, when grid sizing for this project is assigned as 10 to 10, printer can complete this project from 12 different points. Therefore, minimum number of times the printer to be relocated to complete to entire project can be found as 12 with 10 to 10 grid sizing. (Figure 9.)

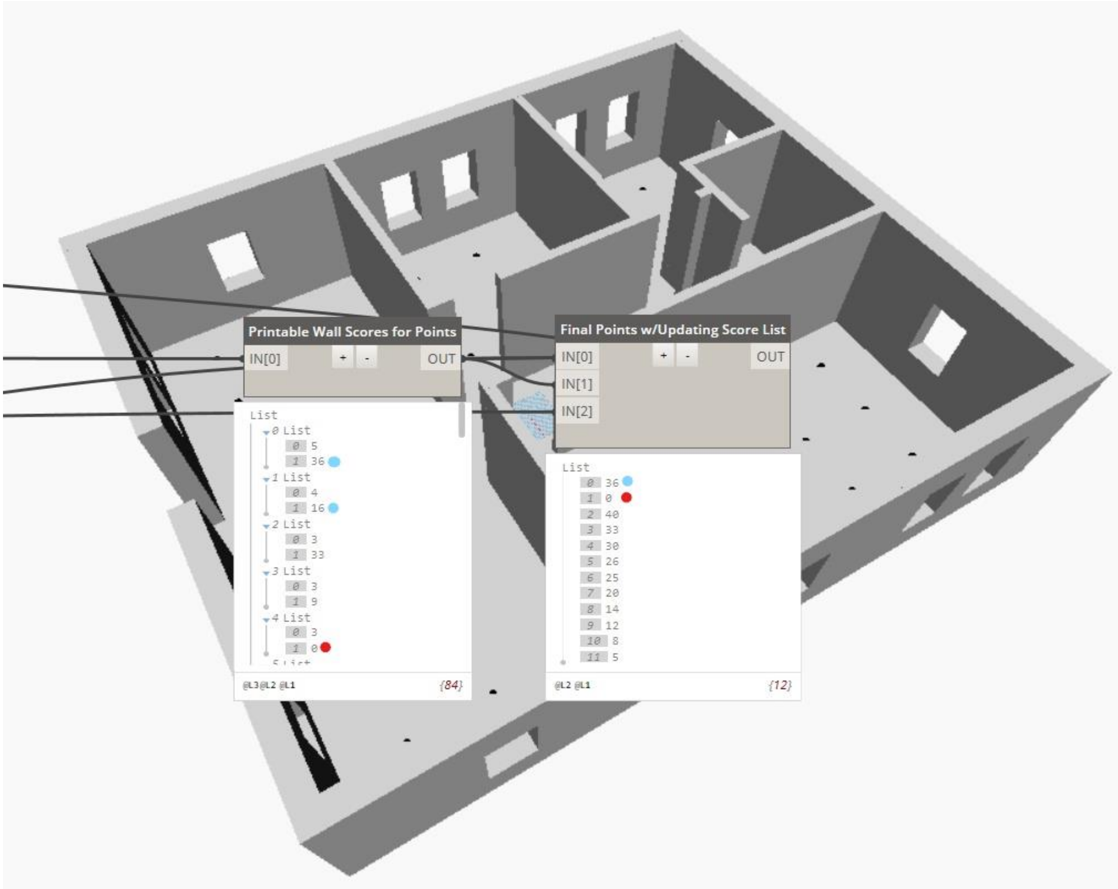

Figure 9: Printing sequence result of the **"Final Points w/ Updating Score List"** with updating score list in every step (Point 16 is not the second step in the result after Score list is updated)

4.4 Editing the algorithm with printing sorting application for gaining optimal pathway

So far, the algorithm calculates the minimum number of times the printer will be relocated to complete the printing process in a project; however, it is also necessary to find the shortest pathway between these final points. This is important in preventing unnecessary energy consumption while relocating the printer from one position on site to another. In Phyton, a script that uses the optimum points list as input from the final points algorithm, the distances between all final relocation points of the printer are measured using the **"Geometry.DistanceTo"** node. Then, the algorithm tries every possible point combination for the robotic arm 3D printer relocation process to calculate the minimum total traveling distance between the final relocation points to complete the project. The algorithm then measures the total traveling distance for all pathway possibilities and compares them with each other. The pathway that has the shortest traveling distance is determined to be the pathway for optimal printer positions.

CHAPTER V

RESULTS AND DISCUSSIONS

The optimum grid sizing for this study was found to be 32 to 32 for the working area of the printer according to the dimensions of the area, printable walls, and robotic arm printer. The BIM-based optimization tool developed in Dynamo divided the slab area of the case study project with a **32x32 grid**. As a result of this division, **1024 points** have been created in the working area. Then intersection check nodes found 221 of these 1024 points have intersected with printable wall surfaces over the slab, and 803 points have remained. Another intersection check has found that 309 of 803 points were not available for locating printer because the footprint of printers over these points was clashing with walls, and **494 points** have remained finally. According to these 494 available final points, the optimization tool determined seven printing points for the 20 walls in the project. As mentioned earlier, in the real-world printing process of the case study project, the printer had to be moved 20 times to 20 different printer locations to complete the project. The seven printing points determined by the algorithm (**Point 228**, **Point 475**, **Point 369**, **Point 317**, **Point 349**, **Point 23**, and **Point 428**) and the printing sequence are demonstrated in Figure 10. The following paragraphs elaborate on certain aspects of the developed optimization tool and the applied two-step verification.

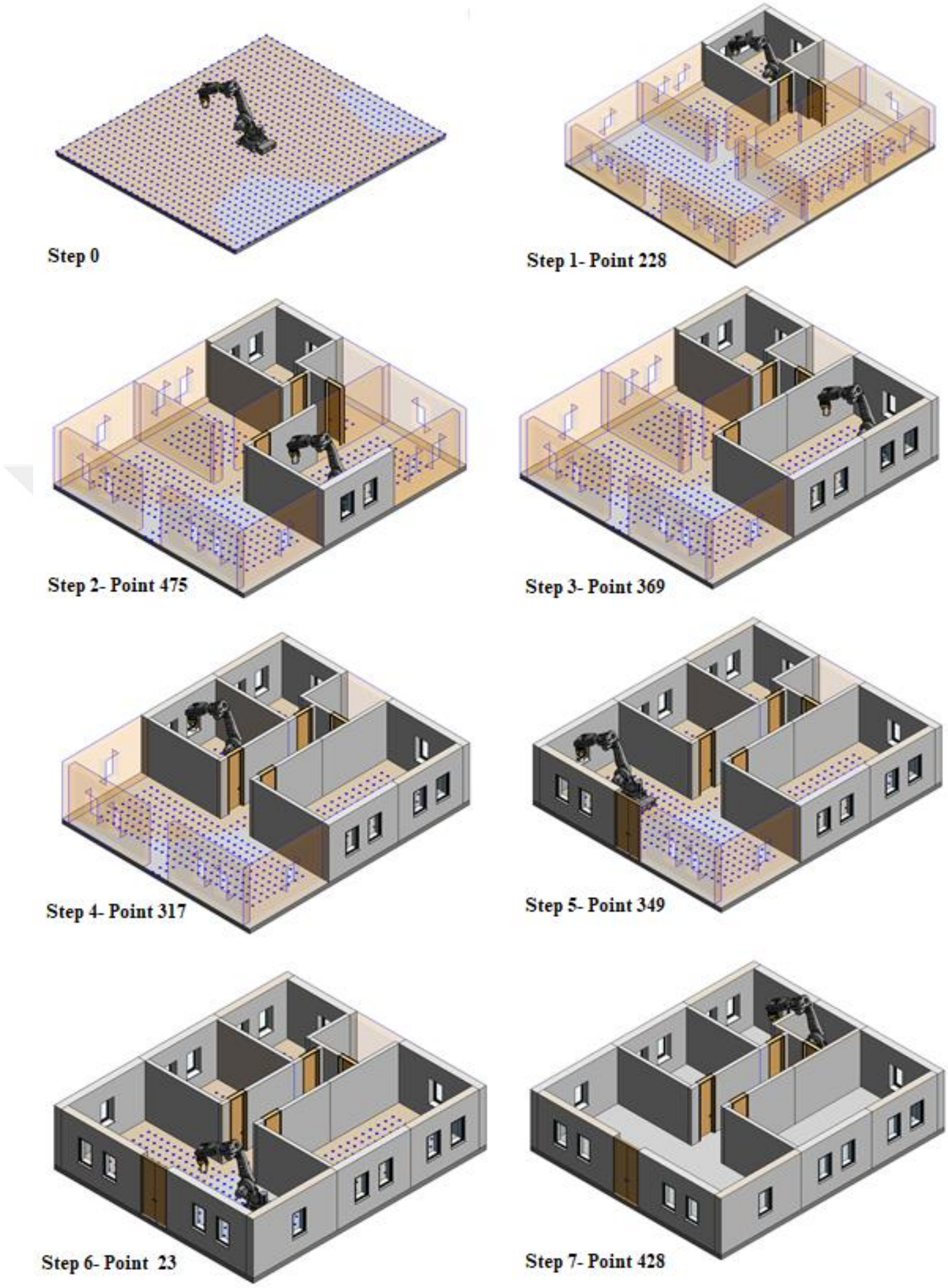

Figure 10: The optimum printing sequence of the case study project in 7 steps determined by the developed BIM-based optimization tool

5.1 Applicability to other projects

This tool can be applied to optimize the printing process in other digitally fabricated construction projects for different designs, number of walls, and project areas. One of the parameters in the developed algorithm that will change from project to project is the sizing of the grid that will divide the slab to assign points on the project area in Revit. This is based on the size of the project area and the dimension of the 3D printer that is used in a given project. This step is crucial in finding the minimum number of steps to relocate the robotic arm 3-D printer during the printing process for any given project. The sizing of the grid is calculated based on three parameters: (1) the working diameter of the robotic arm of the printer (i.e., max. reaching distance), (2) the maximum length of the printable walls, and (3) the distance between the printer and the walls. A printer is envisioned to be located in the middle point of a wall, and the difference between the working radius of the robotic arm and half of the wall length is used in determining the minimum division number. Based on the dimensions of the working area and the printer, the algorithm divided the project area with a 32x32 grid to provide the optimum number of possible printer locations (1024 points) to initiate the process.

5.2 Correct grid sizing number determination approach

When the printer is located across a wall in the middle point, the difference between the working radius of the robotic arm and half of the wide length of the wall is crucial for determining the minimum grid sizing amount. This is critical because the change of the printer location as far as this value can change the status of the wall as printable or not for this point. For example, suppose the maximum width of walls for a project is 5 meters, and the diameter of the robotic arm's working range is 5.20m when the printer is located on the cross of the middle point of the wall. In that case, the half-wide value will be 2.50 meters, and working range of the robotic arm from this point to the left and right will be 2.60 meters. There is a 10cm gap between these two values. Therefore, a more than 10cm change for the printer location to a left or right neighbor possible point will change the printability status of the wall. For this reason, the distance between two neighbor possible printer position points over the slab area should be 10cm maximum or lower.

In this project, the robotic arm 3D printer has a 360 cm radius working range from a specific point. Also, the maximum wall width in this project is 490 cm. When the robotic arm 3D printer is located in the middle point of the wall, it can print 360 cm to the left and right side from this specific point, and the wall actually has 245 cm length to the left and right side from this middle point. Therefore, if the location of the printer is changed to up 115 cm (360-245 = 115) or more in left to right or right to left directions, the printer cannot reach some parts of the wall, and the status of the wall can be changed as non-printable for this new neighbor location point. The slab area of this project has 1360 cm and 1160 cm side lengths. If the division number for the x and y direction of the slab is assigned as 11, distances between two neighbor points will be approximately 123 cm (1360/11 = ~ 123, 6 cm). Therefore, the x and y direction grid sizing amount of the slab area for this project should be a minimum 12 (1360/12 = ~ 113,3cm) to provide possible printable points for every wall in this project. However, the printer cannot be located over the projection of the middle point for the wall because the printer and wall will intersect with each other. The printer should be found across the middle point of the wall at some distance. The maximum distance from the wall for providing printability should also be calculated to estimate the optimum grid sizing amount for the slab area. When the printer is located far from the wall's middle point, a right triangle occurs. If the printer is in the point with maximum distance without losing printability property for the whole wall, the hypotenuse distance will be 360 cm. The horizontal side of this triangle is known as the half-length of wall wide measurement, and this is also known as 245 cm. Therefore, according to the hypotenuse rule calculation, the printer's vertical distance from the middle point of the wall will be a maximum of approximately 263 cm ($245^2 + 263^2 = 360^2$). When the printer is located more than 263 cm far from the middle point of the wall, this wall cannot be printable with this robotic arm 3D printer. According to these calculations, the ratio between horizontal 115 cm and vertical 263 cm distances from the middle point of the wall will be the optimum location change distance for providing a minimum relocation step amount. The ratio coming from 115 over 263 is calculated as 0,437. According to this approach, when the grid sizing for the slab area is determined, if the distances of neighbor points to each other is approximately 0,437 or less, the algorithm probably will give the best results for gaining the minimum step amount for the printer’s relocation process. When the grid sizing for the slab area is assigned as 31, the distance between two neighbor points will be approximately 0,438 cm. Therefore, the optimum result of the step amount algorithm probably will be gained when the grid sizing number is assigned as thereabouts 32 for the x and y direction.

5.3 Incorporating the concrete mix properties

The developed optimization tool can incorporate the properties of different concrete mixes if needed. To demonstrate this, another printing scenario was applied to the case study project. The goal was to ensure efficient thermal insulation was achieved in the neighboring exterior walls located on the corners of the project area. In this case, the exterior corner walls will be printed simultaneously; therefore, the gaps between asynchronously set walls will be eliminated. In this scenario, the printable walls were separated into two groups as exterior and interior walls. The walls' printing process was envisioned to be completed in two stages. First, the exterior walls were taken as a group and printed, and then the interior walls were taken as another group and printed. For this scenario, since the working area of the printer did not change, the division number of the slab remained the same. The project has 11 exterior walls, eight located on the corner points (Figure 2).

Every two walls located on the four different corners of the project were printed as a monolith to provide efficient insulation. The algorithm determined seven points to locate the printer to print the 11 exterior walls (**Point 669, Point 524, Point 478, Point 33, Point 681, Point 660, and Point 584)**. Next, the interior walls were examined as a second group regardless of their insulation property, unlike the exterior walls. For the remaining nine walls, the algorithm determined four different points (**Point 616**, **Point 626**, **Point 608**, and **Point 633),** and the entire project could be printed in 11 steps. When the setting properties of the concrete mix were considered, the optimization algorithm decreased the number of times the printer needed to be relocated from 20 to 11.

5.4 The two-step verification

To verify that the developed algorithm can effectively determine the sizing of the invisible grid applied to the project area, different grid sizes are evaluated by manually changing the grid size. For dividing the slab, a number of alternative grid sizes were tested, such as 35x35, 40x40, 50x50, 60x60, 70x70, 80x80, 90x90, and 100x100. It was observed that while the grid size was going up to 100 from 32, the minimum number of times the printer needed to be relocated remained the same, and seven new locations were determined according to the new possible points in each test. This was tested with numbers smaller than 32, and the results required the printer to be relocated eight or nine times to complete all the walls. This test demonstrated that the sizing of the grid assigned by the algorithm gives the minimum number of times the printer needs to be relocated.

The next test was conducted to verify that the developed algorithm can calculate the minimum number of printers relocating times for a given project. This is done in the Spyder coding environment with python scripting language, and necessary lists such as score lists, wall ID lists, and possible printer locations were called from Dynamo as inputs. This script tried every possible point combination for the robotic arm 3D printer relocation process using Python's "Random" approach and checked more than 1 billion possible printer position combinations. As can be seen from Figure 11, the results demonstrated that always the same number, seven, is obtained as the minimum number of times the printer needs to be relocated to complete the whole project. This was also the case when the basic seek algorithm tried other grid sizes in addition to 32x32, such as 55x55or100x100(Figure11).

```python
def random_seek(printable_walls_per_point, number_of_seek): #Finds the best, shortest 5 (if avaliable) paths regardless of the order of visit
    start_time = time.time()
    printable_walls_per_point.sort()
    printer_locations_lists = []
    wall_list = []
    for i in range(len(printable_walls_per_point)):
        if len(printable_walls_per_point[i][1]) != 0:
            for j in range(len(printable_walls_per_point[i][1])):
                if printable_walls_per_point[i][1][j] not in wall_list:
                    wall_list.append(printable_walls_per_point[i][1][j])
    for r in range(number_of_seek):
        pwpp = copy.deepcopy(printable_walls_per_point)
        selected_printer_locations = []
        printer_locations = []
        for i in range(len(pwpp)):
            printer_locations.append(i)
        walls_printed = []
        while len(walls_printed) < len(wall_list):
            while True:
                loc = random.choice(printer_locations)
                if len(pwpp[loc][1]) != 0:
                    break
            selected_printer_locations.append(loc)
            printer_locations.remove(loc)
            for i in range(len(pwpp[loc][1])):
                walls_printed.append(pwpp[loc][1][i])
            for i in range(len(walls_printed)):
                for j in range(len(pwpp)):
                    if walls_printed[i] in pwpp[j][1]:
                        pwpp[j][1].remove(walls_printed[i])
        selected_printer_locations.sort()
        printer_locations_lists.append(selected_printer_locations)
    printer_locations_lists.sort(key = len)
    end_time = time.time()
    print("\n--------------------       RANDOM SEEK        -------------------")
    run_time(end_time - start_time)
    best_strategies = printer_locations_lists[:5]
    print_result(best_strategies)
    print("\n-----------------------------------------------------------------")
# ==============================================================================
# ============================ ELIMINATION SEEK
# ==============================================================================
# elimination_seek(import_csv("30scorelist.csv"))          #   7 steps: [37, 46, 80, 99, 128, 411, 449]               Run time: 0.07 seconds.
# elimination_seek(import_csv("55scorelist.csv"))          #   7 steps: [12, 59, 77, 157, 198, 691, 1159]             Run time: 1.03 seconds.
# elimination_seek(import_csv("100scorelist.csv"))         #   7 steps: [34, 68, 109, 117, 130, 781, 3171]            Run time: 23.59 seconds.

# ==============================================================================
# ============================ RANDOM SEEK
# random_seek(import_csv("32scorelist.csv"))          #  7 steps:    [37, 46, 80, 99, 128, 411, 449]              Run time: 0.1 seconds.
# random_seek(import_csv("55scorelist.csv"))          #  7 steps:    [12, 59, 77, 157, 198, 691, 1159]            Run time: 1.5 seconds.
# random_seek(import_csv("100scorelist.csv"))         #  7 steps:    [34, 68, 109, 117, 130, 781, 3171]           Run time: 24.32 seconds.
```

Figure 11: The basic seek algorithm created in the Python Spyder coding environment for the verification of the developed algorithm

CHAPTER VI

CONCLUSION

6.1 Key findings of the optimization project

This study proposes a BIM-based automated position optimization tool for robotic arm 3D printers for on-site 3D printing applications. This tool automatically determines the minimum number of position changes for the printer during the construction, therefore, it aims to bring time and energy savings in digitally fabricated construction projects. Considering the design of a project and specific project characteristics, the goal is to determine the positions where a robotic arm 3D printer could be located on a job site while keeping at a minimum the number of times the printer will be relocated. This tool is applied to a single-story office building case study. While in the real-world application, the case study building was completed by relocating the printer 20 times to 20 different points around the project area; the developed optimization tool completed the project by relocating the printer only seven times to 7 different locations. This result demonstrates that there were 13 unnecessary relocation steps for the robotic arm 3D printer to print some of the walls in the project. This result also indicates that excessive energy consumption can be eliminated when the 13 unnecessary steps are removed, and a more effective construction plan can be achieved. This ensures energy savings and time and labor force efficiency in the field operations of 3D printers with 65% yield with decreasing relocation step counts from 20 to 7.

The developed optimization tool is adaptable to other construction projects and can improve the printing process's efficiency on-site while preventing unnecessary labor and energy consumption. Even though the developed algorithm is validated in a small-size project, the integration of BIM and AM will be more significant for larger construction sites or more complex projects. Based on the positioning of the printer on-site over the project duration, this method can be used to determine possible interferences between the printer and the structural elements well in advance of the construction. Currently, the developed tool is for use by robotic arm 3D printers and could be modified for cartesian system 3D printers. In that case, since these printers are at a fixed location throughout the project; the algorithm can help with finding the optimum printing pathway or the shortest route for energy saving energy by eliminating unnecessary movement of the printheads.

The main achievements of the developed BIM-based optimization tool can be listed as follows:

- Determining the optimum positioning and pathway of a robotic arm 3D printer on a construction site based on its BIM to increase the productivity of the construction operation process by eliminating the unnecessary energy consumption for redundant repositioning of 3D printers.
- More effective robotic arm 3D printer usage on the construction site and more effective site planning by taking into account the dimensions of the robotic arm 3D printer being used and the size of the construction project built with additive manufacturing methods.
- Enabling proper thermal insulation for the project's exterior walls by modifying the printing sequence of the walls according to the initial setting time of the concrete mixture used in the project.

Scope and Limitations

Although algorithm is giving beneficial results in terms of energy, time and labor force consumption with decreasing the relocation step counts for robotic arm 3D printer in the construction area, there are some limitations for applicability of this algorithm for the construction projects. These limitations will affect the yield ratio of the created optimization algorithm. Limitations for this research can be listed as:

- The working range of the used robotic arm 3D printer
- The dimensions and shape of the area that robotic arm 3D printer can be located over
- Dimensions of the printable elements (walls) of the construction project.

Any differentiation for these limitations can directly change the results of the created optimization algorithm. When parameters and necessary coding application were arranged according to these limitations, the main scope of this research can be procured with consistent results. Main scopes of this research can be also listed as:

- Decreasing the number of steps for relocating 3D printer on the construction site
- Achieving minimum travelling distance between determined final positions for 3D robotic arm printer during all printing process of construction elements
- Increasing productivity of the project in terms of energy, time and and workforce consumption thanks to eliminating unnecessary steps of relocation process.

6.2 Future Works

According to the created optimization algorithm, this project has shown that this type of project constructing with a robotic arm 3D printer can be done by approximately three times lower relocating step amounts on the construction site, and more optimistic a printing sequence can be applied for the projects. The generated algorithm can be adopted for larger scale projects that requires higher number of printable elements on a large scale field. Here the critical point is finding grid size number correctly for printer’s working area and creating possible printer position over this area with regularly according to shape of the area. When correct approach and values are appended to optimization tool for the related construction area, higher yield values will be gained from the optimization tool also from higher scale projects. For example when the wall sizes of the project or circular working range capacity of the used robotic arm 3D printer change, all parameters of the grid sizing system should be regulated according to new parameters and general algorithm coding also can be improved. On the other hand, technological improvements on this approaches and developments about automation of the robotic arm 3D printers will shape on the future of these applications and their optimization works. As part of future works, this optimization tool can be expanded by adding different variables, or several new editions of this tool can be regulated for various additive manufacturing systems and other types of printers. For example:

- The optimization tool can be changed by time variable addition, and a new printing sequence will be arranged according to a time-dependent criterion. As a result of this type of addition for the optimization algorithm, the completion period of a 3D-printed construction project will be much shorter than the non-optimized construction process.
- A cost-based optimization tool can be derived from this existing algorithm with an appendage of expenditure variable examining the cost of the relocation process for the 3D robotic arm printer on site and the construction process of the building.

According to the cost analyses with the tool, the implementation method of the project will be changed, and another type of printer can be preferred to complete the construction project for financial gains.

- Printing pathway optimization will be integrated for more than one printer on the construction site. Usage of two, three, or more three robotic arm 3D printer, which has a wider circular working range on the construction site, will be planned by regulating this printing sequence algorithm and the project can be completed without needing any relocation step for the printers. As a result of this approach, cost, energy, or time consumption analyses of different printing scenarios can be done by the new edition of the optimization tool.
- Also, the algorithm can be applied to the community projects that have started in recent years, including more than one building construction at the same time, such as 3D printable 100 houses. The optimization algorithm will be arranged according to this type of a vast construction site, and printing sequences, installing and demoulding processes of different types 3D printers such as gantry type or robotic arm 3D printers will be optimized with the new generated tool.

APPENDIX A- DYNAMO NODES, SCRIPTS, ALGORITHIMS AND CREATED GROUPS

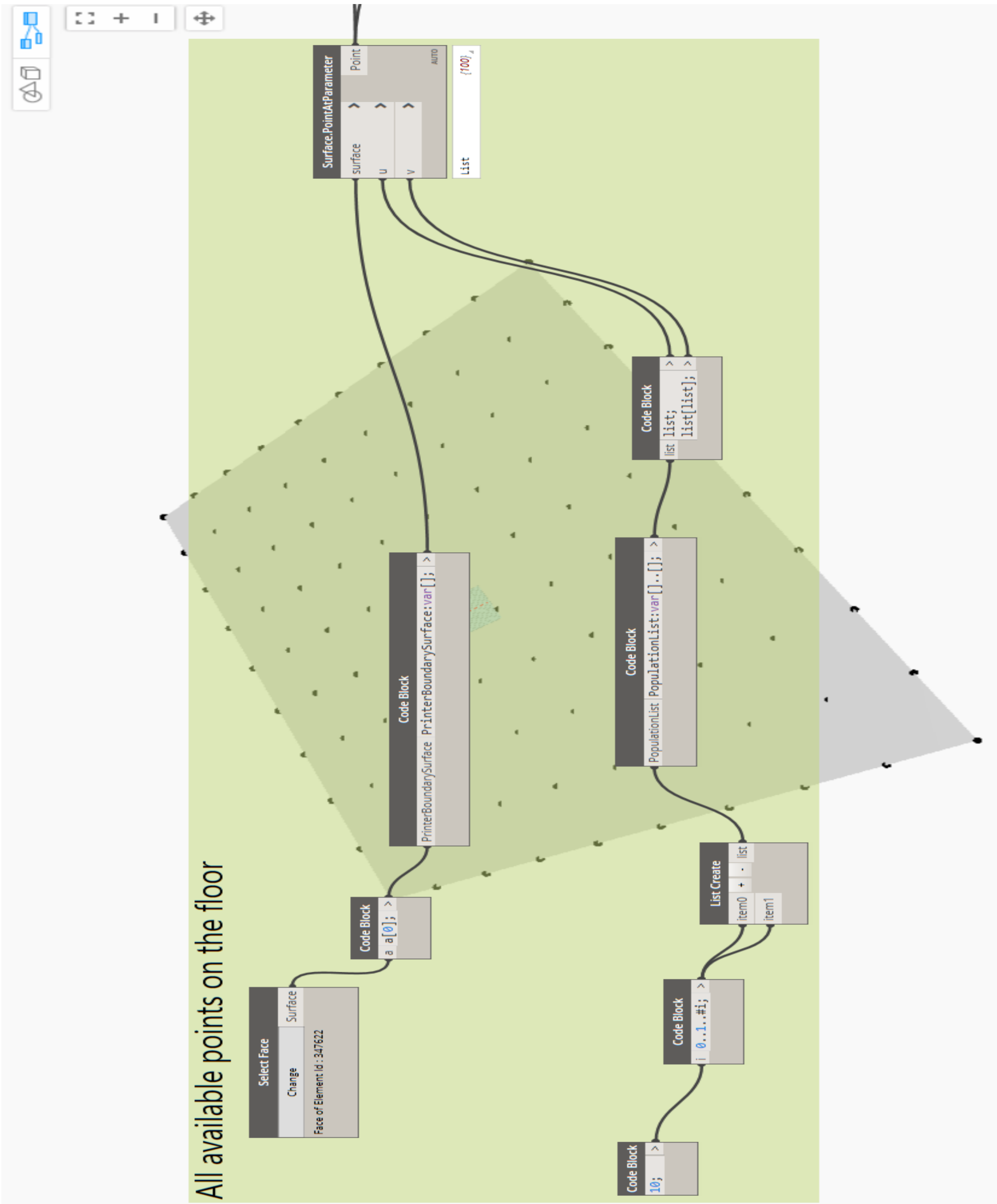

Figure A. 1: 10 x 10 grid sizing on the slab with **"Surface.PointAtParameter"** node group to create 100 possible point for locating printer

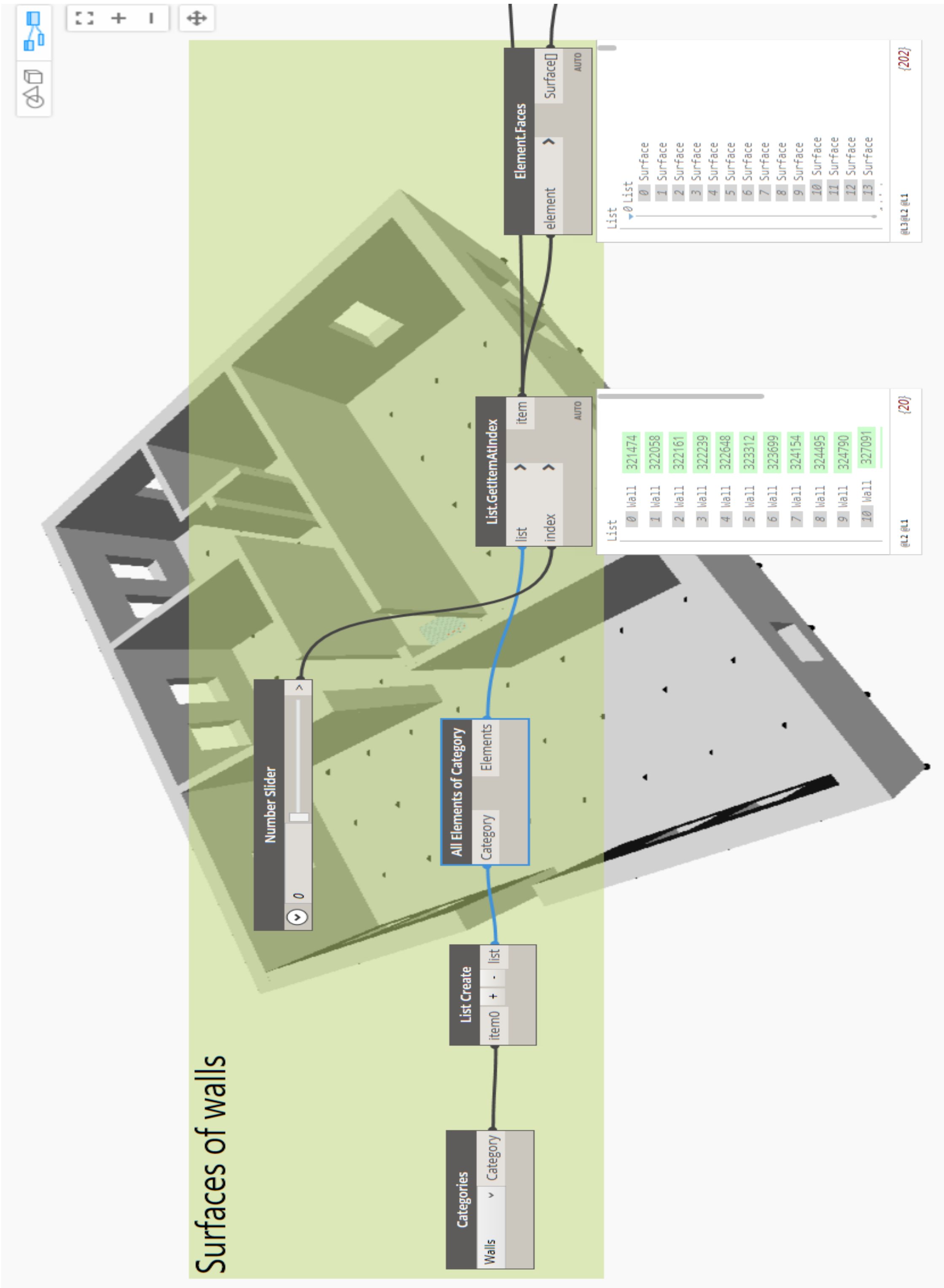

Figure A. 2: Determining wall surfaces over the slab area for examining intersection problems of these surfaces with possible printer positions or printer's widht properties

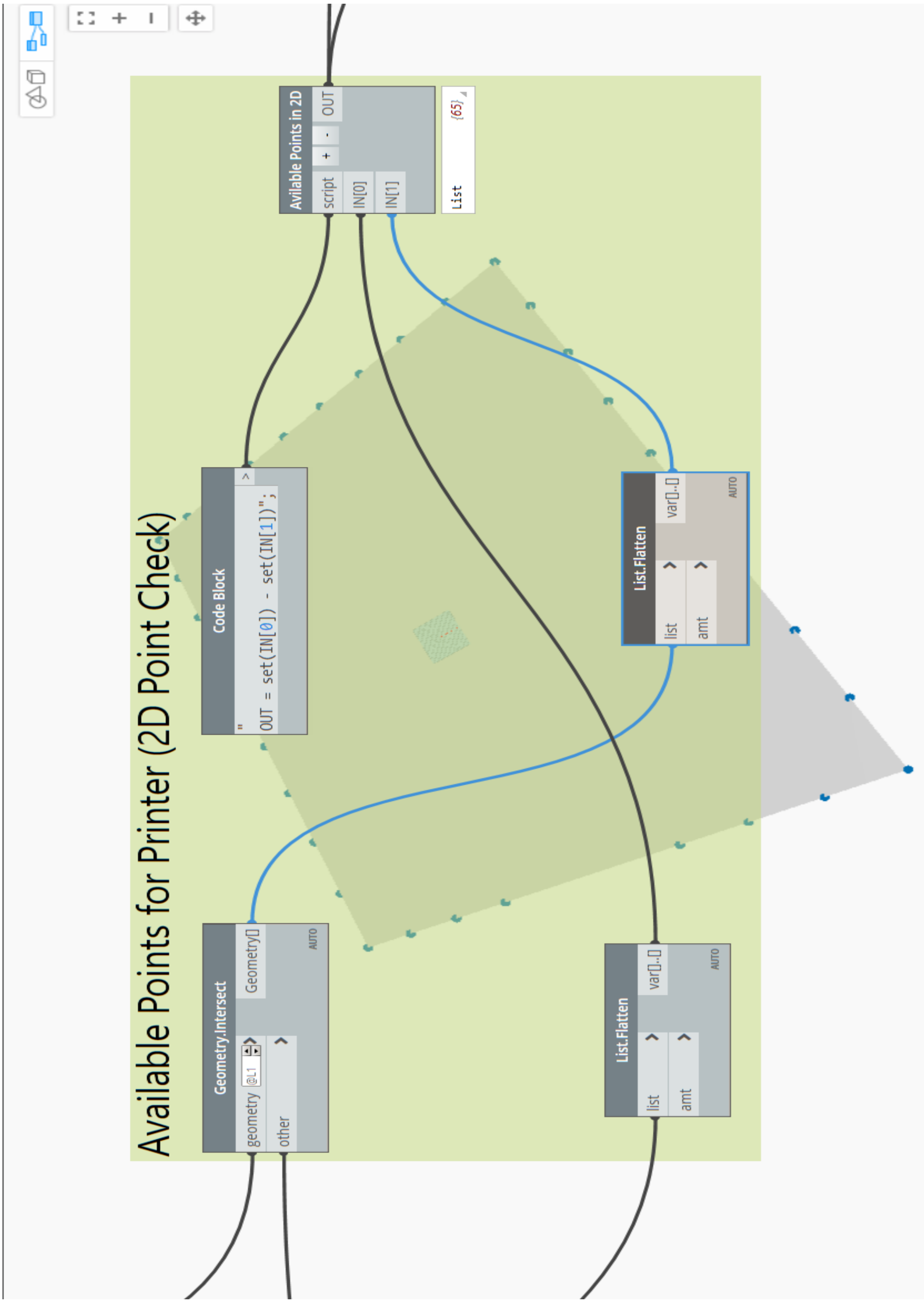

Figure A. 3: "Geometry.Intersect" node group for specifying which points from the general list are intersecting with any wall surfaces over the slab

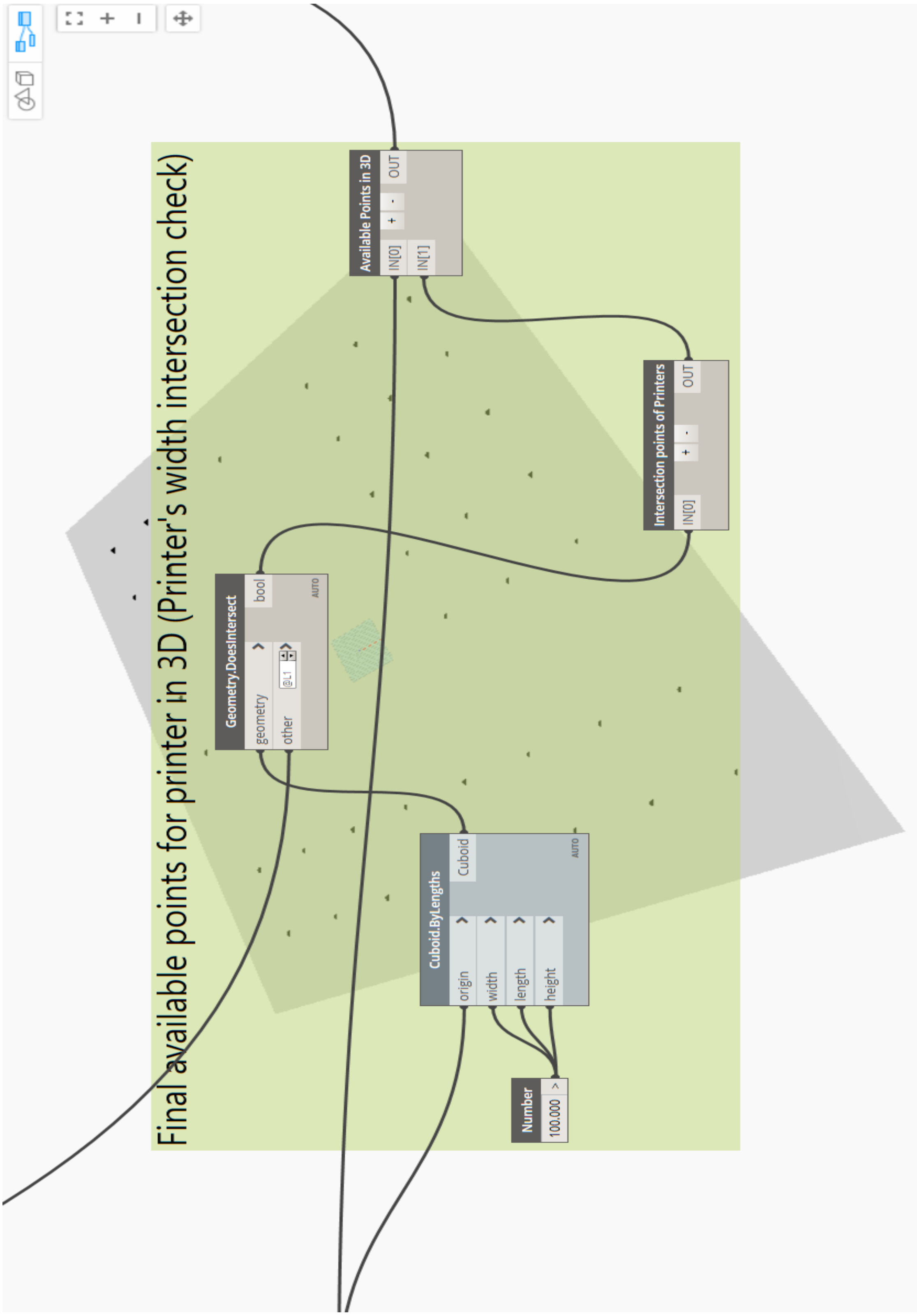

Figure A. 4: "Cuboid.ByLengths" and "Geometry.DoesIntersect" node group for simulating which points are unavailable because when the printer located over a spesific point, printer is intersecting with a wall due to the space that the 3D printer takes up.

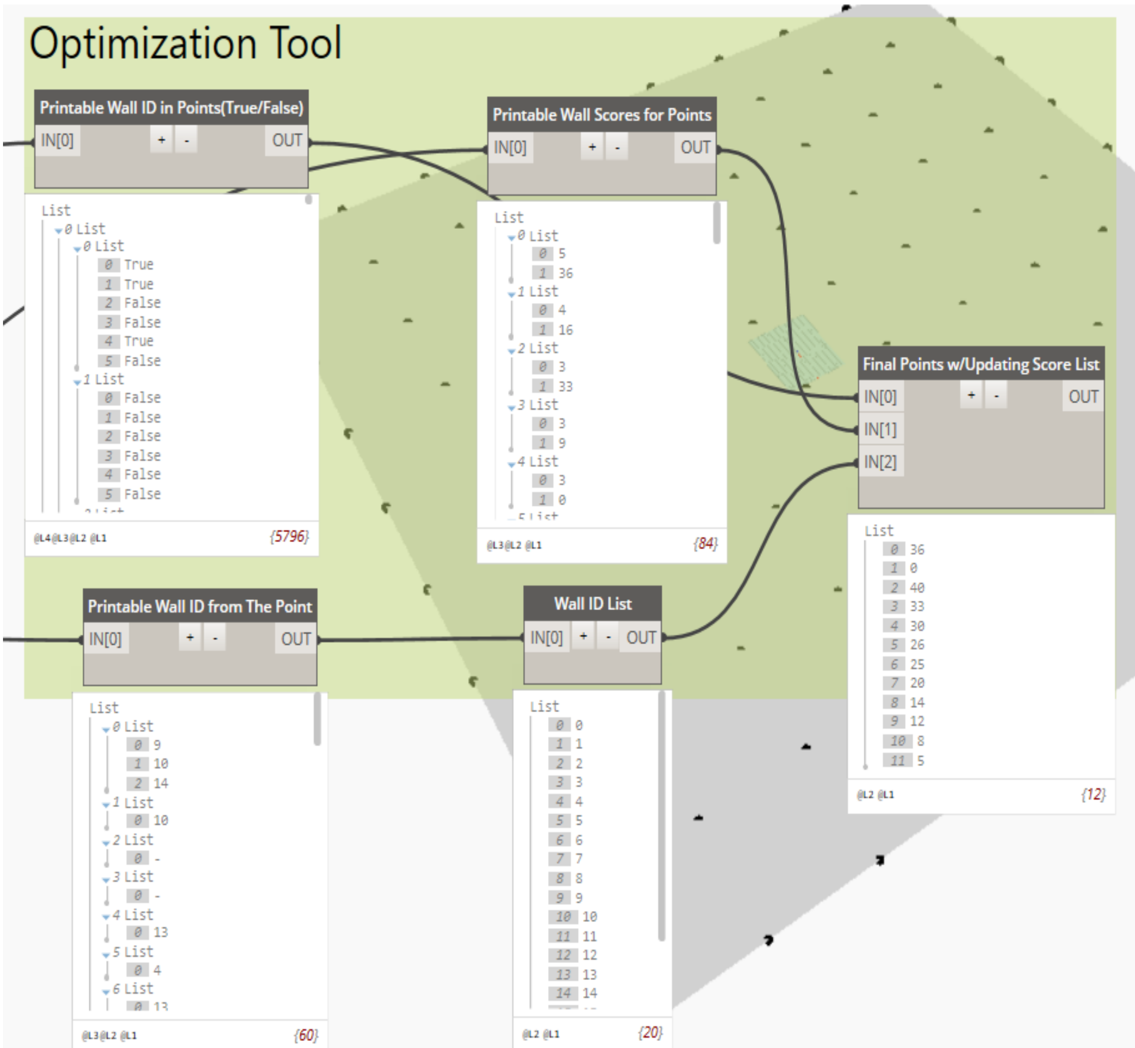

Figure A. 5: Created optimization tool with **"Python.Script"** nodes group for examining which walls can be printable from which spesific point, which point has higher wall printability score according to others and finally how many relocation steps need for the printer to complete all project printing sequence with minimum relocation count and shortest path

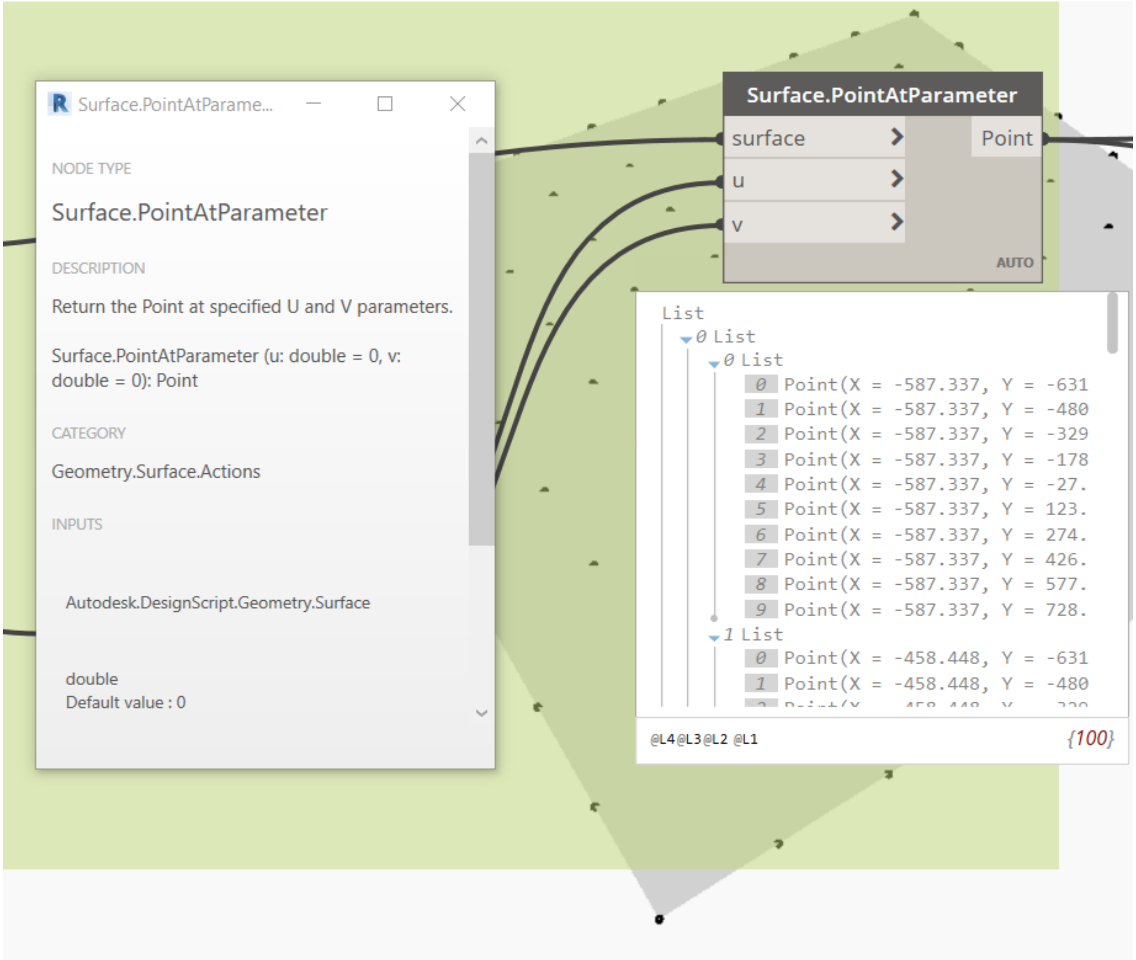

Figure A. 6: The working system of the **"Surface.PointAtParameter"** node for determining grid sizing over the used area with creating u and v division from the sides of the area

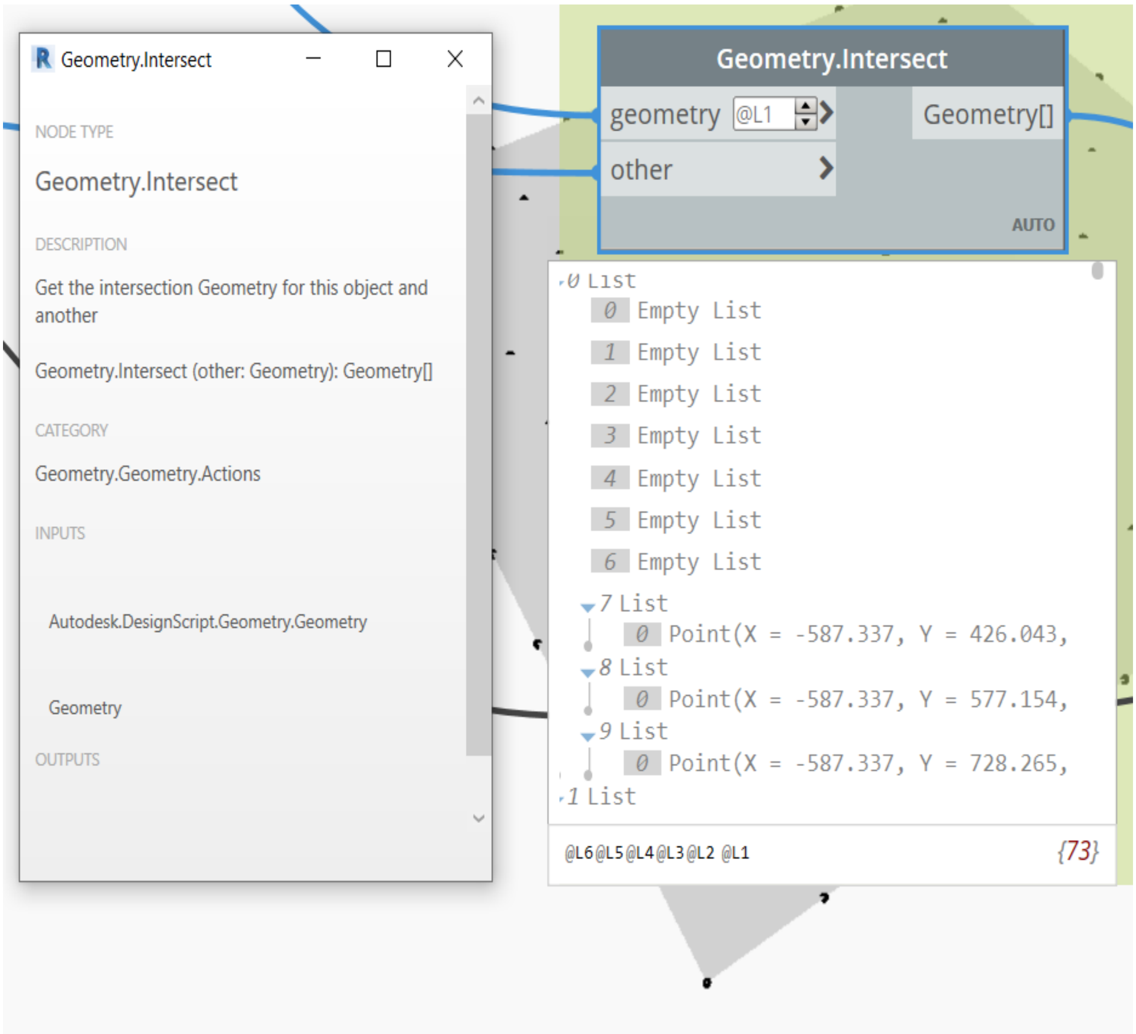

Figure A. 7: The working principle of **"Geometry.Intersect"** node for examining to different geometries finding the interfered area between this two different geometric objects such as overlapping area between wall surfaces and slab area of the project

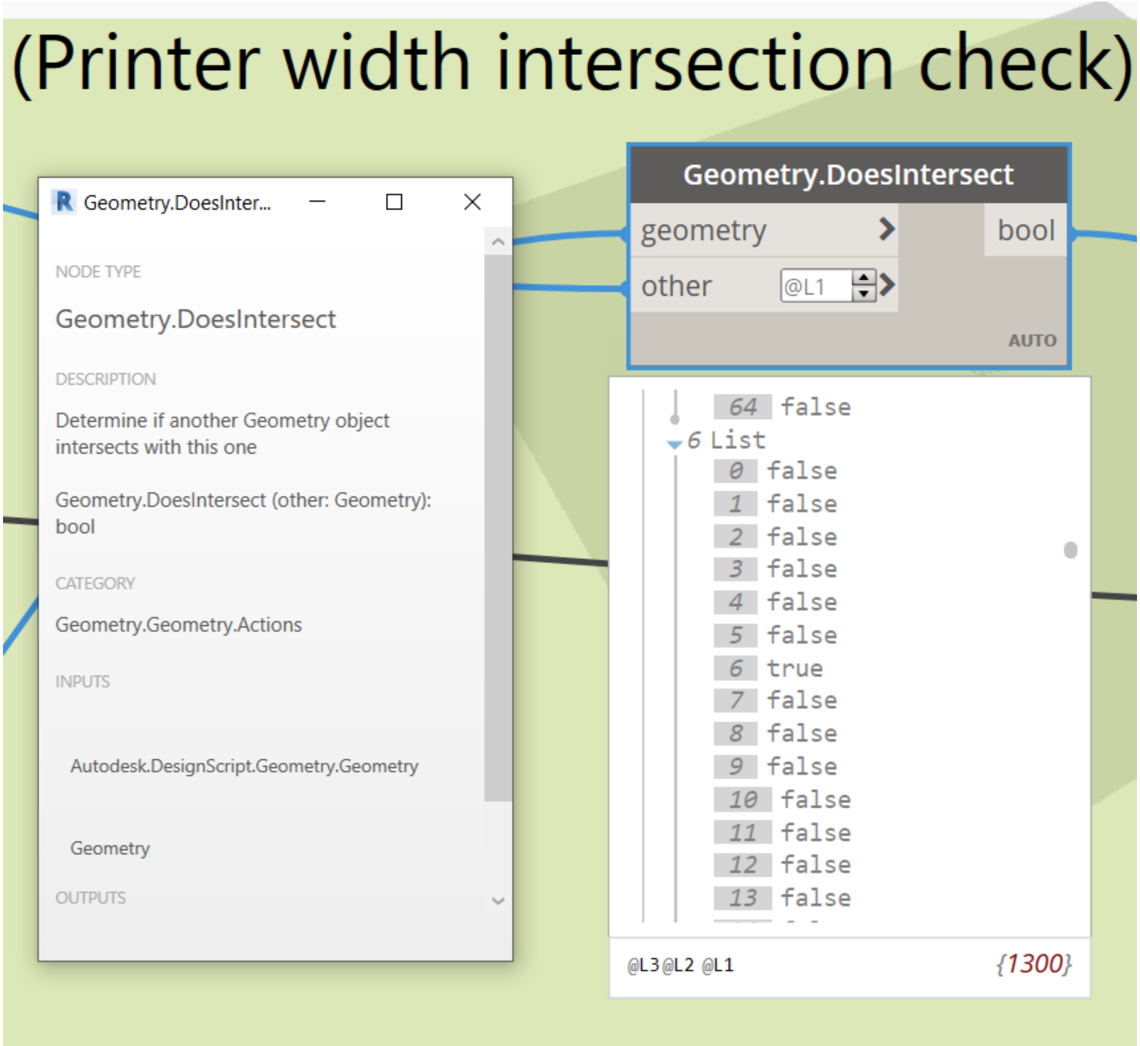

Figure A. 8: The working system of the **"Geometry.DoesIntersect"** ready-built node block for understanding that is there any intersecting points existing between two different objects or geometries. If node block shows true result that means examining objects are intersecting with each other.

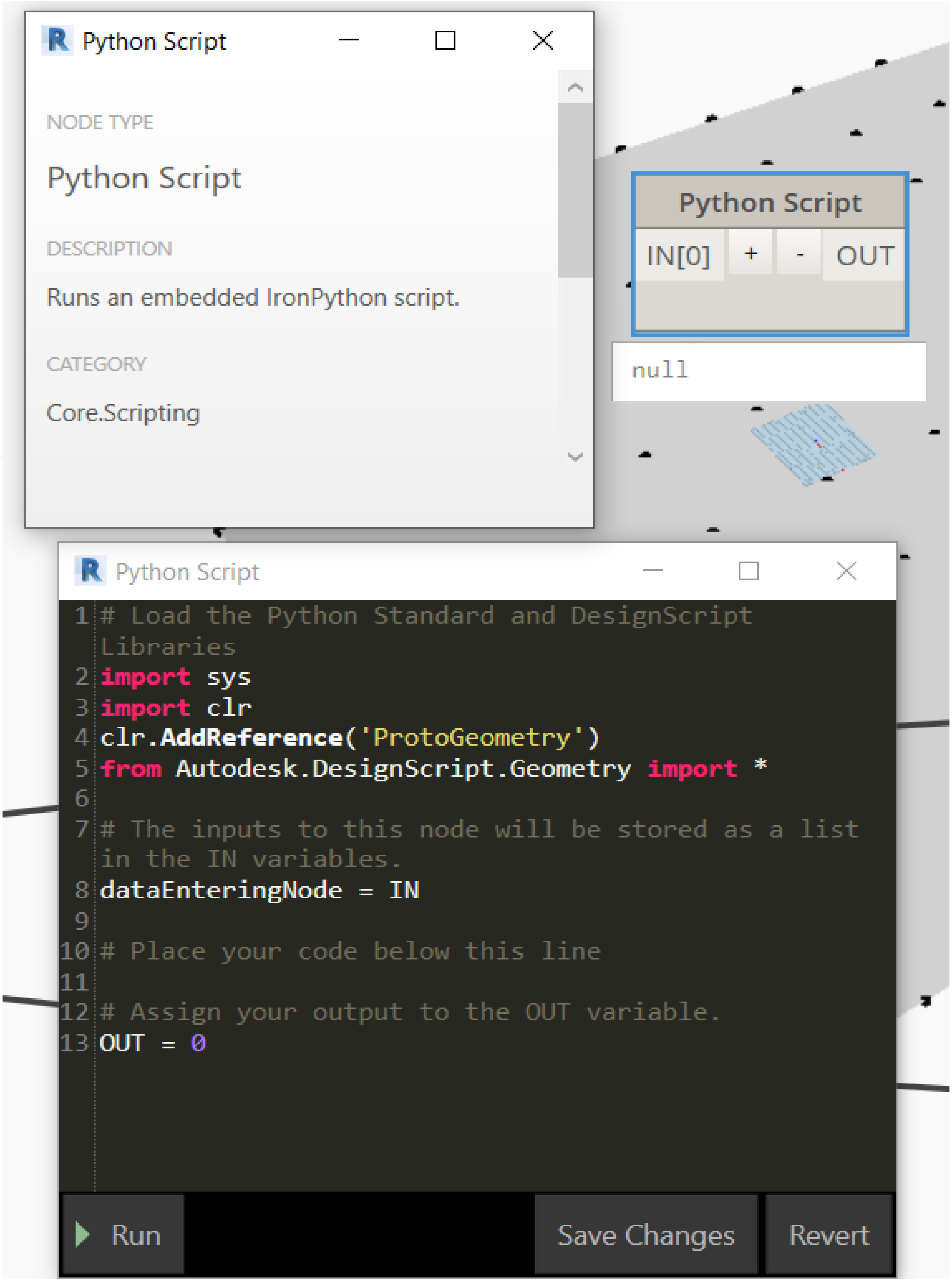

Figure A. 9: "Python.Script" ready-built node block of the Dynamo and its working interface on the Dynamo which allows creating Python Scriptings for examining different variables, creating some loops, lists or making some algortihms for investigating several data coming from the project.

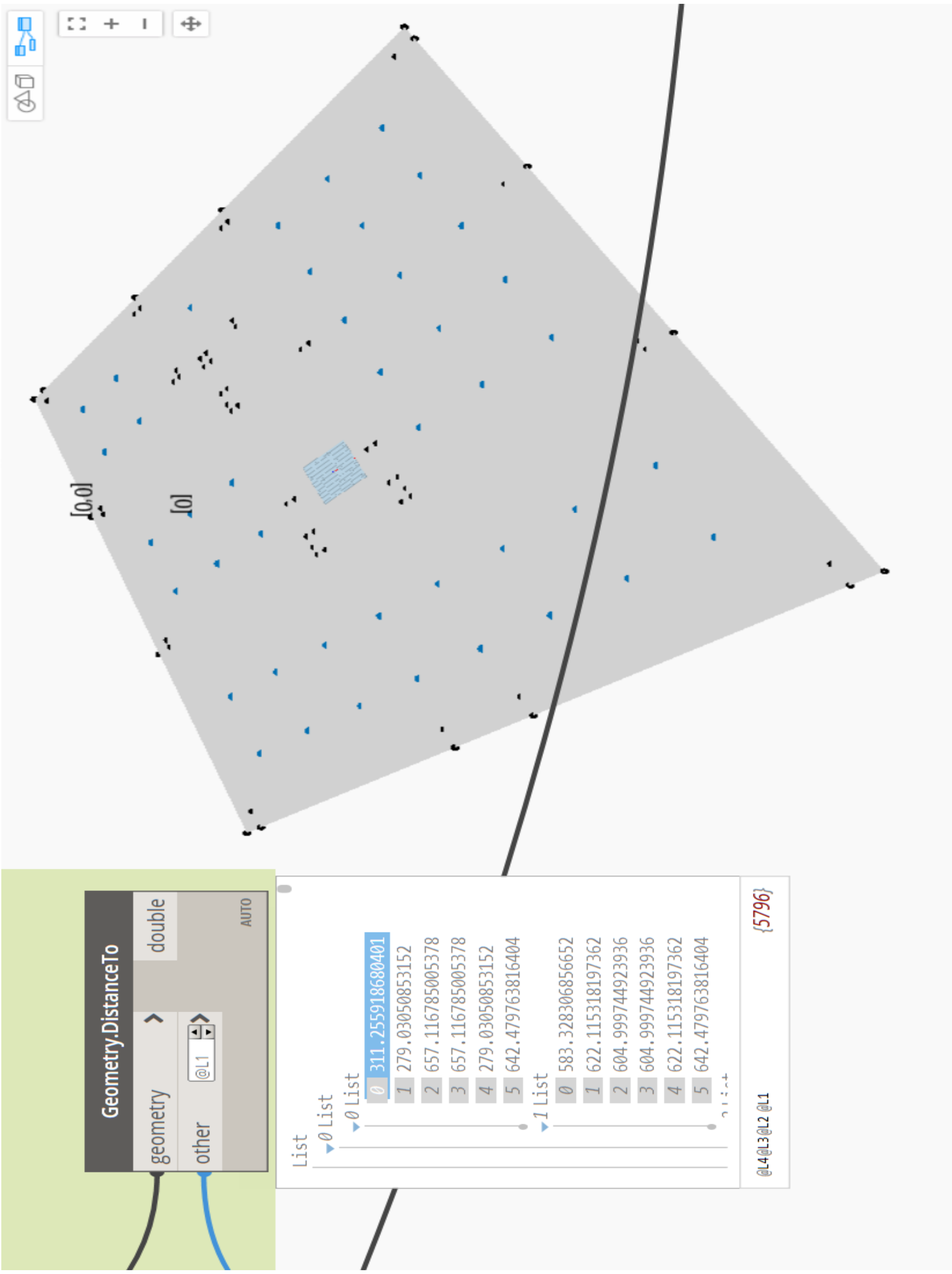

Figure A. 10: "Geometry.DistanceTo" ready-built node in Dynamo for understanging distances between different points over the project. This node represents the distance **(311.25 cm)** between **Point"0"** from the final possible point list and **Point[0,0]** from the wall edge points list which means **Edge "0"** of **Wall"0"**.

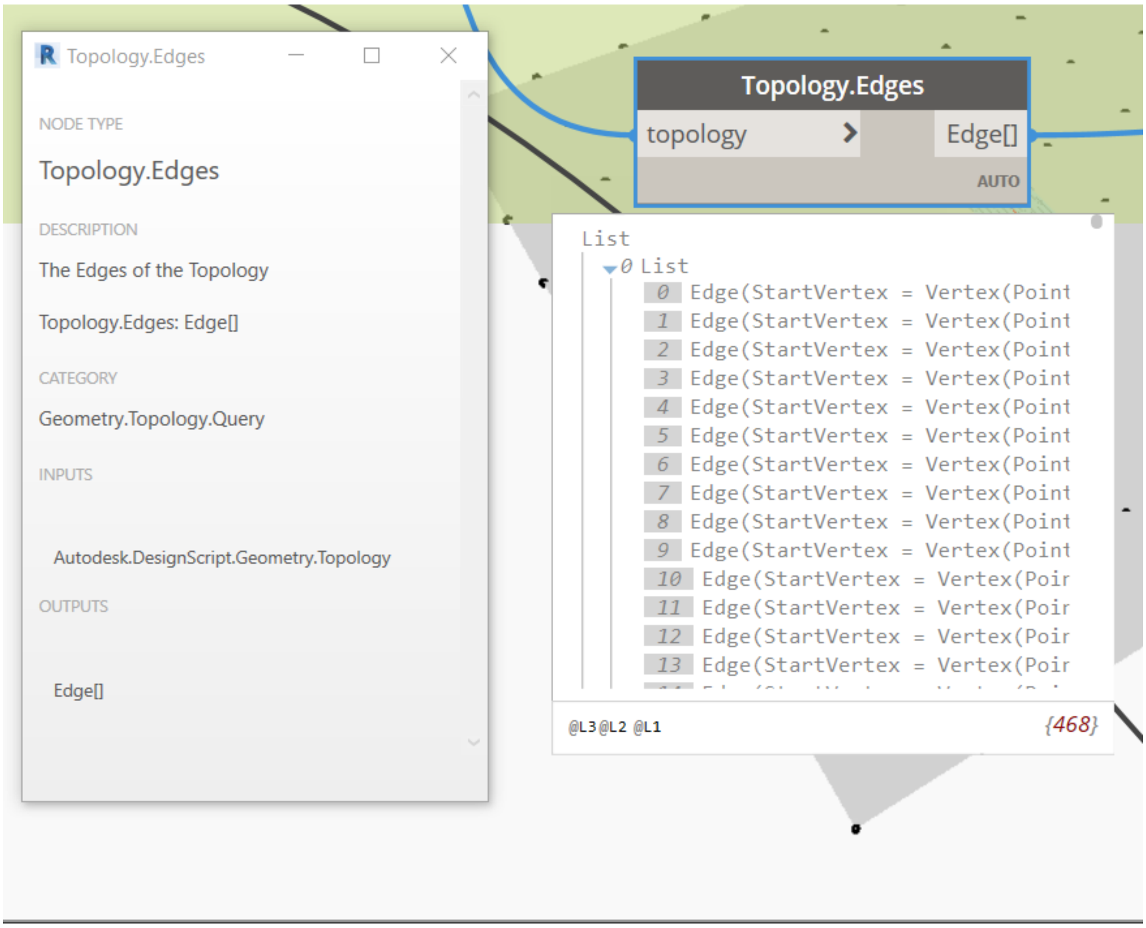

Figure A. 11: "Topology.Edges" ready-built node of the Dynamo for determining edge points of the walls (most distant points) for examining when printer is located over a point these edge points can be reachable from this location or not.

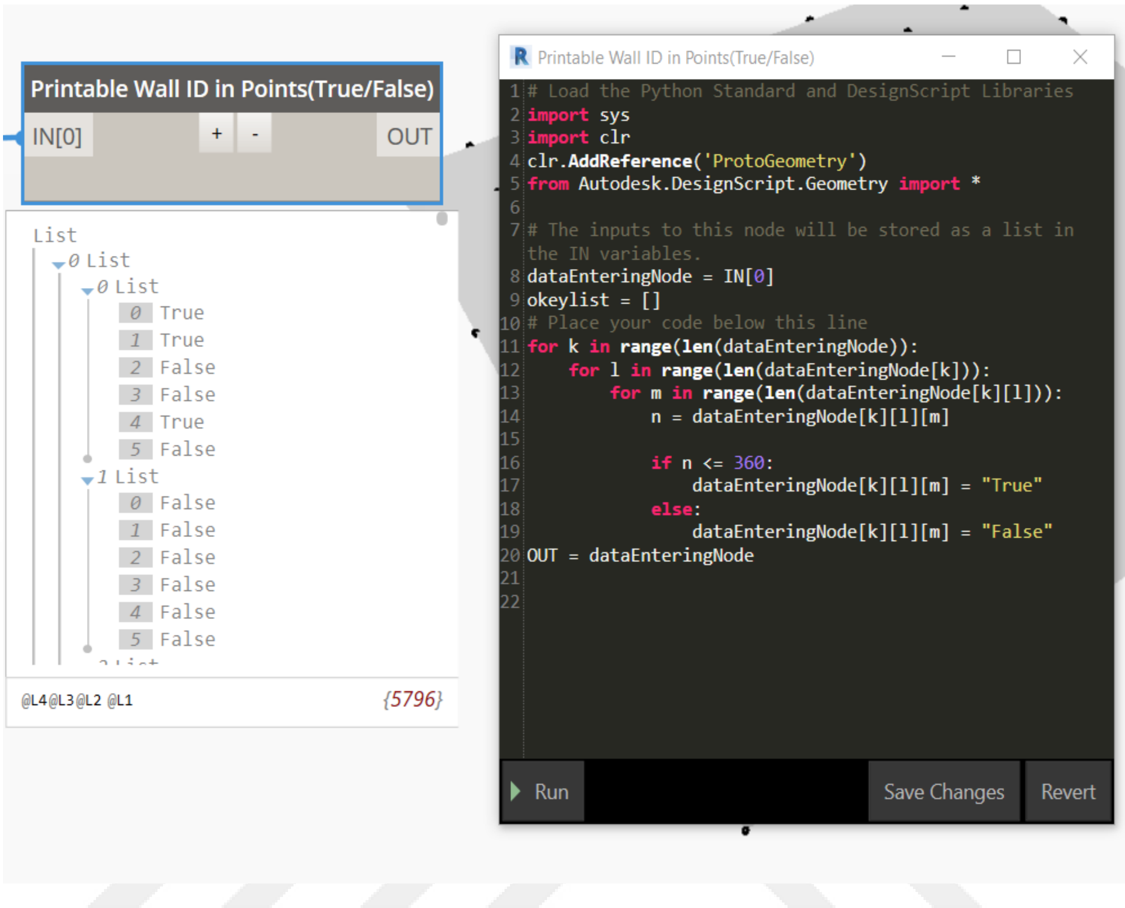

Figure A. 12: The detailed coding works and algorithms were applied behind the **"Printable Wall ID in Points(True/False)"** node block which were created for examining printability of the walls from the points.

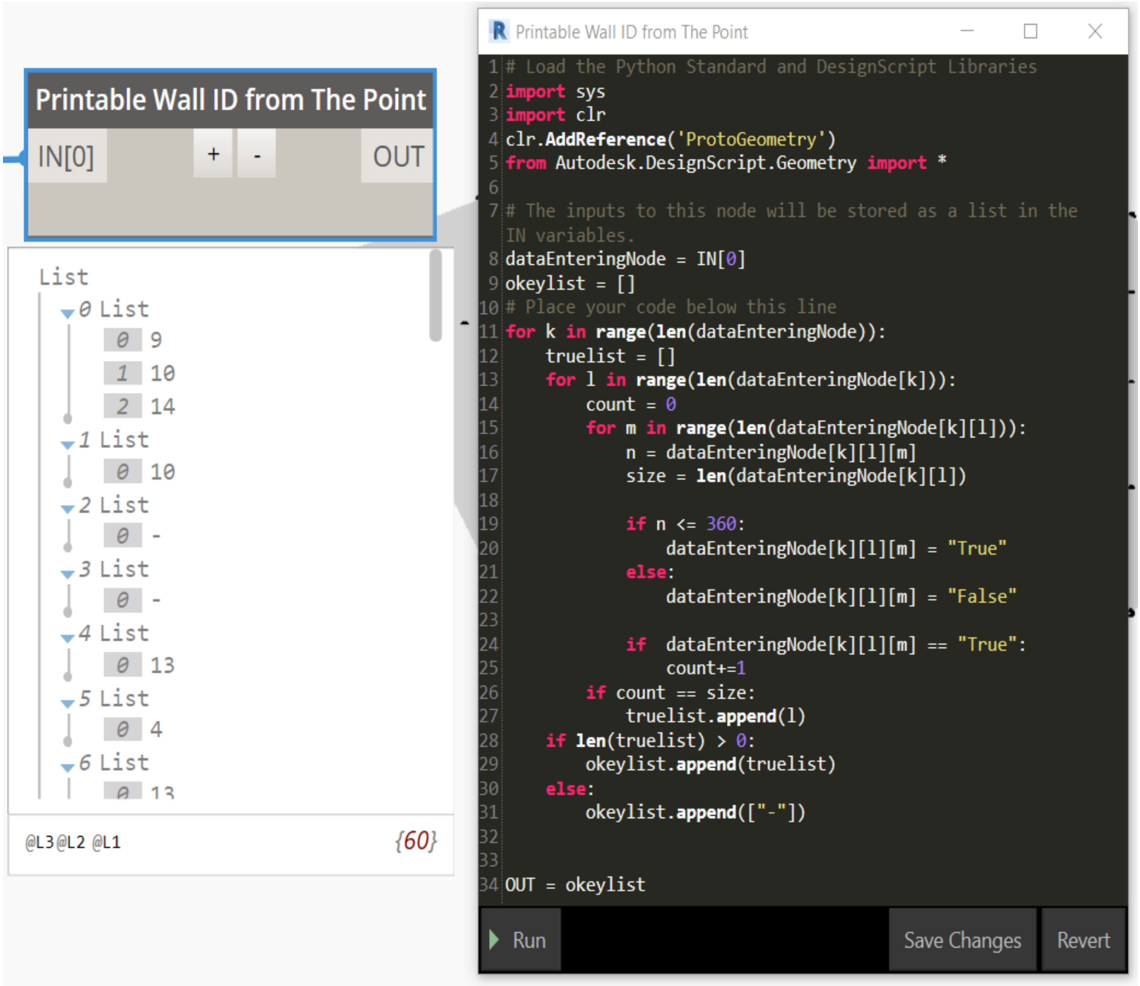

Figure A. 13: The detailed coding works and algorithms were applied behind the **“Printable Wall ID from the Point”** node block which were created for examining that which wall can be printable from which spesific point.

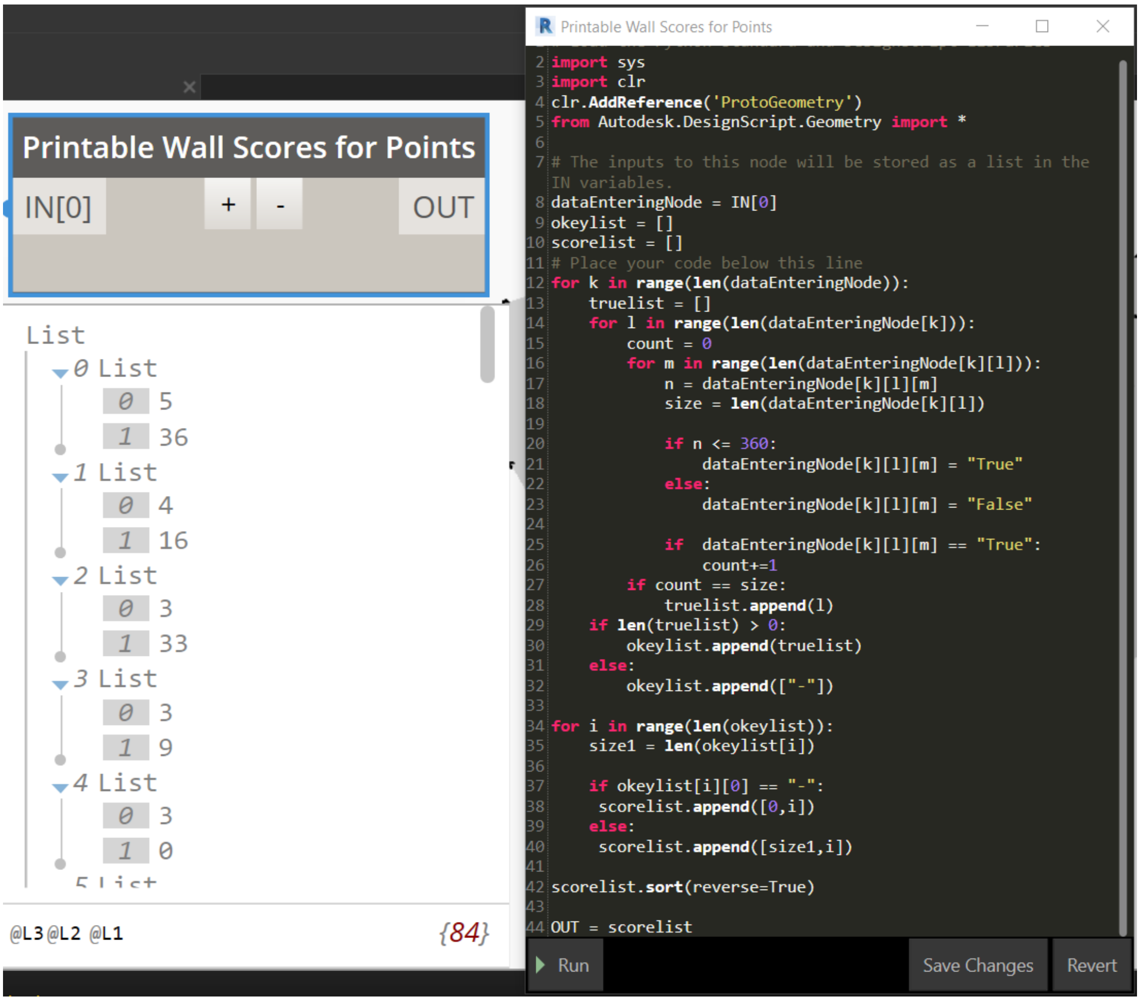

Figure A. 14: The detailed coding works and algorithms were applied behind the **"Printable Wall Scores for Points"** node block which were created for examining that which point can print more wall according to the others.

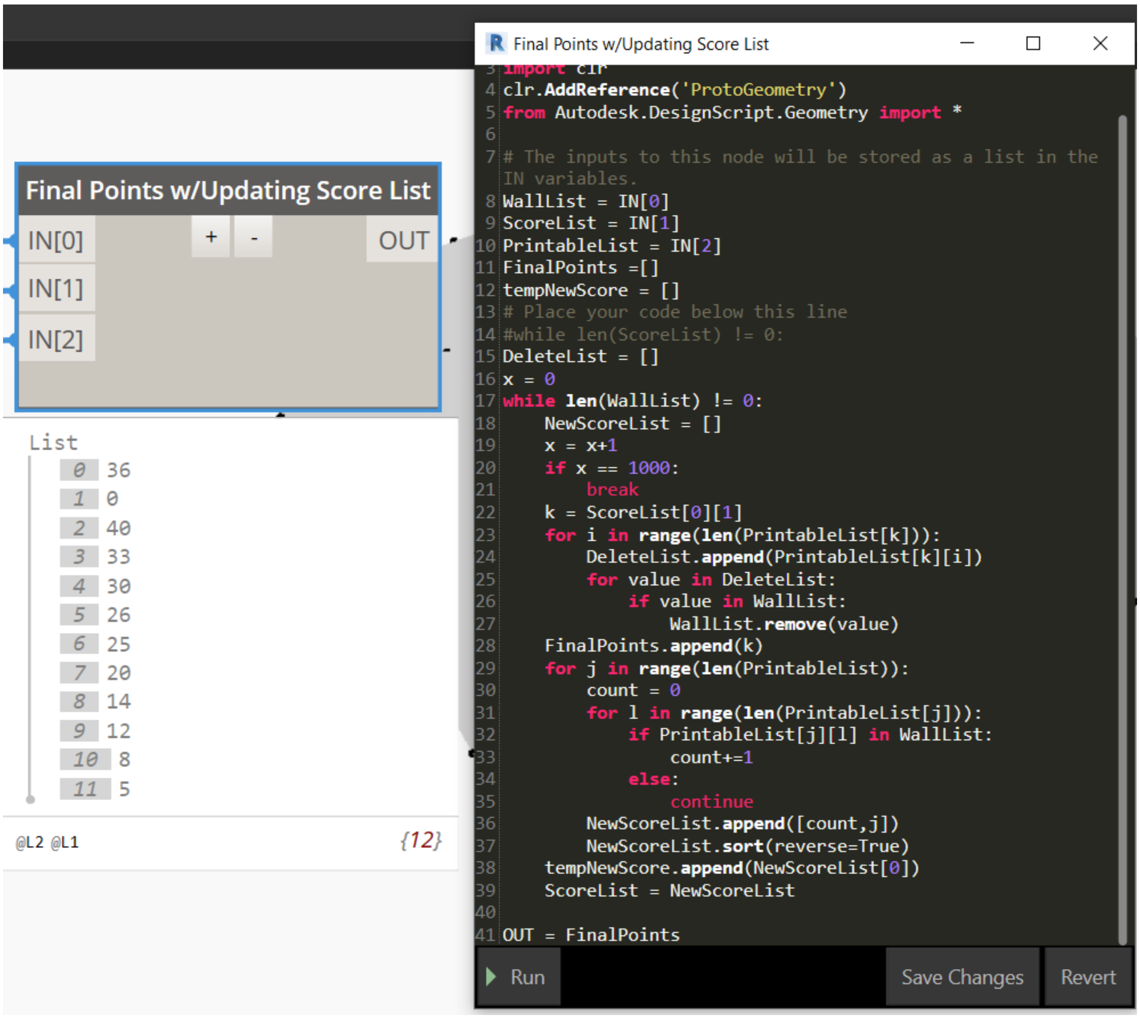

Figure A. 15: The detailed coding works and algorithms were applied behind the **"Final Points w/Updating Score List"** node block which were created as final tool to determine minimum step counts to relocate the 3D printer in the construction area for completing all printing process of the project.

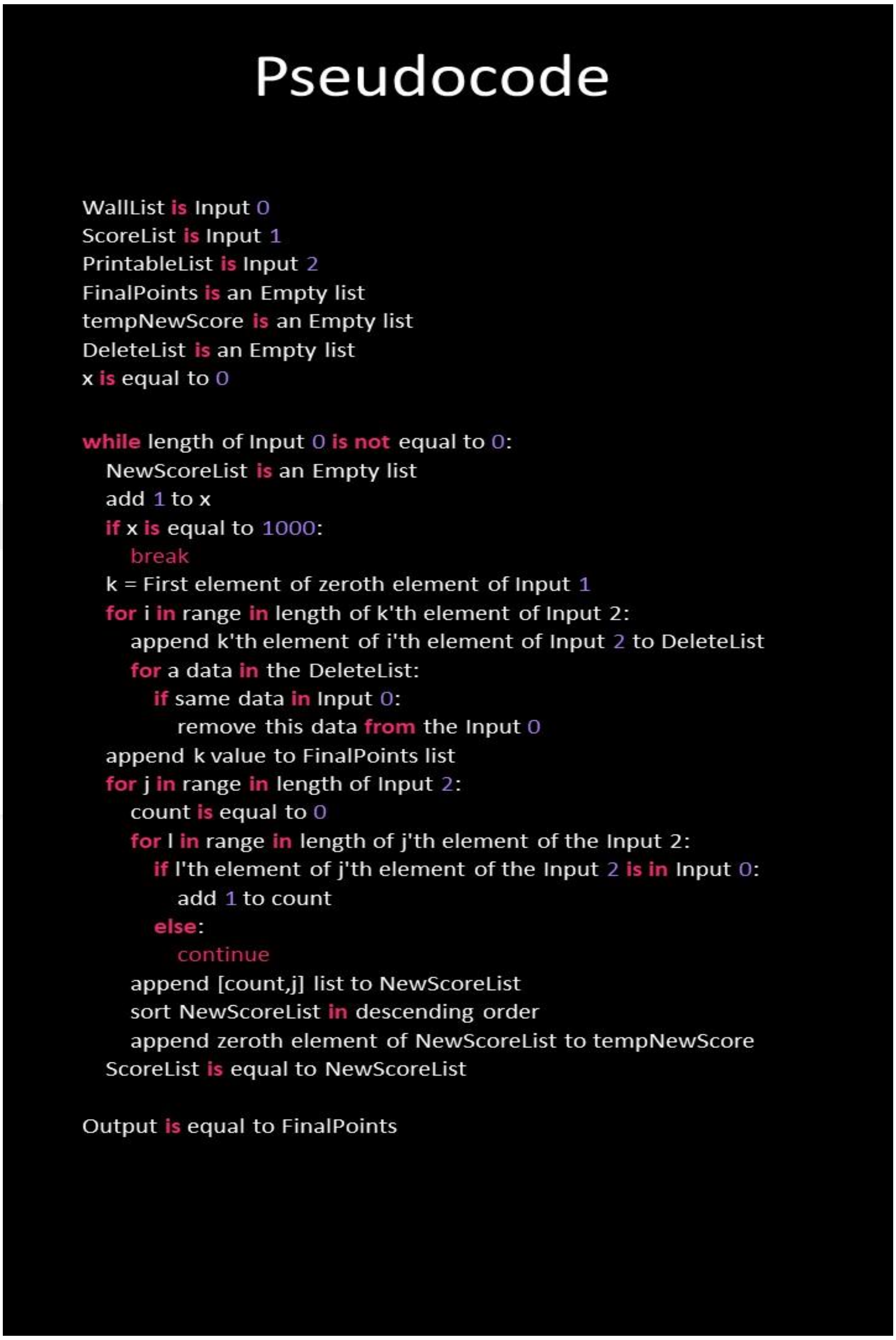

Figure A. 16: The detailed coding explanation step by step as an example of Pseudocode

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VITA

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