buildings

Article

Automated Layout Design Approach of Floor Tiles: Based on Building Information Modeling (BIM) via Parametric Design (PD) Platform

Shihai Wu [1,2], Nan Zhang [1,*], Yujing Xiang [1], Dizi Wu [3], Danping Qiao [1], Xiaowei Luo [2] and Wei-Zhen Lu [2,*]

[1] School of Architecture and Art, Central South University, Changsha 410083, China; shihaiwu2-c@my.cityu.edu.hk (S.W.); xiangyujing@csu.edu.cn (Y.X.); qiaodanping@csu.edu.cn (D.Q.)
[2] Department of Architecture and Civil Engineering, City University of Hong Kong, Hong Kong SAR, China; xiaowluo@cityu.edu.hk
[3] School of Architecture, Changsha University of Science and Technology, Changsha 410004, China; diziwu@hotmail.com
* Correspondence: zhangnan_archi@163.com (N.Z.); bcwzlu@cityu.edu.hk (W.-Z.L.)

Citation: Wu, S.; Zhang, N.; Xiang, Y.; Wu, D.; Qiao, D.; Luo, X.; Lu, W.-Z. Automated Layout Design Approach of Floor Tiles: Based on Building Information Modeling (BIM) via Parametric Design (PD) Platform. *Buildings* **2022**, *12*, 250. https://doi.org/10.3390/buildings12020250

Academic Editors: Elena Ferretti, Nikos A. Salingaros, Alexandros A. Lavdas, Michael W. Mehaffy and Ann Sussman

Received: 6 December 2021
Accepted: 18 February 2022
Published: 21 February 2022

Abstract: Building Information Modelling (BIM) technology has been widely used in the construction industry in recent years. However, to date, it still cannot sufficiently meet the requirements of construction practitioners in terms of the layout design of floor tiles. Recently, the BIM-based Parametric Design (PD) platform has presented considerable potential in automatically generating and optimizing floor tile layout design. In this paper, we propose a workflow to generate and optimize the layout design of floor tiles globally. To develop the workflow, we first formalize the design algorithm of floor tiles according to the trade know-how cutting and planning rules. Then, we combine the design algorithm with an evolutionary algorithm (EA) to generate and optimize the layout design for floor tiles automatically while minimizing material wastage. A prototype system is established in the ArchiCAD (BIM) and Grasshopper (PD platform) software. An apartment room tiling layout is used to demonstrate the feasibility and effectiveness of the proposed approach. Compared with the existing design methods, the proposed approach (1) reduces the material waste rate by 14.58% and 11.46%; and (2) improves the calculation efficiency and reduces the required computation time by 17.3 s to 50.0 s. Moreover, this research improves the existing design algorithm, enabling the BIM- and PD-based approaches to be used reliably in optimizing floor tile planning with arc-shaped boundaries. The outcomes are summarized in order to provide valuable insights in terms of floor tile waste reduction for further sustainable construction practice.

Keywords: BIM; Parametric Design (PD); automated floor tile design; evolutionary algorithm; material waste minimization

1. Introduction

Floor tiles are some of the most essential construction materials used in floor decoration [1]. However, the production process of floor tiles has adverse environmental effects. For example, ceramic tiles, a type of floor tile, require high-temperature firing in factories for their production, leading to high energy consumption and significant pollutant emission [2,3]. The United States Environmental Protection Agency reports that the process of ceramic tile production emits an average of 0.23 kg of HF/t, 0.27 kg of NO_x/t, 1.6 kg of CO/t, 2.4 kg of SO_2 kg/t, and 300 kg of CO_2/t, thereby posing a serious threat to human health [4–7]. The annual consumption of ceramic tiles reached 13 billion square meters in 2020, and more than half were used as floor tiles [8,9]. Based on this, the research of how to reduce the waste of floor tiles in the construction project life-cycle, to achieve the purpose of environmental protection, has attracted widespread attention [10].

It has been reported that the refined design is one of the most significant influencing factors in the life cycle of a construction project in terms of material waste reduction [11,12].

A well-designed method can effectively improve material processing and use efficiency and reduce rework rates, reducing waste by up to 40%, which means fewer harmful gas emissions [13]. In addition, the introduction of advanced technology to improve construction is linked to reducing material waste, which is also inseparable from adequate design support. Gharbia et al. [14] reviewed the rapid development of construction-site robotics, noting that robotics can demonstrate greater efficiency and lower cost than manual labor in tile-related engineering. The accurate and comprehensive design support enables robots to effectively replace human labor, reduce experience-based decision-making and manual operations, and demonstrate a new way of revolutionizing construction while reducing tile materials and labor waste.

Regardless of manual or robotic technologies, architects need to preplan the floor tile material on the construction drawing in the tile-related engineering [15,16]. Preplanning should theoretically include accurate floor tile cutting and laying, as well as reuse planning to guide subsequent engineering steps, such as procurement and construction [17]. In a preplanned system, the overall arrangement and management of uncut and cut tiles should be comprehensive and detailed in order to provide comprehensive and accurate material preplanning in terms of graphical and numerical results. However, due to the current design-aided approaches focusing on simulating manual-based design methods and lack of attention to cut tiles, the architects lack proper tools to generate comprehensive and accurate design results. On this basis, the further optimization of floor tile design to minimize the material waste rate from a design perspective is impossible due to the lack of overall control of floor tile preplanning. In order to promote the sustainable development of floor tile-related engineering, it is an urgent task to propose an approach that enables architects to generate the preplanning results of floor tiles comprehensively and accurately while minimizing the material waste rate effectively.

1.1. The Current Design-Aided Approaches of Floor Tiles

In current design practice, architects cannot provide accurate cutting, reuse planning, or the exact required purchase quantity of floor tiles on shop drawings, due to the lack of appropriate design-aided approaches [18–20]. Such shop drawings affect a series of subsequent tile-related engineering links. For example, procurement engineers can only make procurement estimates based on industry benchmarks (e.g., 10–20%, as stipulated in the industry guidance manual of Hunan Province, China [21]) rather than specific projects. Furthermore, due to the lack of comprehensive and accurate preplanning, construction practitioners make ad hoc decisions on cutting and reusing tiles based on rules of thumb and experience rather than comprehensive and accurate preplanning, to minimize tile waste [11,22]. Ding and Xiao's [13] research confirmed that industry standards and empirical judgments generally lead to higher waste rates than accurate design guidance, indicating that the material waste rates can locally exceed 20% of the theoretical optimal value. Additionally, Liu et al. [23] studied from a construction perspective, showing that the cutting and reuse decision method based on industry benchmarks and experience resulted in much material waste and rework on the construction site, which has a significant negative impact on the industry's sustainable development.

Existing floor-tile-design-aided tools lack the ability to provide comprehensive and accurate graphical and digital results, partly because their historical development has focused on improving manual design simulations rather than overall layout preplanning. The first design-aid tools to assist the architect in conducting the layout design of floor tiles can be traced back to the invention of Computer-Aided Design (CAD) tools [24,25], enabling architects to use digital drawing methods instead of paper and pen to draw horizontal and vertical lines. The invented CAD tools methods have been iteratively optimized in subsequent decades, from the early limitation of simulating pen and paper to the later provision of multiple computing and linking functions [26–28]. This is a universal architectural design-aid tool, not only for floor tile design but also for other aspects of the AEC industry. Later, in order to optimize floor tile design in a more targeted way, the Nation

Tile Contractor Association (NTCA) launched a particular design-aided tool for floor tile optimization [29]. NTCA has advanced the work of floor tile design from the simulation of pen and paper drawing to automated estimation based on particular input room layout, and then output the estimation-based graphics and digital results. Although the estimates are based not on accurate calculations but on industry experience, NTCA's work has improved the accuracy of the estimates by evolving them from experience-based estimates to project-specific estimates. NTCA's work provided a pathway for developing specialized tools for floor tile design, and a series of floor tile design-aided tools were developed. For example, Autodesk Labs developed a series of specific tools (e.g., Roombook for Revit and Tile design plugins for 3d Max [30,31]) to aid architects in improving design efficiency. The developed specific design-aided tools enable users to obtain the tile planning based on the input tiling area information; the tools then output the results, including graphical and numerical, as the standard format (i.e., Design Web Format) for user's further application. The specific design-aided tools developed by organizations like Autodesk Lab are significantly more accurate than NTCA in terms of design accuracy [30,31]. However, these tools still overlook the attention on the cut tiles and do not focus on the global cutting and reuse of floor tiles, and they cannot provide users with truly accurate results (i.e., graphical and numerical) [17]. As a result, procurement and construction engineers are still working based on estimates, and the waste of materials and labor has not been substantially addressed. Recently, Wu et al. [17] proposed a goal-oriented optimization method for floor tile layout, which reduced the material waste rate. However, there are still two defects in Wu et al.'s method. First, because the design algorithm of Wu et al. is based on "cyclic logic: overlay—cut—overlay", it is easier to fall into a cycle in the calculation than from the perspective of "global consideration", resulting in less efficient calculation, and the optimization process falls into the trap of local optimization [17,32]. Second, due to the defects of the reused module (i.e., Opennest [33,34]), it may segment too much when dealing with the curved boundary, so that the curved cutting and reuse problems on the boundaries may not be properly dealt with. As a result, the design algorithm proposed by Wu et al. has the risk of miscalculation when dealing with the floor tile layout optimization related to the arc-shaped boundaries. These two defects show that the method of Wu et al. still (1) has a possibility of improving computing efficiency; (2) is necessary to improve the arc-shaped cutting algorithm and related research on waste rate reduction to expand its applicability.

Optimization methods of similar building materials may have potential reference significance to solve the mentioned problem. Manrique et al. [35] developed a preplanning method for Oriented Strand Boards (OSB), which effectively globalized the preplanning design of the OSB and reduced the material waste rate by paying attention to global planning of cutting and reuse. Moreover, the method developed by Manrique et al., from the global perspective, adopts the method of "cutting and distributing" rather than the logic of repeated superposition to carry out the layout planning of OSB, which effectively improves the calculation efficiency. Liu et al. [11] proposed a "cutting-distributing-generating" optimization design algorithm focusing on boardings' global preplanning of cutting and reuse. Liu's research shows that by preplanning the cutting and reuse of boardings globally, the waste rate of all building boards has been reduced by about 5% (compared with the industry benchmark) while effectively reducing rework by workers and improving the benefits of multiple stakeholders. More theoretically, Mellouli et al. [36] deeply discussed the relationship between the reuse and planning of two-dimensional cutting building materials and the output of accurate graphics and numerical results. Mellouli et al. indicated that preplanning for cutting and reuse from a global perspective is more conducive to producing precise results while minimizing the waste of two-dimensional cutting materials. Later, Liu et al. [23] identified global cutting and planning methods that efficiently output accurate designs and implemented them in the design of light-frame structures, reducing material waste rates by 12.1% and 12.9%.

Briefly, existing design-aid methods lack a global plan for cutting and reuse, resulting in floor tiles that cannot be accurately calculated and laid out by architects. The design uncertainty brings about a lot of labor and material waste in the subsequent engineering stages. Previous studies have shown that preplanning with a global focus on cutting and reusing similar building materials can accurately calculate material layout and numerical results, and further reduce labor and material waste rates. Such research provides a pathway for floor tile layout optimization. In addition, although Wu et al. [17] have paid attention to the relationship between cutting and reuse of floor tiles and used it to reduce the material waste rate, their research still has two problems to be solved: (1) optimizing the layout design from the global perspective, and (2) dealing with arc-shaped boundaries.

1.2. BIM and Parametric Design (PD) Approach

Recently, Building Information Modeling (BIM) technology has been seen as having the potential to meet the demands of excellent design in terms of improving design accuracy and reducing material waste [37]. In a BIM platform, users can input the details of thousands of building components in a single file while accurately simulating their design and construction. The waste rate of building materials thus can be gradually reduced owing to the iterative design and testing of the inputted building components [38–40]. Over the past few years, various applications of BIM technology have been proposed to reduce material wastage in engineering practice, such as the detailed design of materials, site management, and supply chain management [41–43]. However, due to the fact that the BIM software itself cannot provide data collection and analysis functions for the inputted information of building components, designers are essentially simulating manual drawing when using BIM software for floor tile design [17].

The application of a BIM-based Parametric Design (PD) approach may help solve this problem. The PD enables users to code design rules and algorithms (i.e., design decisions) into computer languages based on the required design logic [26]. Such an approach provides access to computational model data and automates the computation and optimization of repetitive and complex design tasks through programming. PD approach and BIM build a symbiotic environment, that is, BIM provides digital information of building components, and PD, as a data processor, provides building components based on design logic, to realize the user's intention [44]. On this basis, the primary conditions are available to establish "bottom-up" generative logic to dominate the building components and achieve precise global materials optimization. In addition, the logic-based generative design approach can be combined with the evolutionary algorithm (EA) to achieve goal-oriented design optimization. Such integration of design algorithm and EA enables the users to complete a high-precision design while achieving goal-oriented design optimization for design results. For example, Liu et al. [23] developed a logic-based design algorithm based on the BIM-based PD approach and then integrated it with a greedy algorithm to obtain a minimized waste rate of materials, reducing the material waste of the roof sheathing by approximately 8%. Banihashemi et al. [45] proposed a workflow that includes a design algorithm and the genetic algorithm, intelligently optimizing the planning of vertical and horizontal modules of building materials by programming generative design algorithms on the BIM-based PD platform, reducing the panel waste volume by more than 2%.

There has been an increasing amount of research on the design optimization of building materials to improve design accuracy and reduce material waste by using the BIM and PD approaches [44,46,47]. The previous research shows a possibility to conduct global floor tiles optimization while minimizing material waste. However, the application of this method to the optimization of floor tile design is still yet to be realized, according to the authors' knowledge. The current methods based on BIM and PD oriented to optimizing floor tile design still focus on better simulating manual design and even optimizing floor tile pattern [48,49]. Such tools cannot aid architects in globally optimizing the layout design of floor tiles, partly due to the developers not paying attention to the preplanning of cutting and reuse of the cut tiles [17]. Therefore, even though BIM and PD approaches have been equipped with the foundation of auxiliary floor tile design, the labor and material waste caused by floor tile planning, procurement, and construction based on manual design and estimation are still unchanged in the current engineering practice.

1.3. Amis of This Research

This research aims to propose a workflow to globally generate and optimize the layout design of floor tiles while minimizing the material waste rate by using BIM and PD approaches. The research gaps and objectives of this research are summarized as follows.

Because the global cutting and reuse of floor tiles are ignored, the current design-aided tools for floor tile design cannot provide accurate details. As a result, the current floor tile design, procurement, and construction are still based on estimation, with long-term estimation resulting in a large amount of labor and material waste. Although several scholars [17] have studied and discussed this problem and put forward solutions recently, referring to similar material layout optimization problems, two issues still need to be addressed. First, previous studies have shown that computing from a global perspective, rather than a local perspective, can effectively improve efficiency and avoid falling into the local optimization trap. Second, due to the design defect of the "cutting and reusing" module, the layout design of the arc-shaped boundaries cannot be generated reliably [17,34], resulting in the limitation of the applicability of the design algorithm. A global design algorithm based on "cutting-distributing" logic is proposed in this research to address the challenges. The proposed design algorithm meets the current demand of producing accurate graphic and numerical results. Moreover, the proposed algorithm enhances the computational efficiency of the existing design algorithm and solves the problem that the arc-shaped boundaries cannot be reliably dealt with, improving the adaptability of the design algorithm in complex engineering requirements.

The BIM and PD approaches demonstrate the potential for precise floor tile preplanning while minimizing material waste. In the BIM and PD platform, the design logic can be programmed as a design algorithm to generate the building components' accurate planning and then combine the developed design algorithm with EA to minimize the material waste. In order to verify the proposed automated design and optimize workflow, this research develops workflow based on the programming logic of BIM and PD approaches and develops a prototype system in the corresponding platform for calculating specific cases.

The main contributions of this research are from two aspects. From the perspective of engineering practice, this research develops the existing floor tile design algorithm, adopts the global design optimization methods to improve the efficiency of the existing design, and enables it to compute the tile planning with arc-shaped boundaries reliably. On the other hand, this research verifies that the global "cut-planning" design algorithm is more efficient than the local "cycle: cut-substitution-cutting" design algorithm in calculating the layout of two-dimensional cutting materials. In addition, the differences in computational efficiencies can be further amplified by the fitting EA to search for optimal global solutions. The results lay the groundwork for further planning optimization research in terms of BIM- and PD-based two-dimensional layout design.

2. Methodology

Figure 1 shows the framework of this research. Two processes require further explanation to achieve the proposed objectives: (1) developing a floor tile design algorithm based on trade know-how cutting and planning rules, and (2) the collaborative workflow involving the proposed design algorithm and the EA. Following this, a waste analysis of the floor tile design optimization is detailed in this section.

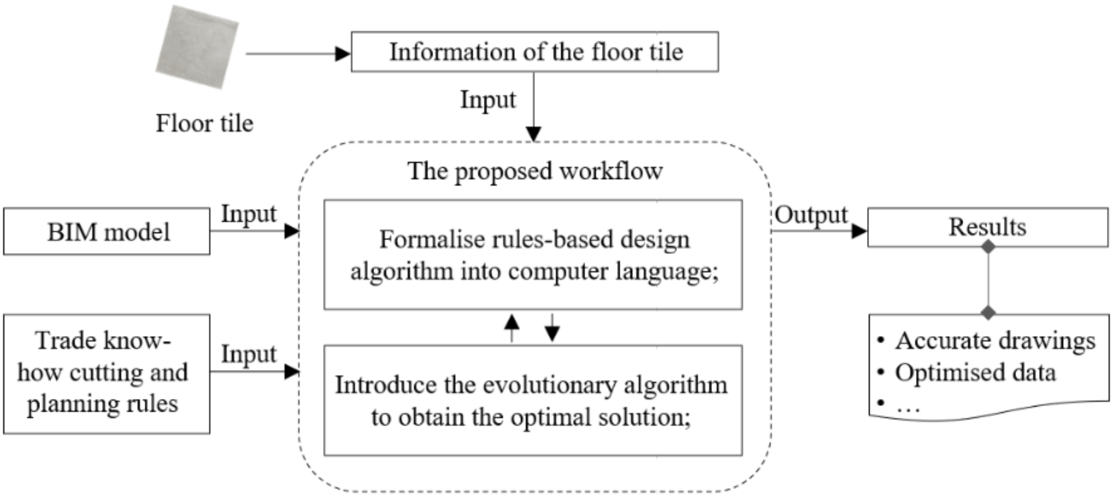

Figure 1. Research framework.

2.1. Cutting and Planning Rules-Based Design Algorithm for Floor Tile

Although the floor tile is a 3-D material, it is seldom cut apart from the thick-side in construction practice, so the optimization problem of floor tile design can be transformed into an optimal solution issue of 2-D graph cutting and planning. As such, this research focuses on the optimization process from the perspective of 2-D cutting and planning. The floor tile cutting rules commonly used by construction practitioners can be categorized into the following four types, see Figure 2: (1) cutting of the long side, (2) cutting of the short side, (3) cutting of both the long and short sides, and (4) arc-shaped cutting.

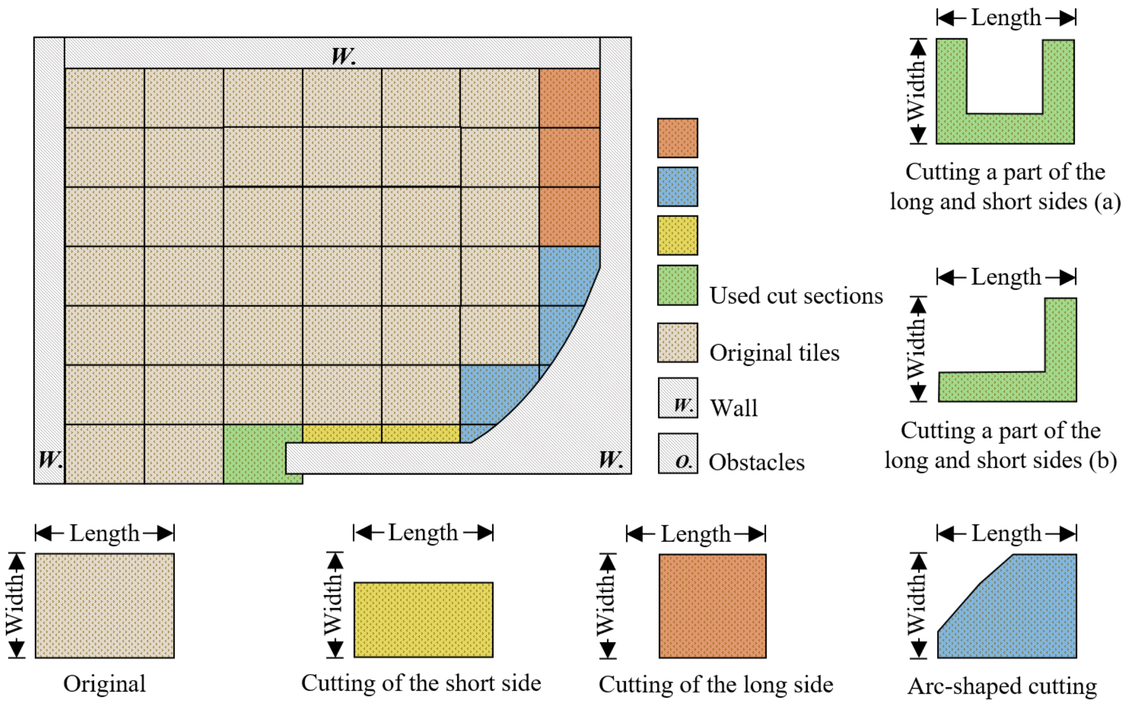

Figure 2. Cutting rules for floor tiles in the layout design.

Figure 3 shows the flowchart of the proposed rules-based design algorithm. First, input the tiling room's boundary, the floor tile's start point, and the floor tile's size. Subsequently, establish grids of floor tile based on the inputted size of a single tile to cover the entire tiling area. Following this, match the tiling room pattern with the established grids, ensuring that each grid corresponds to the room. After the matching, count the gaps between the established grid and the tiling room. Then, store the gaps information in the intermediate nodes. Since all gaps information is stored in a single intermediate node, the global search can be carried out to determine whether existing arc-shaped cutting or planning exists. If arc-shaped cutting exists, polygonal meshes will be established to ensure cutting is carried out reliably because the reuse module adopted in this research cannot correctly process the arc-shaped graphics [34]. Afterward, additional grids were cut and distributed to fill the gaps. Then, the layout of the floor tiles was completed. It should be noted that the additional grids are also stored in a single intermediate node, and the calculations for cutting and dividing will also perform a global search in the tilling area. In the process of generating floor tile layout, the number of floor tiles built in the grid is determined by the size of floor tiles and the tiling area. The lowest waste rate is to obtain the least amount of "additional grids" to fill the gap. Compared with the mainstream floor tile planning approaches [20,29,30], the "cutting-distributing" approach adopted in this research focuses on the reuse and preplanning of the cut tiles, thus effectively reducing material waste and calculating accurate information for each piece of material (e.g., see Figure 4). Compared with the recent design algorithm proposed by Wu et al. [17], the global design algorithm is adopted in this research to replace the local "cutting-replacing-cutting", aiming to effectively improve the computational efficiency. It is still worth mentioning that the cutting and reusing functions are achieved by combining the reuse tool of similar materials (i.e., Opennest) [33]. According to the experiments and the author's explanation, the method is unreliable when dealing with arc-shaped boundaries [34]. This research uses polygon meshes to avoid this problem, enabling the design algorithm of this research to reliably deal with the layout design of floor tile with the arc-shaped boundary. Refer to Section 3 for detailed implementation procedures.

2.2. Combing the Design Algorithm and the EA

The design algorithm is mainly implemented by (1) establishing grids of floor tile based on inputted information (including tiles and tiling area); (2) computing the gaps between grids and boundaries; (3) dividing additional tiles, and then distributing the divided tiles to fill the gaps. Since the design algorithm has been determined, finding the optimal solution is actually searching for the starting point of the optimal planning (i.e., with the minimized material waste rate). Figure 5 presents the collaborative workflow of the design algorithm and the EA. The design algorithm generates the initial design result based on the manually set starting point and other computational conditions (e.g., the shape of room, size of floor tile), then transmits the information of starting point to the EA to start the automatic optimization process. Subsequently, the EA releases novel starting points based on the design results of the transmitted starting point and its evolutionary computational logic. The released starting points are then inputted into the design algorithm to generate novel design alternatives. After iterative computation, the layout with better performance (i.e., lower waste rate) will be reserved for further optimization by comparing the resulting design alternatives. In summary, the process comprises three critical steps: (1) releasing novel starting points based on the result of iterative computation by the EA, (2) generating novel design alternatives by design algorithm, and (3) selecting the starting point with relatively better performance and sending them as feedback to the EA. The three steps are repeated to continue the optimization until the optimal solution (i.e., minimized material waste) or the expected optimization result is obtained.

2.3. Waste Analysis and Objective Function

In this research, the optimization of the floor tile design is addressed as a 2-D graphics cutting and planning problem. The basic unit of floor tile is the original tile rather than the area in construction procurement. Thus, the objective function (*O.F.*) is the ratio of the area of the minimum number of original floor tiles covering the tiling area to the tiling area, which can be expressed as follows:

$$O.F. = min\left[\left(\sum_{i=1}^{n}(A_{cu} + A_u) + \sum_{j=1}^{m} A_{cp}\right) / \ A_r\right] - 1$$

where n is the number of rows in the floor tile grids; A_{cu} is the area of used cut sections of floor tiles in row i; A_u is the area of used uncut floor tiles in row i; A_{cp} is the area of the number j unused cut section; A_r is the area of the selected tiling room; m is the total number of unused cut sections of floor tiles.

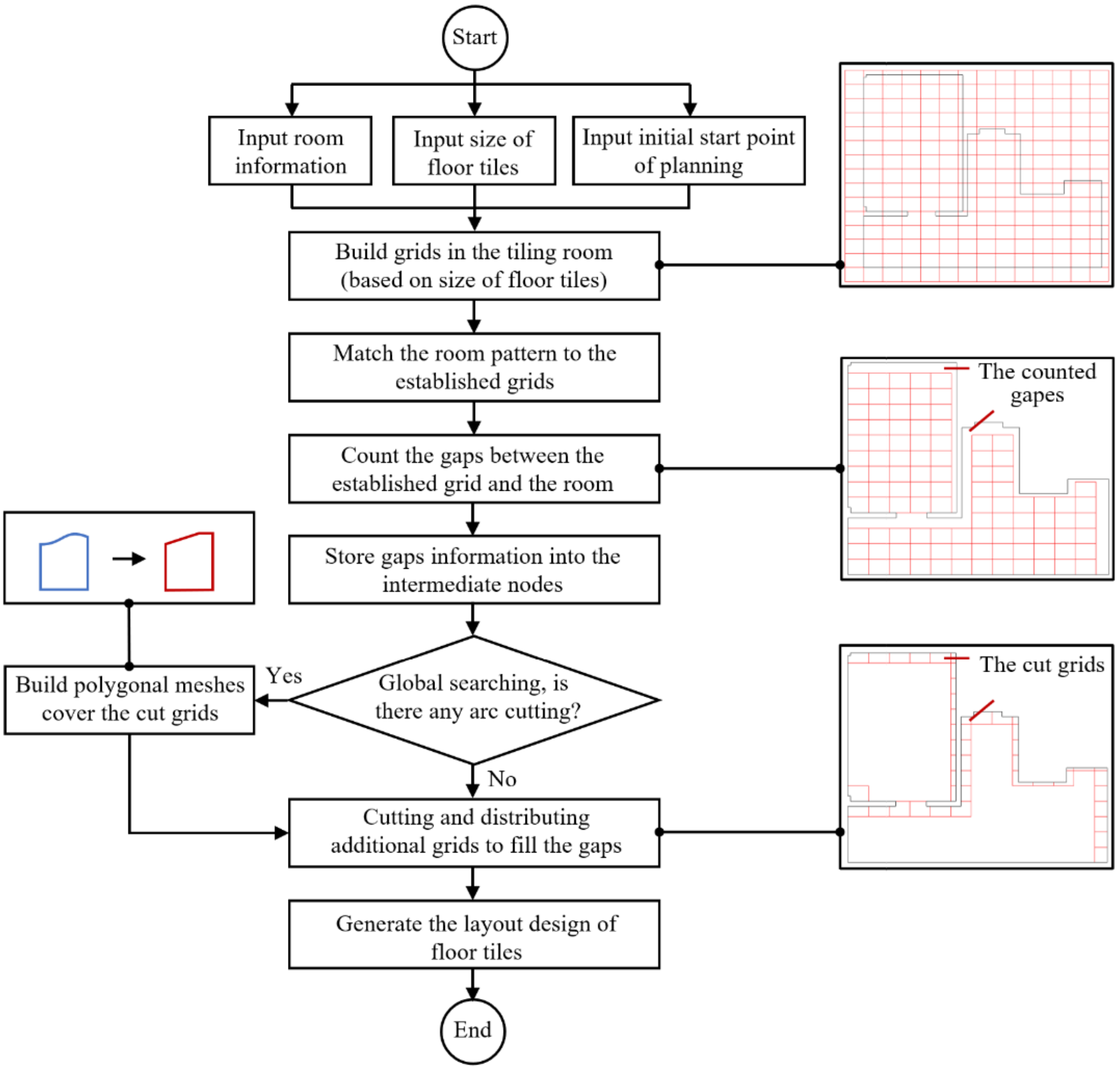

Figure 3. Cutting and distributing rules-based design algorithm of floor tile.

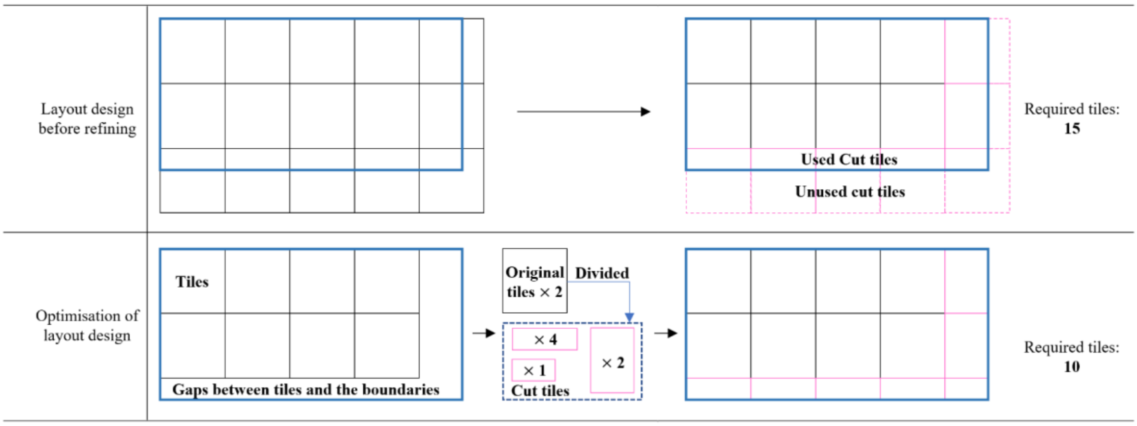

Figure 4. Examples of floor tile design.

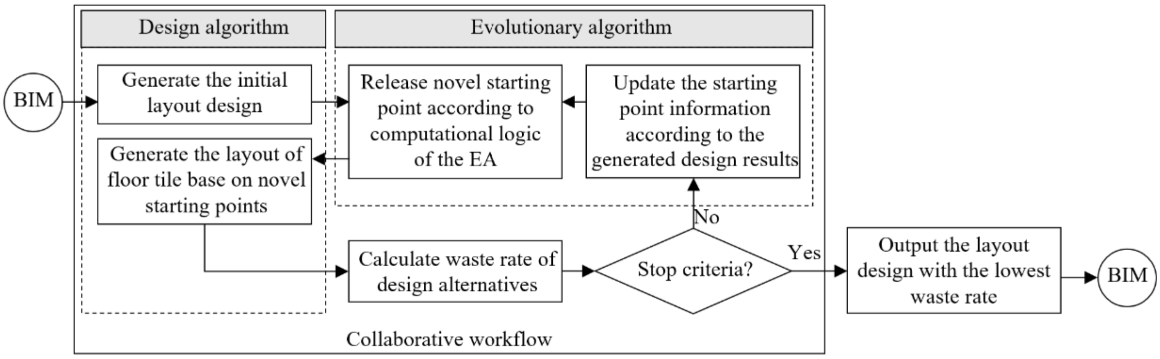

Figure 5. Collaborative workflow of the design algorithm and the EA.

3. Development of the Prototype System

To implement the proposed workflow, a prototype system is developed in the Grasshopper. Grasshopper is a representative PD platform that has been widely used in architectural design [50]. Figure 6 presents the details of the prototype system in the Grasshopper. The developed functional code blocks provide the data processing functions, jointly constituting the proposed system for optimization of floor tile design. For example, the first functional group extracts the inputted information (e.g., floor tile size, the room's shape) from the BIM platform and transmits them to the other functional groups for further processing (see Figure 6b). The following functional groups provide the function of the design algorithm and the integration with EA, acting as data processors in the prototype system.

In the prototype system, two programs are critical: (1) formalizing the cutting and distributing rules-based design algorithm, and (2) realizing the collaborative workflow to generate and optimize the design alternatives. It is worth mentioning that the development of the prototype system is mainly carried out in Grasshopper. The BIM platform is mainly used to provide tiling area information to Grasshopper to generate and optimize floor tile layout design. Therefore, information providers are not limited to a single type of BIM platform. ArchiCAD has been used in this research to provide tiling area information. Other platforms, such as Rhino, can use this algorithm to optimize floor tile layouts design, as long as they provide Grasshopper with information about the tiling area.

3.1. Functional Groups of the Design Algorithm

Figure 7 shows the details of the design algorithm implementation. First, input the established grids to the functional group "Define the gaps between the grids and boundaries" and then match the boundaries of grids with tiling area. Subsequently, collide the tiling area and grids and remove the grid units that overstepped the boundaries, ensuring that the remaining grid units meet the requirements of the design algorithm: retain gaps from the boundaries. Following this, retain dispatch gaps information from the grids and tiling area, then store the information into intermediate nodes for global searching and computing. On the other hand, the "cutting and distributing" design logic need to provide additional grids according to the design algorithm. The additional grids information is built based on the input tiles information and then stored in a single intermediate node to provide the computing module with global cutting and distributing calculation. After inputting the gaps and additional grids information, the system first determines whether the arc-shaped boundaries exist. If yes, the control points of its outer contour are captured and meshed with polygons, and then the calculation is processed. After the calculation, the redundant parts (i.e., parts that exceed the boundaries) are removed to generate the final result. If not, the calculation step is carried out directly. The computing module performs global calculations to determine the shapes and location information of the cutting and distributing of grids (i.e., the tiles). Finally, the uncut grids are filled in blank space to complete the layout planning according to the alignment line of calculated cut grids. It should be noted that the function code of judgment was developed by Petrasvestartas [33]. The innovation point of this research is to propose the workflow for floor tile generation and optimization rather than any single code block.

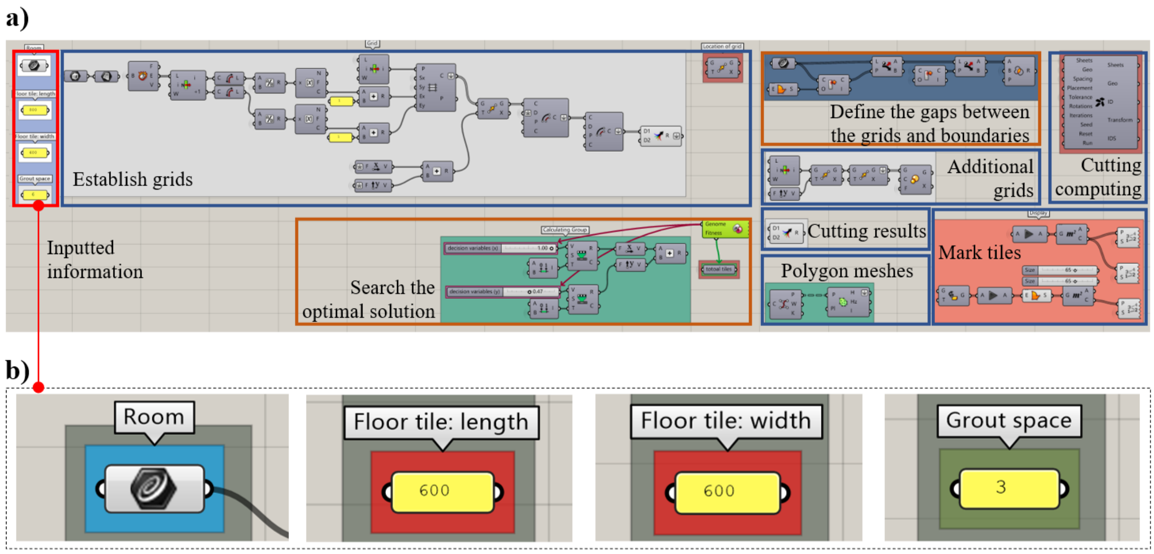

Figure 6. (**a**) Overall process of the proposed optimization system in the Grasshopper; (**b**) the functional group of information extractor (in Grasshopper).

Figure 7 also shows the visual programming by the code blocks in the PD platform. As shown, the functional groups process two types of information (i.e., graphic information and numerical information), then output the processed information to the next series of code blocks (i.e., functional group). This data-processing step involves object comparison (i.e., Collision node), list dispatch (i.e., Dispatch node), and Boolean intersection (i.e., intermediate nodes of gaps), enabling graph data to be digitized and categorized to import into the collaborative workflow for intelligent computation and optimization. For example, as "Result" nodes in Figure 7 show, the users can directly extract the number of cut tiles as 32 (i.e., items 0 to 31), composed of closed curves. The number of used original (i.e., uncut) floor tiles is 39 (i.e., items 0 to 38), formed by polylines. In addition, Figure 7 also shows the operation logic of the involved data processing nodes. For example, the "Surface" node stores the information of tiling area, including shape and sizes, entering the "Collision" and the "Boolean intersection" nodes to judge and calculate accordingly. Among them, the "Dispatch" nodes separate the grids according to the inputted conditions, which is carried out twice: (1) separate the grids in and outside the tiling area; (2) separate the cut and uncut grids to help define the gaps (by the "Boolean intersection" node, logic: A and B) between grids and boundaries. Afterward, the "Surface" node collects the gaps information and input into the "cutting and distributing" functional group to global computing. The mathematical structure of the design algorithm can be described as the Logical Operators (1)–(3):

$$(tiling\ room) \cap \{grid\ 11,\ grid\ 12, \ldots, grid\ 1j, \ldots, grid\ ij\} \xrightarrow{collision} \{gird\ 11, \ldots, grid\ i_x j_y\}.$$

$$\xrightarrow{dispatches} \left\{ \begin{array}{c} grids\ on\ or\ out\ the\ boundaries\ (grid\ 11,\ grid\ 12, \ldots,\ grid\ 1j, \ldots,\ grid\ i_n j_m), \\ grids\ in\ the\ boundaries\ (grid\ 11, grid\ 12, \ldots,\ grid\ 1j, \ldots,\ grid\ i_{x-n} j_{y-m}) \end{array} \right\}.$$

$$\xrightarrow{} yields \left\{ \begin{array}{c} gaps\ information\ between\ grids\ and\ boundaries,\ and \\ grids\ in\ the\ boundaries\ (grid\ 11, grid\ 12, \ldots,\ grid\ 1j, \ldots,\ grid\ i_{x-n} j_{y-m}) \end{array} \right\}.$$

$$\xrightarrow{dispatches\ and\ stores} gaps\ information\ between\ grids\ and\ boundaries \tag{1}$$

$$tiles\ information \xrightarrow{extracts} grid\ unit \xrightarrow{list} item\ unit \xrightarrow{move} item\ units \xrightarrow{stores} additional\ grids \tag{2}$$

$$\left\{ \begin{array}{c} (gaps\ information\ between\ grids\ and\ boundaries), \\ and\ (additional\ grids) \end{array} \right\}.$$

$$\xrightarrow{global\ computing} \{cut\ grid\ 11,\ cut\ grid\ 12, \ldots,\ cut\ grid\ 1f, \ldots,\ grid\ tf\} \xrightarrow{distributing} final\ results \tag{3}$$

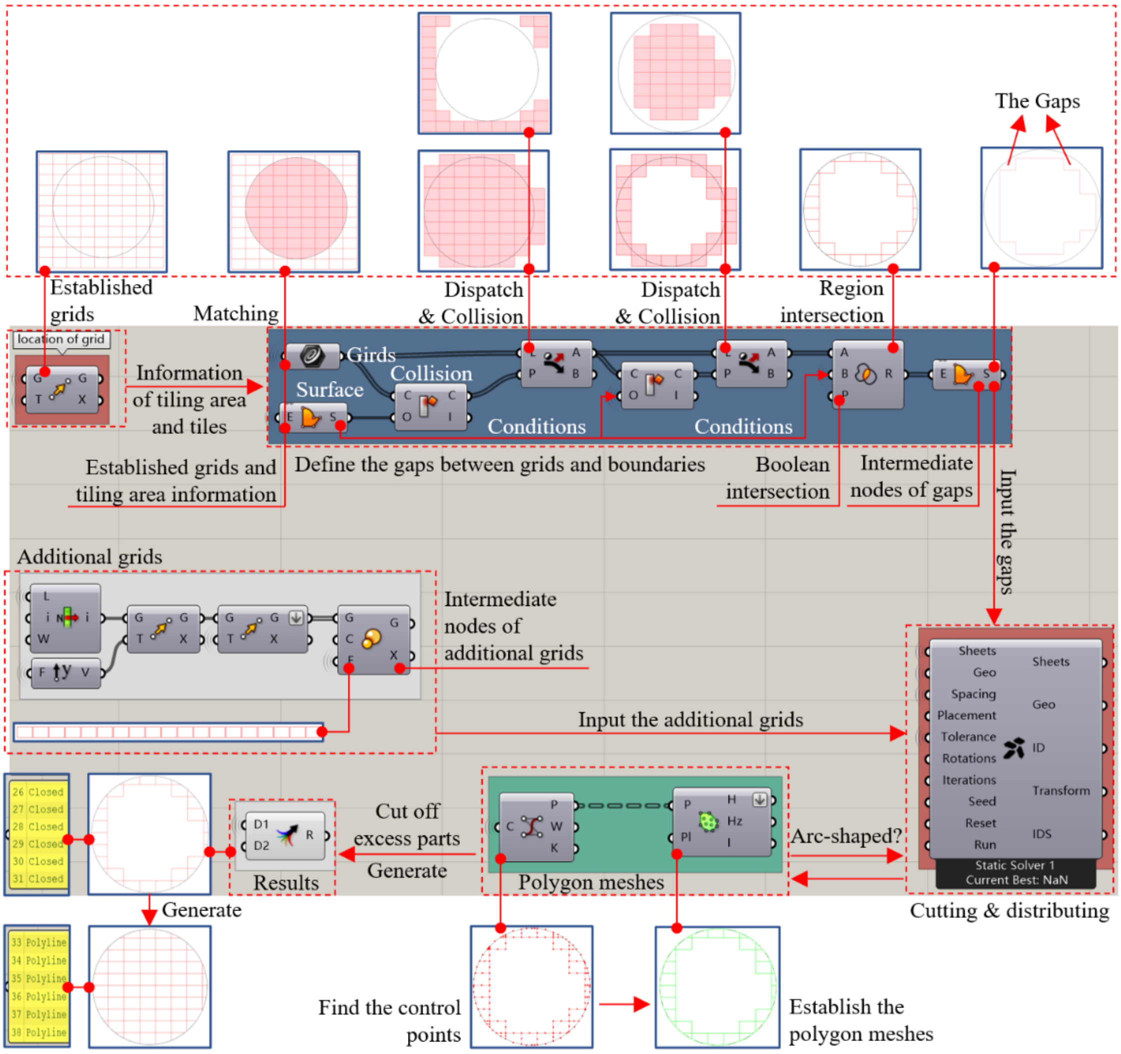

Figure 7. Formalizing the cutting rules-based design algorithm (in Grasshopper).

3.2. Integration of the Design Algorithm and EA

Figure 8 presents the critical steps in realizing the collaborative workflow of the design algorithm and the EA. As mentioned in Section 2.2, the problem of optimizing the floor tile design can be translated into finding the optimal starting point (with the lowest waste rate). As such, the collaborative working mechanism is mainly completed by two programs: (1) the coordinates of the starting point, which two controllers control to regulate the coefficient (i.e., in the range of 0~1) and the corresponding range based on the inputted size of floor tile (e.g., 0~800); and (2) a computational code block of the EA based on the genetic algorithm for extracting the generated digital results and giving novel coefficients to the two controllers. In the process of searching for the optimal solution, the different graphical and digital results based on the continuously released starting points are then generated and compared. Based on the results of generation and comparison, the computational code block then explores the novel coefficients to obtain better solutions. Repeating the process, the design layout with the lowest material waste rate can be explored by constantly adjusting the starting point position coefficients. The mathematical structure of the collaborative workflow can be described as the Logical Operator (4):

$$\begin{aligned} &\textit{digitized results} \xrightarrow{\textit{extraction}} EA \xrightarrow{\textit{yields}} \begin{pmatrix} \textit{parameter } i \\ \textit{parameter } j \end{pmatrix} \xrightarrow{\textit{remap}} \begin{pmatrix} \textit{value } i_x \\ \textit{value } j_x \end{pmatrix} \xrightarrow{\textit{vector}} \begin{pmatrix} x \textit{ vector} \\ y \textit{ vector} \end{pmatrix} \\ &\xrightarrow{\textit{design algorithm}} \textit{novel layout design} \xrightarrow{\textit{stop index}} \left\{ EA \xrightarrow{\textit{yields}}, \ldots, \xrightarrow{\textit{stop index}} \textit{final results} \right\} \\ &\qquad\qquad\qquad\qquad \textit{or } \{\textit{final results}\} \end{aligned} \tag{4}$$

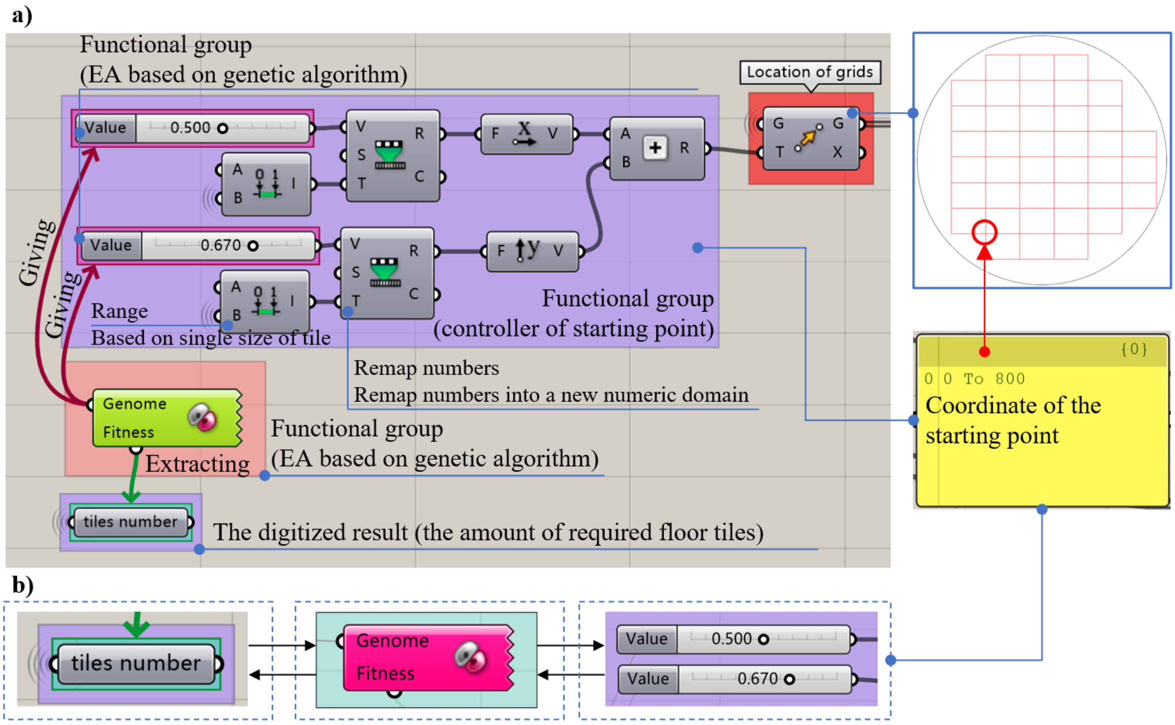

Figure 8. (**a**) Realizing the collaborative workflow of the design algorithm and the EA; (**b**) simplified repetitions of the collaborative workflow for obtaining optimal solutions (in Grasshopper).

4. Case Study

The proposed rules-based optimization method is developed to automatically generate and optimize floor tile layout while minimizing material waste rate. The motivation of the research is to allow designers to obtain an accurate design with the lowest waste rate in a short time. This section presents case studies conducted to verify and validate the proposed workflow and prototype system.

4.1. Information of Tiling Area and Floor Tiles

An apartment is selected as a case study to test the developed prototype system (see Figure 9). This project is located in Chengdu city, which is a typical apartment in a mansion. The planned tiling area of this apartment is 46.08 m^2. The tiling area boundaries are irregular, including at least three irregular types: (1) protuberance, (2) nonorthogonal, and (3) curvilinear. Floor tiles with the size of 800 mm × 600 mm were selected. The prototype system is developed in the Grasshopper to help the designer generate and optimize the floor tiles' layout designs. A computer with Intel (R) Core (TM) i7-9750H CPU @2.60 GHz 16 GB of RAM and 64-bit operating system is used.

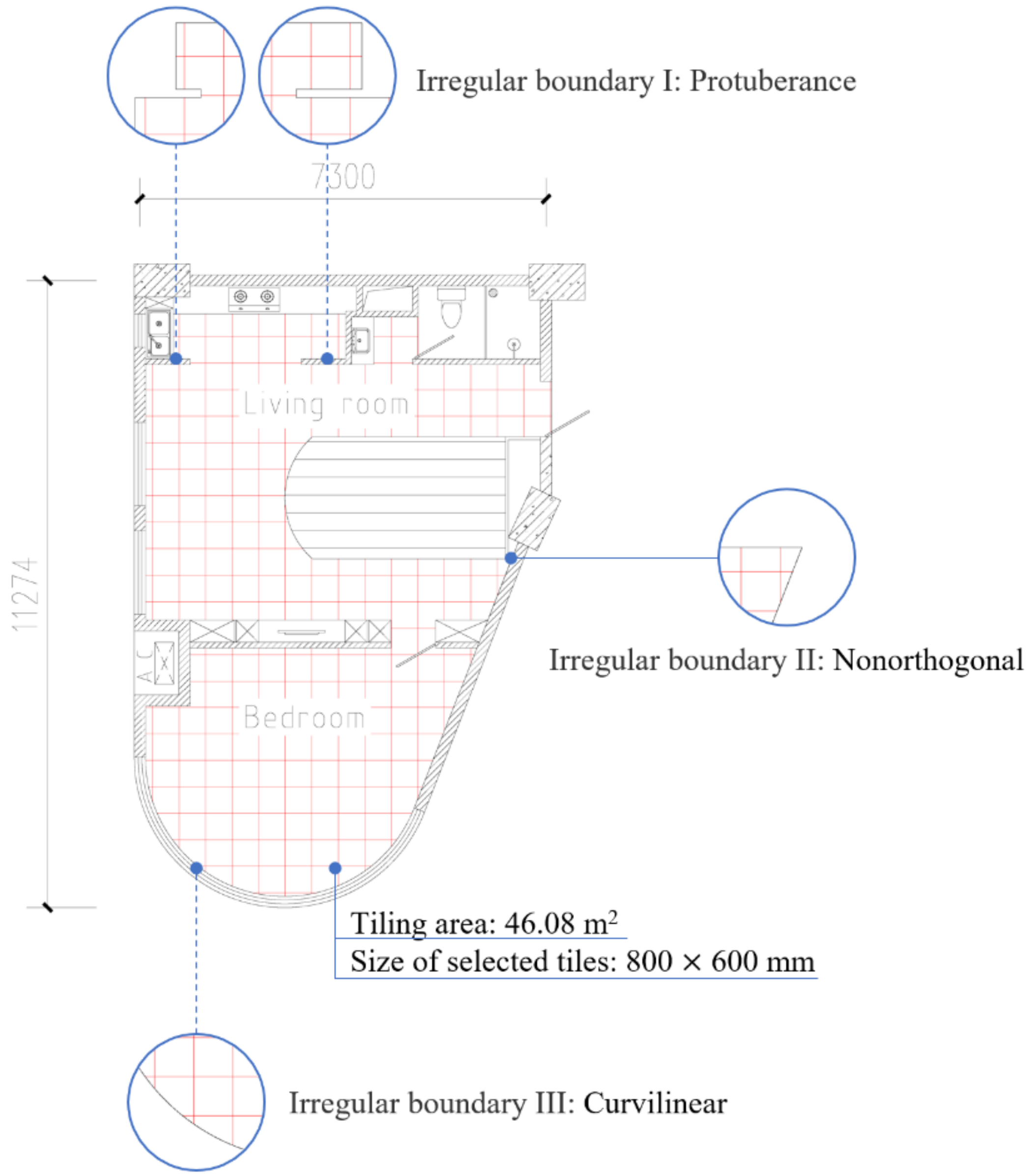

Figure 9. Layout of the selected apartment.

4.2. Results and Discussion

The presentation and discussion of the results are mainly from three aspects: (1) graphical results, (2) numerical results, and (3) the optimization process of the collaborative workflow. By demonstrating the results of these three aspects, the innovation and significance of the proposed workflow in this research can be indicated.

4.2.1. Graphical Results

Figure 10 shows the drawings outputted by the prototype system, where all used tiles (including the original tiles and cut tiles) and unused cut tiles are presented. The prototype system automatically generates and optimizes the graphical results into the drawing area and the display area of cutting planning. The drawing area mainly marks where each floor tile needs to be placed and marks the cut tiles by numbers. In the display area, the used cut tiles are marked with the same number as in the drawing area, and the cut tiles' cutting relationship is presented in detail. To make the preplanning clearer, the used and unused cut tiles are marked in the display area, while the reused cut floor tiles are marked in color, and unused cut floor tiles are marked in the blank. In addition, the anchor points and angles in the two-dimensional coordinate system are established to accurately mark the cutting and planning. Figure 11 partly shows the positioning of the cutting and planning. The workflow sets the intersection point of the left and bottom two sides of the tiling as the origin of the coordinates (i.e., 0, 0), that is, the starting point controller at (0, 0) in Section 3.2. On this basis, each cutting point and angle is positioned in detail with the size of a single floor tile as the coordinate grid. Such methods are commonly used in CAD-based positioning of the shop drawing. The specific positioning and cutting methods can be referred to work of King et al. [15]. Moreover, the design result of floor tiles can be exported directionally based on the format required for cutting, such as DWG or DXF, or IFC format for further customized manual modification.

The graphical results show the possibility of achieving the precise global preplanning on the layout design of floor tiles. Such precise preplanning is based on a feasible design algorithm, using BIM and PD approaches to generate a logic-based (i.e., trade know-how cutting and planning rules) floor tile design layout. Unlike previous research [29–31], the graphical results in this research include used and unused cut tiles and consider the reuse of cut tiles as the trade know-how cutting and planning rules to serve engineering practice. Precise graphical results and proactive global planning provide design support to the relevant work processes for cutting and planning, producing more precise management conditions. For example, by enabling procurement engineers to order materials on a project-specific basis rather than based on industry standards, precise procurement methods can effectively reduce material waste and avoid repeated transportation [13,17]. Additionally, enabling engineers to plan the optimal cutting and reuse of floor tiles globally effectively reduces the waste of materials and labor [11]. In addition, the results show the effectiveness of the proposed design algorithm in dealing with floor tile layouts with arc-shaped boundaries. This is because the polygon meshes are introduced in this research, transforming the arc-shaped cutting into polygons (see Section 3.1), then providing corresponding calculations for reuse tools (i.e., Opennest). Compared with Wu et al.'s [17] research, the proposed design algorithm in this research has better adaptability because of the treatment of the arc-shaped boundaries problem.

Furthermore, the precise graphical output of the cut floor tile planning extends the applicable scenarios for floor tile preplanning. Gharbia et al. [14] reviewed and summarized the application of robot technology to on-site and off-site floor tile cutting and planning scenarios, indicating that the current lack of precise design support hindered the development of robot technology in tiling-related work. The research of King et al. [15] also proves that accurate graphic results are essential for laying floor tiles by robotics in construction sites. Furthermore, a series of research results show that accurate material graphical planning is beneficial to the on-site and off-site transportation of building materials [43], shortens the construction period [22], and reduces the probability of rework [51], which also demonstrates the significance of this research.

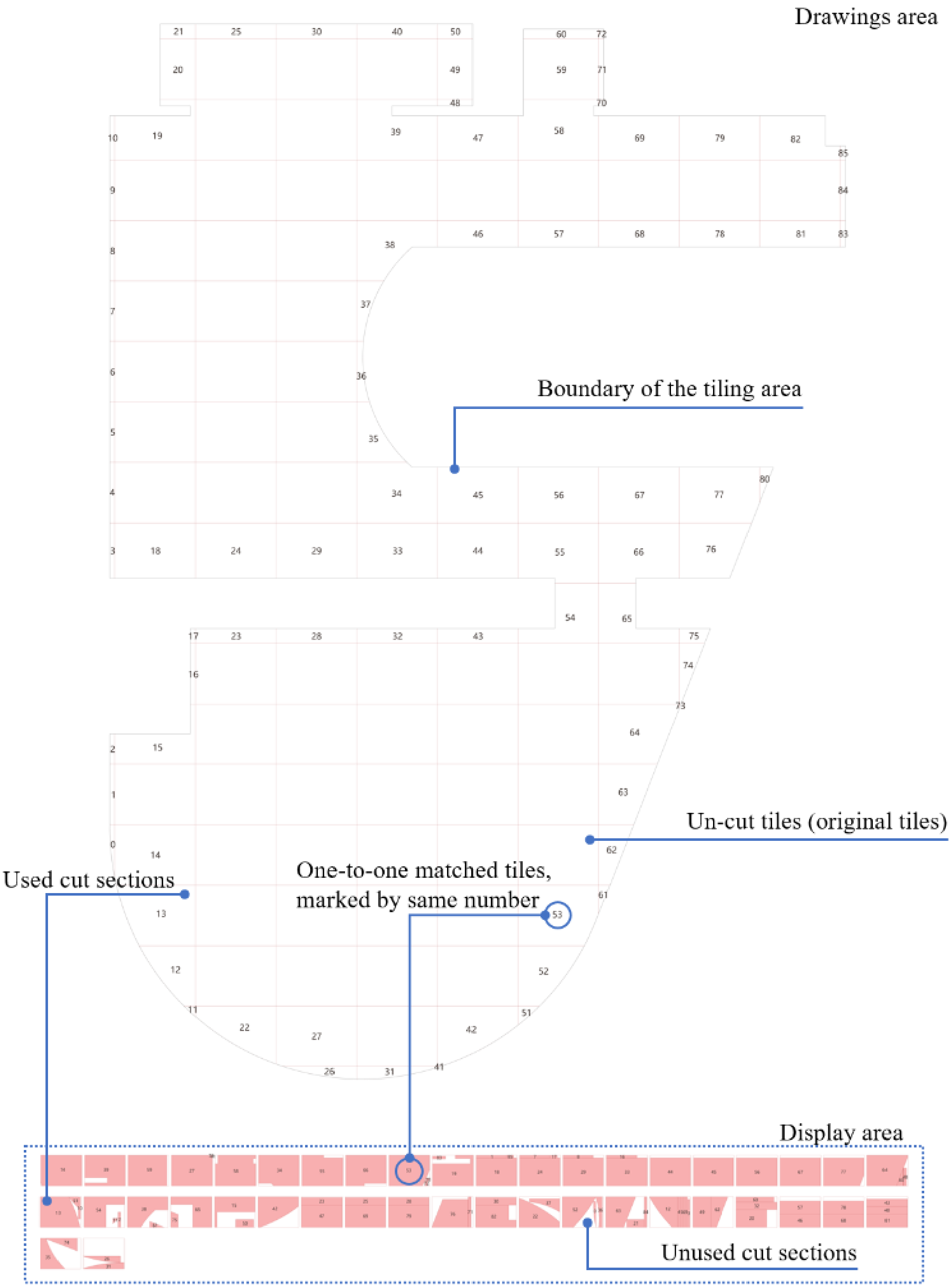

Figure 10. Optimized floor tile planning of the layout.

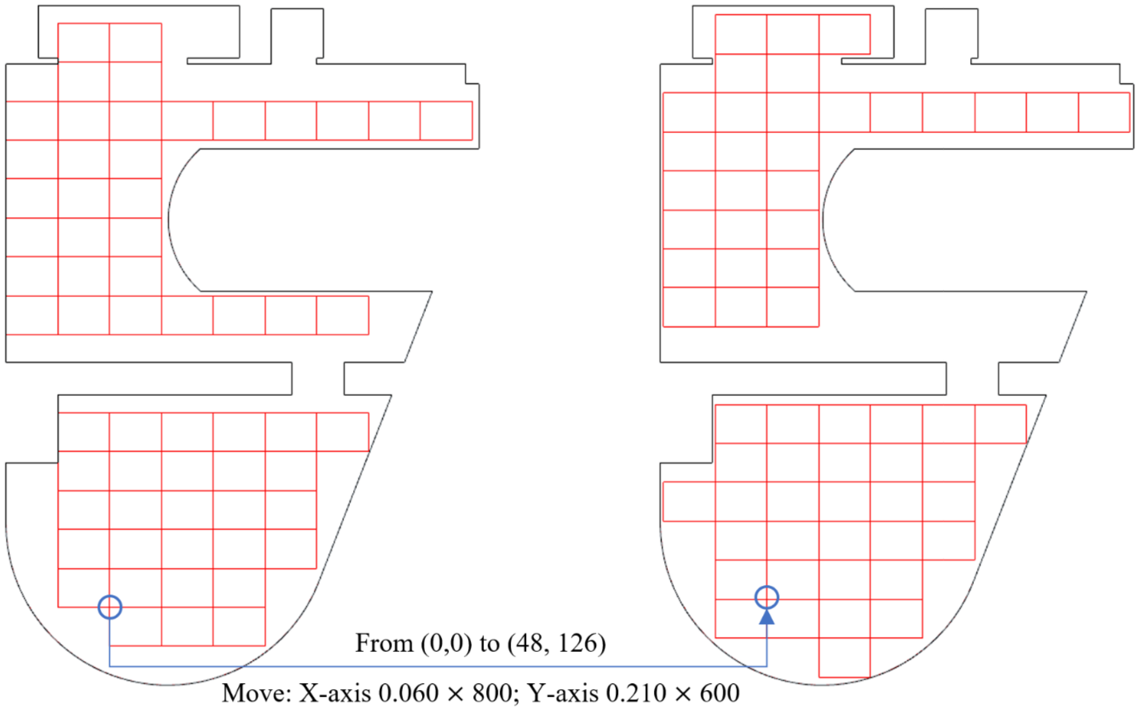

Figure 11. Positioning the planning and cutting of tiles.

4.2.2. Numerical Results

The numerical results are shown in Table 1. The required numbers of floor tiles for different planning methods are shown in the following:

Table 1. Material waste of different planning methods.

	Number of Required Tiles	Waste Rate (%)
Planning I	101	4.17
Planning II	103	7.29
Planning III	114	18.75
Planning IV	106–111	15.63

Planning I: plan by the proposed prototype system, which is also the numerical results matching the graphic results in Section 4.2.1.

Planning II: plan by the trade know-how design algorithm (proposed by this research) and according to the cutting and planning rules of trade know-how, setting the starting point at (0,0) (i.e., the corner of the tiling area).

Planning III: plan by the existing design-aided tools [31], that is, planning the layout of floor tiles but not preplan the reuse of cut tiles.

Planning IV: the procurement and construction engineers estimate and provide data according to the industry benchmark, which is closer to the actual engineering data provided by our commercial partners.

The numerical results are shown in Table 1. Planning I to III required 101, 103, and 114 tiles for the selected room, respectively, and the corresponding waste rates are 4.17%, 7.29%, and 18.75%, respectively. The waste rate of Planning IV is 15.63%, which is estimated based on the number of floor tiles required by the industry benchmark (i.e., operating manual [18,52]); accordingly, the number of the required tiles of planning IV is 111.

From the numerical results, Planning I shows some advantages. The waste rates of Planning II to IV are 3.12%, 14.58%, and 11.46% higher than that of Planning I, respectively. Compared with Planning I, the starting point of Planning II is different, reflecting the significance of introducing EA to explore the optimal solution (with optimal starting point) under the same planning and cutting rules. The optimal solution (e.g., with minimized waste rate) under the same conditions is explored by combining the proposed design algorithm with EA. In addition, the waste rate of Planning I is lower than that of Planning III, which to some extent indicates that the workflow proposed in this research has improved in reducing the material waste rate compared with the existing design-aided tools [31]. The lower waste rate is mainly achieved through two aspects of optimization. The first is to establish a workflow to reuse cut tiles, reducing the material waste rate. The second is the introduction of EA to explore a better starting point for planning. Moreover, the proposed workflow significantly reduces material waste compared with floor tile waste's industry benchmark-based estimate (i.e., Planning IV). To some extent, this shows that accurate floor tile cutting and reuse planning can effectively reduce the material waste rate, which is consistent with the results of previous research [11,13].

In addition, to show the advantages of global computing, the design algorithm proposed in this research is compared with that of Wu et al. [17] in Table 2. The computations of six different sizes from 600 × 600 mm to 900 × 1200 mm were compared to avoid the contingency of a single calculation. Design algorithm I means the design algorithm proposed in this research, and design algorithm II was proposed by Wu et al. In the "Time per generation" item, each calculation of design algorithm I is no more than that of design algorithm II. From the calculations of 600 × 600 mm to 900 × 1200 mm, the time required for design algorithm I was less 5.2 s, 6.2 s, 5.5 s, 4.7 s, 4.7 s, and 3.4 s than for design algorithm II, respectively. Such results indicate that "cutting-distributing" instead of "cycle: cutting-cover-cutting" (proposed by Wu et al. [17]) can effectively reduce the computing resources occupied in the cycle process, thus improving the computing efficiency. Considering the number of iterations required, design algorithm I can save 50.0 s, 30.2 s, 16.5 s, 23.6 s, 17.3 s, and 31.3 s, respectively, compared with design algorithm II. According to Table 2, design algorithm I takes less time than design algorithm II for two reasons: (1) it takes less time per generation, and (2) it takes fewer generations (i.e., it requires 2,1,0,1,1,2 generations less than design algorithm II, respectively) to obtain the optimal solution. These two aspects show a certain advantages of design algorithm I in terms of searching for the optimal solution with EA to design algorithm II. Although the number of comparative cases is not enough to fully analyze and compare quantitatively, the results show a trend: the algorithm of global computation has advantages in computational efficiency and combination with EA, which is consistent with the previous research [11,35,53]. Moreover, Table 2 also shows the difference of reliability in the calculation of these cases. The reliability of cases calculated by the design algorithm I all pass, and no unreliable representation occurs (see references [34]). The reliability of algorithm II shows unreliable characteristics in case calculation of 600 × 800 mm and 800 × 800 mm sizes. The appearance of unreliable representations also demonstrates the problems of cutting and distributing nodes, which the authors have proposed, in arc-shape processing. By establishing polygon meshes for cutting and distributing calculation, the problem of calculation reliability is solved. Therefore, the optimization algorithm of floor tile layout design is improved effectively, enabling the algorithm to help users solve problems in more complex engineering environments.

In sum, compared with several current floor tile planning methods, the workflow proposed in this research shows the potential of effectively reducing the waste rate. EA is introduced to calculate the optimal starting point of tile planning, which is more economical than setting the starting point at the corner of the tiling area. Such results also prove the significance of combining design algorithm and EA in the proposed workflow. Moreover, compared with previous studies, the development of a global algorithm shows advantages in computational efficiency and, to a certain extent, a higher computational fitness with the EA algorithm. Compared with recent research (i.e., Wu et al. [17]), the proposed design algorithm also solves the problem of reliability when cutting arc-shaped boundaries, enabling the optimization to adapt to more complex engineering requirements.

Table 2. Required time of computation.

Size of Selected Floor Tiles (mm)	Design Algorithm I			Design Algorithm II			
	Generation of the Optimal Solution	Time Required of Each Generation (s)	Total Time Required (s)	Generation of the Optimal Solution	Time Required of Each Generation (s)	Total Time Required (s)	Whether Unreliable Results Occur
600 × 600	2	13.2	26.4	4	19.1	76.4	No
600 × 800	2	11.6	23.2	3	17.8	53.4	Yes
800 × 800	3	10.8	32.4	3	16.3	48.9	Yes
800 × 900	2	9.5	19.0	3	14.2	42.6	No
900 × 900	1	7.9	7.9	2	12.6	25.2	No
900 × 1200	3	7.4	22.2	5	10.7	53.5	No

Approaches: Design algorithm I is the design algorithm proposed by this research, and design algorithm II is the design algorithm proposed by Wu et al. [17]. The unreliable results show as the reply of the node author [34].

4.2.3. Optimization Process

Figure 12a shows the simulation process of iterative calculation in generations 0 to 20 based on the employed EA. As per the setting of the collaborative workflow in the prototype system, the starting point simulation conducts 100 times for each iterative calculation. This research aims to find the layout design with the lowest required number of tiles rather than the true minimum area used value (as analyzed in Section 2.3). As per the nature of the nondeterministic polynomial (NP) problem, the design alternatives based on the minimum number of used tiles are multiple rather than one. Therefore, as the workflow setting, the EA cannot obtain the true minimum area, but it can obtain a range value, which will continuously release the starting points to explore the possible existence of a better solution (with a lower waste rate). Figure 12a shows the optimization process. The data were optimized from 103 in the 0th generation to 101 in the 2nd generation. Since then, although the optimal solution has been maintained at 101, the starting point is continuously released due to the NP problem's failure to obtain the optimal solution.

In addition, EA showed sufficient advantages in performing efficient calculations in this research. Theoretically, 100 iterations of layout alternatives are generated in each generation. If the accuracy of the two control axes is set to 0.001, millions of calculations (i.e., (0.001 to 1.000) × (0.001 to 1.000)) are needed to obtain the optimal solution, and hundreds of generations of calculations are generally required to obtain the optimal solution. The introduced EA algorithm is based on genetic logic [32]. After analyzing and classifying the results of each generation, it conducts iterative directional calculation. Therefore, the optimal solution can be obtained within several generations. Figure 13 presents the process of EA screening the optimal solutions and iterating through its genetic-based logic. The optimal solution is sought in each generation of computation, and a better solution is obtained by inheritance and evolution of the optimal solution. Figure 13 also shows the distribution of the solution set after twenty generations of calculation. There is apparent solution aggregation near the optimal solution, which is more concentrated than other regions, reflecting the optimization characteristics of inheritance and evolution.

Although the evolutionary algorithm based on genetic logic shows efficiency advantages in computing, due to its own limitations, it may fall into local optimization rather than global optimization [32]. In order to verify the reliability of the proposed system, another global algorithm (i.e., simulated annealing algorithm) is introduced for verification. According to previous studies, when two global algorithms are used to check each other, the results are reliable with high probability [54]. Figure 12b shows the calculation process of the simulated annealing algorithm. The calculated temperature ranges from order of magnitude 10^0 to order of magnitude 10^{-34}, and over 10,000 calculations, were performed [32], presenting the same result as EA (i.e., 101 tiles required). Such verification results match previous studies [55,56] and strengthen the reliability of the introduction of EA for evolutionary optimization in this research. This also shows that the workflow adopted in this research can effectively calculate the optimal solution.

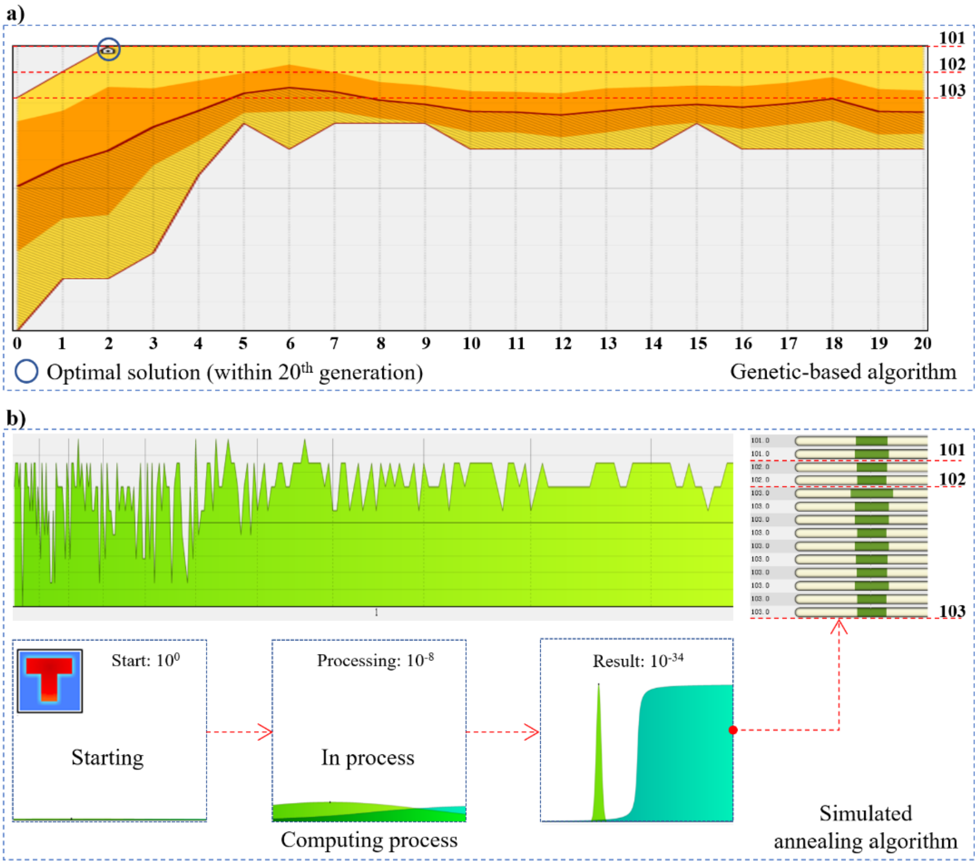

Figure 12. Optimization processes of EA: (**a**) Iterative calculation process of the genetic algorithm-based prototype system (in Grasshopper); (**b**) The calculation process of simulated annealing algorithm.

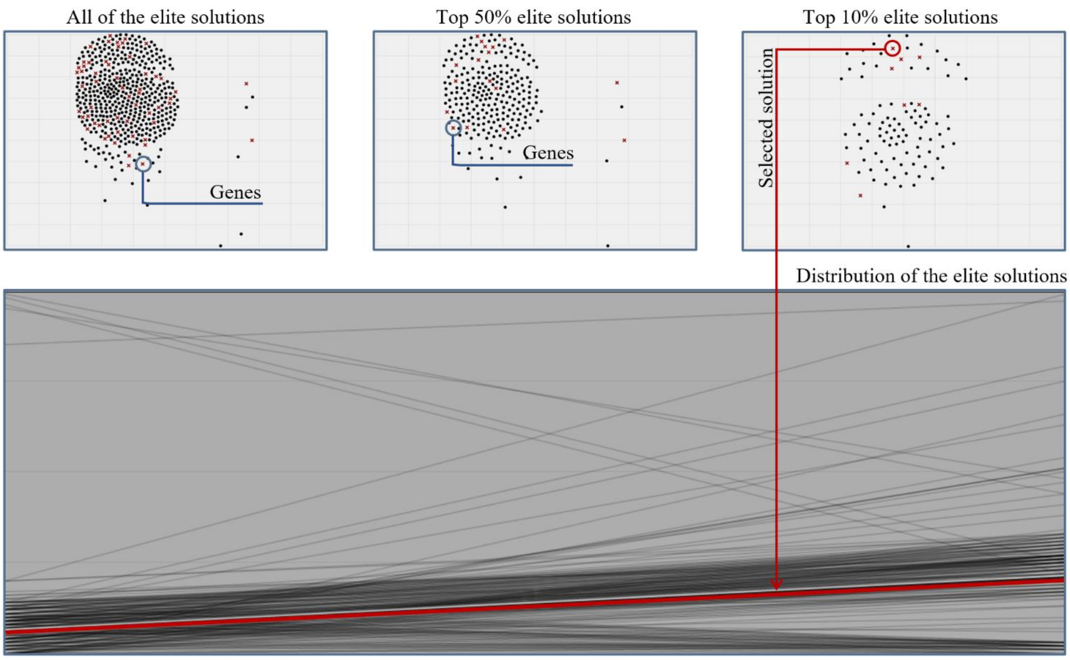

Figure 13. The distribution of solutions and the location of selected solutions in the EA generation (in Grasshopper).

5. Limitations and Future Work

Although the proposed workflow and prototype system can successfully generate and optimize the floor tile layout design, these still needs to be optimized and further developed.

1. Establishing a more direct optimization and verification system for floor tile layout design is necessary. Although it is necessary to adopt another global algorithm to verify the results after calculation, if the calculation and checking are carried out separately, the calculation process will be increased, which is not conducive to practical use. Establishing a mutual verification system in the workflow and directly verifying the calculated results ensures that the output results are globally optimized and avoid secondary verification.
2. Improving the system's adaptability to optimize the layout design of more 2-D cutting construction materials is necessary. Many other similar materials have optimization requirements in the design stage in engineering practice. Since different materials use different design and construction rules, the layout design method is challenging to combine. For example, the support force is not a significant problem when discussing the cutting and planning rules of floor tile; however, some other 2-D cutting construction materials (e.g., glass) need to consider the support force problem when reusing the cut sections. This research only considers the floor tiles design optimization; there is a strong potential for expansion and application in the AEC industry.
3. The design algorithm and waste rate calculation method proposed in this research entails purchasing a single floor tile. However, it is possible to encounter a minimum purchase quantity unit that is not one but 10 or 100 in engineering practice. The design algorithm proposed in this research aims to minimize material waste. Therefore, in future work, research will take the purchase of units of different orders of magnitude into consideration and find the solution of the lowest waste rate under different purchase conditions.
4. The design algorithm is developed in the Grasshopper PD platform, and the current use is still limited to the BIM platform that has the interface with the Grasshopper platform. The reason for this is that there is still a lack of a proper way to efficiently translate the workflows (or prototype systems) developed in Grasshopper into other higher-level programming languages (e.g., Python, C#). Future work may need to consider using other languages to rewrite the program based on the logic of this research, extending the adaptability of the proposed design algorithm.

6. Conclusions

Protection of the environment and sustainable development in the AEC industry is an underlying theme of this paper. Based on the BIM technology and Parametric Design (PD) approaches, this paper proposes a method to minimize the wastage of floor tiles to reduce the generation of construction waste. The proposed approach formalized the floor tiles' trade know-how cutting and planning rules into a design algorithm. The paper then presents a collaborative workflow integrating the proposed design algorithm and the EA to generate the layout design while minimizing wastage. Based on the proposed workflow, a prototype system was developed, and then an apartment was introduced as a case study to verify the proposed approach. Compared with the mainstream existing design methods, the proposed design algorithm reduces the material waste rate by 14.58% and 11.46%. An apartment is optimized by the prototype system, outputting accurate construction drawings with a minimal waste ratee, thus verifying the effectiveness of the proposed approach. Moreover, the proposed approach provides detailed design conditions for mechanical processing and floor tile laying, demonstrating the potential to improve the efficiency of on-site and off-site construction.

The main contribution of this research is the proposal of a method to formalize the rules-based design algorithm for floor tiles in the BIM and PD platforms; the design algorithm can be integrated with the EA to automatically generate and optimize the layout design of floor tiles while minimizing material wastage. It retains the experience and knowledge of senior industry professionals in floor tile layout design and accurately calculates and outputs the graphics and numerical values of floor tiles, providing a design basis for related work. Compared with currently proposed design algorithms, a global "cutting and distributing" design algorithm is proposed in this research, which effectively improves computational efficiency. In addition, this research improves the existing design algorithm, which can be used reliably for floor tile layout design with arc-shaped boundaries, extending the applicability of floor tile layout algorithm based on BIM and PD approaches. Moreover, this paper provides construction practitioners with an automated approach for the use of design-centric BIM software, overcomes the limitations of the existing BIM technology, and meets the specific requirements of the construction industry in obtaining automated and accurate layout design of floor tile. Further, this research can be combined with the current floor tile construction automation method, thus laying a foundation for further research in BIM-based architectural design.

Author Contributions: Conceptualization, S.W. and N.Z.; methodology, W.-Z.L.; software, D.W.; validation, S.W., X.L. and D.Q.; formal analysis, Y.X.; investigation, N.Z.; resources, X.L.; data curation, S.W.; writing—original draft preparation, S.W.; writing—review and editing, W.-Z.L.; visualization, X.L.; supervision, N.Z. and W.-Z.L.; project administration, W.-Z.L. All authors have read and agreed to the published version of the manuscript.

Funding: Strategic Research Grant, City University of Hong Kong (7004867), and Innovation and Technology Fund (ITF) (CityU-9678142).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the first author.

Acknowledgments: This work was partially supported by Strategic Research Grant, City University of Hong Kong (7004867), and Innovation and Technology Fund (ITF) (CityU-9678142). We thank the reviewers for their valuable comments on the paper.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wattanasiriwech, D.; Saiton, A. Paving blocks from ceramic tile production waste. *J. Clean. Prod.* **2009**, *17*, 1663–1668. [CrossRef]
2. Elçi, H. Utilisation of crushed floor and wall tile wastes as aggregate in concrete production. *J. Clean. Prod.* **2016**, *112*, 742–752. [CrossRef]
3. Daniyal, M.; Ahmad, S. Application of Waste Ceramic Tile Aggregates in Concrete. *Int. J. Innov. Res. Sci. Eng. Technol.* **2007**, *3297*, 12808–12815. [CrossRef]
4. Tikul, N.; Srichandr, P. Assessing the environmental impact of ceramic tile production in Thailand. *J. Ceram. Soc. Jpn.* **2010**, *118*, 887–894. [CrossRef]
5. Lu, W.-Z.; He, H.-D.; Leung, A.Y. Assessing air quality in Hong Kong: A proposed, revised air pollution index (API). *Build. Environ.* **2011**, *46*, 2562–2569. [CrossRef]
6. Lu, W.-Z.; Wang, D. Assessing the relative importance of surface ozone influential variables in regional-scale analysis. *Atmos. Environ.* **2009**, *43*, 3621–3629. [CrossRef]
7. Park, H.S.; Ji, C.; Hong, T. Methodology for assessing human health impacts due to pollutants emitted from building materials. *Build. Environ.* **2016**, *95*, 133–144. [CrossRef]
8. Cersanit SA; Florim Ceramiche SPA; Grupo Lamosa SAB de CV. Global Market Study on Ceramic Tiles: The Shift from Dry Pressed to Casting Formulation Technology Is Underwa. Available online: https://www.persistencemarketresearch.com/market-research/ceramic-tiles-market.asp (accessed on 3 June 2020).
9. Garside, M. Consumption of Ceramic Tiles Worldwide in 2018, by Region. Available online: https://www.statista.com/statistics/938523/global-ceramic-tile-consumption-by-region/ (accessed on 3 June 2020).
10. Lu, W.; Chi, B.; Bao, Z.; Zetkulic, A. Evaluating the effects of green building on construction waste management: A comparative study of three green building rating systems. *Build. Environ.* **2019**, *155*, 247–256. [CrossRef]
11. Liu, H.; Singh, G.; Lu, M.; Bouferguene, A.; Al-Hussein, M. BIM-based automated design and planning for boarding of light-frame residential buildings. *Autom. Constr.* **2018**, *89*, 235–249. [CrossRef]
12. Esa, M.R.; Halog, A.; Rigamonti, L. Strategies for minimizing construction and demolition wastes in Malaysia. *Resour. Conserv. Recycl.* **2017**, *120*, 219–229. [CrossRef]

13. Ding, T.; Xiao, J. Estimation of building-related construction and demolition waste in Shanghai. *Waste Manag.* **2014**, *34*, 2327–2334. [CrossRef] [PubMed]
14. Gharbia, M.; Chang-Richards, A.; Lu, Y.; Zhong, R.Y.; Li, H. Robotic technologies for on-site building construction: A systematic review. *J. Build. Eng.* **2020**, *32*, 101584. [CrossRef]
15. King, N.; Bechthold, M.; Kane, A.; Michalatos, P. Robotic tile placement: Tools, techniques and feasibility. *Autom. Constr.* **2014**, *39*, 161–166. [CrossRef]
16. Ceramic Tile Limited Planning Your Wall & Floor Tile Layout. Available online: https://www.britishceramictile.com/how-to-tile/planning-your-tile-layout (accessed on 10 July 2020).
17. Wu, S.; Zhang, N.; Luo, X.; Lu, W.-Z. Intelligent optimal design of floor tiles: A goal-oriented approach based on BIM and parametric design platform. *J. Clean. Prod.* **2021**, *299*, 126754. [CrossRef]
18. WRAP Designing out Waste: Design Detail Sheet. Available online: https://www.cewales.org.uk/files/6514/4369/9241/designing_out_waste.pdf (accessed on 1 March 2020).
19. Vaghadia, B.K. A Study on Effect of Waste Ceramic Tiles in Flexible Pavement. *Int. J. Adv. Eng. Res. Dev.* **2016**, *3*, 26–28. [CrossRef]
20. *Building and Construction Authority Ceramic Tiling*; Hunan Construction Project Cost Management Station: Changsha, China, 2018; ISBN 9789811163050.
21. Construction Engineering Establishment Team. *Hunan Provincial Department of Housing and Urban-Rural Development Hunan Province Construction Project Budget Quota*; Hunan Construction Project Cost Management Station: Changsha, China, 2018.
22. Yin, X.; Liu, H.; Chen, Y.; Al-Hussein, M. Building information modelling for off-site construction: Review and future directions. *Autom. Constr.* **2019**, *101*, 72–91. [CrossRef]
23. Liu, H.; Sydora, C.; Altaf, M.S.; Han, S.; Al-Hussein, M. Towards sustainable construction: BIM-enabled design and planning of roof sheathing installation for prefabricated buildings. *J. Clean. Prod.* **2019**, *235*, 1189–1201. [CrossRef]
24. Sutherland, I.E. Sketchpad a man-machine graphical communication system. *Conf. Proc. Spring Jt. Comput.* **1963**, *1963*, 329–346. [CrossRef]
25. Davis, D. A history of parametric. *Retrieved August* **2013**, *6*, 2013.
26. Santos, L.; Schleicher, S.; Caldas, L. Automation of CAD models to BEM models for performance based goal-oriented design methods. *Build. Environ.* **2017**, *112*, 144–158. [CrossRef]
27. Khalafallah, A.; El-Rayes, K. Automated multi-objective optimization system for airport site layouts. *Autom. Constr.* **2011**, *20*, 313–320. [CrossRef]
28. Antolin, P.; Buffa, A.; Cohen, E.; Dannenhoffer, J.F.; Elber, G.; Elgeti, S.; Haimes, R.; Riesenfeld, R. Optimizing Micro-Tiles in Micro-Structures as a Design Paradigm. *Comput. Des.* **2019**, *115*, 23–33. [CrossRef]
29. National Tile Contractor Association Online Ceramic Tile Designer/Planner. Available online: http://www.ceramic-tile-floor.info/te/ntca/tileEstimatorNTCA.html (accessed on 12 December 2020).
30. Autodesk. Lab Map Collections and Tile and Flooring Design Plugins Available for 3ds Max. Available online: https://knowledge.autodesk.com/support/3ds-max/learn-explore/caas/sfdcarticles/sfdcarticles/Map-Collections-and-Tile-and-Flooring-design-plugins-available-for-3ds-Max.html (accessed on 12 November 2020).
31. Autodesk. Lab Roombook Extension for Revit. Available online: https://knowledge.autodesk.com/support/revit-products/learn-explore/caas/CloudHelp/cloudhelp/2020/ENU/Revit-AddIns/files/GUID-D8896964-32F8-4DE1-9EA0-109EB7571999-htm.html (accessed on 16 April 2020).
32. Rutten, D. Galapagos: On the Logic and Limitations of Generic Solvers. *Arch. Des.* **2013**, *83*, 132–135. [CrossRef]
33. Petrasvestartas Opennest. Available online: https://www.food4rhino.com/app/opennest (accessed on 12 December 2020).
34. Petras_Vestartas Reply of the Author–Opennest. Available online: https://discourse.mcneel.com/t/incorrect-calculation-by-opennest-is-any-limit-in-the-calculation/120235 (accessed on 10 November 2021).
35. Manrique, J.D.; Al-Hussein, M.; Bouferguene, A.; Safouhi, H.; Nasseri, R. Combinatorial Algorithm for Optimizing Wood Waste in Framing Designs. *J. Constr. Eng. Manag.* **2011**, *137*, 188–197. [CrossRef]
36. Mellouli, A.; Mellouli, R.; Masmoudi, F. An Innovative Genetic Algorithm for a Multi-Objective Optimization of Two-Dimensional Cutting-Stock Problem. *Appl. Artif. Intell.* **2019**, *33*, 531–547. [CrossRef]
37. Liu, H.; Zhang, Y.; Lei, Z.; Li, H.X.; Han, S. Design for Manufacturing and Assembly: A BIM-Enabled Generative Framework for Building Panelization Design. *Adv. Civ. Eng.* **2021**, *2021*, 5554551. [CrossRef]
38. Khosakitchalert, C.; Yabuki, N.; Fukuda, T. Improving the accuracy of BIM-based quantity takeoff for compound elements. *Autom. Constr.* **2019**, *106*, 102891. [CrossRef]
39. Liu, Z.; Osmani, M.; Demian, P.; Baldwin, A. A BIM-aided construction waste minimisation framework. *Autom. Constr.* **2015**, *59*, 1–23. [CrossRef]
40. Abanda, F.; Tah, J.; Cheung, F. Mathematical modelling of embodied energy, greenhouse gases, waste, time–cost parameters of building projects: A review. *Build. Environ.* **2013**, *59*, 23–37. [CrossRef]
41. Dore, C.; Murphy, M. Semi-automatic generation of as-built BIM façade geometry from laser and image data. *J. Inf. Technol. Constr.* **2014**, *19*, 20–46.
42. Ekanayake, L.L.; Ofori, G. Building waste assessment score: Design-based tool. *Build. Environ.* **2004**, *39*, 851–861. [CrossRef]
43. Chen, P.-H.; Nguyen, T.C. A BIM-WMS integrated decision support tool for supply chain management in construction. *Autom. Constr.* **2019**, *98*, 289–301. [CrossRef]

44. Eltaweel, A.; Su, Y. Parametric design and daylighting: A literature review. *Renew. Sustain. Energy Rev.* **2017**, *73*, 1086–1103. [CrossRef]
45. Banihashemi, S.; Tabadkani, A.; Hosseini, M.R. Integration of parametric design into modular coordination: A construction waste reduction workflow. *Autom. Constr.* **2018**, *88*, 1–12. [CrossRef]
46. Hudson, R. Strategies for parametric design in architecture. *Civ. Eng.* **2010**, *274*, 77–81.
47. Ansah, M.K.; Chen, X.; Yang, H.; Lu, L.; Lam, P.T. A review and outlook for integrated BIM application in green building assessment. *Sustain. Cities Soc.* **2019**, *48*, 101576. [CrossRef]
48. Oscar3Dr. Random Tiles. Available online: https://www.food4rhino.com/resource/random-tiles (accessed on 10 July 2020).
49. ArchiBlocks, I. ArchBlocks Hatch Patterns. Available online: https://apps.autodesk.com/ACD/en/Detail/Index?id=2366502996612760335&appLang=en&os=Win32_64 (accessed on 20 March 2020).
50. Zimbili, O.; Salim, W.; Ndambuki, M. Ceramic as Aggregates. *Int. J. Civ. Environ. Struct. Constr. Archit. Eng.* **2014**, *1*, 91–95.
51. Guerra, B.C.; Bakchan, A.; Leite, F.; Faust, K.M. BIM-based automated construction waste estimation algorithms: The case of concrete and drywall waste streams. *Waste Manag.* **2019**, *87*, 825–832. [CrossRef]
52. Fricke, A. How to Plan Tile Layout. Available online: https://www.wikihow.com/Plan-Tile-Layout (accessed on 18 July 2020).
53. Tian, Y.; He, C.; Cheng, R.; Zhang, X. A Multi-Stage Evolutionary Algorithm for Better Diversity Preservation in Multi-Objective Optimization. *IEEE Trans. Syst. Man Cybern. Syst.* **2019**, *51*, 5880–5894. [CrossRef]
54. Kheiri, F. Optimization of building fenestration and shading for climate-based daylight performance using the coupled genetic algorithm and simulated annealing optimization methods. *Indoor Built Environ.* **2021**, *30*, 195–214. [CrossRef]
55. Ilbeigi, M.; Ghomeishi, M.; Dehghanbanadaki, A. Prediction and optimization of energy consumption in an office building using artificial neural network and a genetic algorithm. *Sustain. Cities Soc.* **2020**, *61*, 102325. [CrossRef]
56. Harding, J.E.; Shepherd, P. Meta-Parametric Design. *Des. Stud.* **2017**, *52*, 73–95. [CrossRef]