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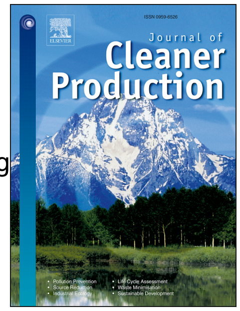

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Towards Sustainable Construction: BIM-enabled Design and Planning of Roof Sheathing Installation for Modular Buildings

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Abstract

Off-site construction and building information modeling technology bring benefits to the construction industry in many respects, such as reduced material waste, and lead to solutions towards sustainable construction. Nevertheless, despite the uptake of off-site construction methods and BIM, massive construction waste in terms of sheathing material (e.g., oriented strand board) is still yielded in the light-frame building industry. This research thus presents an automated building information model (BIM) approach to reducing sheathing material waste by enabling a proactive design and planning of roof sheathing installation for modular buildings. Specifically, a BIM-based sheathing layout design algorithm, which incorporates trades know-how, is developed to achieve the construction design automation. A hybrid algorithm integrating greedy algorithm and particle swarm algorithm is applied in connection with the design algorithm to optimize material cutting plans for the generated layout with the objective of minimizing sheathing material waste. Two case studies are presented to demonstrate the feasibility and effectiveness of the proposed approach in terms of roof sheathing material waste reduction. The results are summarized to provide deeper insights in terms of sheathing waste reduction for more sustainable construction practice.

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Keywords

BIM, Roof sheathing, Off-site construction, Waste minimization, Construction design and planning, Sustainable construction.

1 Introduction

The aim of construction waste management and minimization (CWMM) is to protect the environment by identifying and minimizing wastes from construction and thereby reduce its contribution to pollution of the environment (Shen et al., 2004). In this respect, Giroux Environmental Consulting (GEC) (2014) categorizes the sequences of CWMM as the 5Rs, which are (1) reduce; (2) reuse; (3) recycle; (4) recover (energy); and (5) residuals management/disposal. As the first R, waste reduction targets minimization of waste at source. Any waste that is incurred should be reused or recycled to reduce its impact on the environment. When there is still waste after the second and third Rs, “recover” is implemented to recoup energy in the form of electricity, heat, or steam from waste sources. Finally, any remaining waste is buried in the ground as landfill, which is the most common final disposal option. The recover and residuals management/disposal sequences require several societal responsibilities and efforts, such as a large amount of budget and time allocated to processing waste at the disposal facility. For this reason, better construction planning and management is crucial in CMWM as it can significantly reduce the waste generation by not only avoiding rework and unnecessary material handling, but also using construction materials efficiently (Won & Cheng, 2017). Accordingly, the design and planning stage is the most important period in the life cycle of construction projects in terms of reducing construction waste (Esa et al., 2017; Ghose et al., 2017). Proper design and construction planning provide many environmental benefits, reducing not only construction waste (by up to 40%) but also greenhouse gas emissions (Ding & Xiao, 2014).

Off-site construction is regarded as a promising construction method to reduce the generation of construction waste (Jaillon et al., 2009; Meibodi et al., 2014). Off-site construction is an approach that "brings on-site construction works into a climate-controlled facility where advanced machinery and manufacturing technologies can be utilized to prefabricate buildings in a standardized and efficient manner" (Liu et al., 2017). Off-site construction affords the opportunity to effectively implement managerial improvements and to re-engineer construction processes into efficient manufacturing processes. As such, off-site construction has the potential to significantly reduce the waste associated with conventional construction processes. This has been substantiated by recent research such as studies in Hong Kong, where an average reduction of 52% in construction volume (Jaillon et al., 2009) and a reduction of 70% in concrete waste (Lawton et al., 2002) was achieved through the use of off-site construction methods. Despite the use of the off-site construction method, however, massive amounts of construction material waste, such as in the form of sheathing material (e.g., oriented strand board), is still generated in the light-frame building industry. Building components, including wall studs, floor joists, and roof trusses in light-frame buildings, need to be covered using sheathing sheets to form the building exterior. Raw sheathing sheets, however, come in rectangular shapes of varying dimensions (e.g., 4′ × 8′ and 4′ × 12′). These sheathing sheets of nominal sizes need to be cut to fit the designed dimensions, then fastened to the studs, joists, and trusses. According to the industry benchmark (Liu et al., 2018), the construction waste of sheathing sheets in the light-frame building manufacturing industry falls within the range of 12.57% and 22.62% (percentage of total material used). The amount of sheathing material waste attributable to roof systems in particular accounts for more compared with walls and floors and increases with the increasing level of complexity of roof systems.

In reality, it is challenging to proactively design the sheathing layout and plan material cutting for the roof system of light-frame buildings due to the complexity of its geometry and the absence of specific geometrical representation in design (Formoso et al., 2002; Al-Hajj & Hamani, 2011). To overcome this challenge, Won & Cheng (2017) suggest that building information modelling (BIM) is a promising alternative since it provides digital representation of building components and allows users to extract the geometrical information in order to generate prefabricated shop drawings that may be used for automated and machinery processing on a production line. As such, BIM offers the potential of implementing proactive plan and management techniques in relation to construction material usage. Nevertheless, in current practice the enrichment of construction details, such as the roof sheathing layout, into the BIM model is both manual and tedious such that the model is usually not sufficiently robust and detailed for use by building trades in the field. In this respect, there is a lack of design algorithms for automated enriching BIM for specific construction applications, and this impedes the effective and efficient expansion of BIM in the industry (Ding et al., 2014; Tan et al., 2019). For this reason, construction practitioners still make their decisions regarding the roof sheathing layout and the cutting plan of material sheets on an ad hoc basis using rules of thumb. Such an experience-based approach to roof sheathing installation results in considerable material waste. Partly due to this fact, off-site construction has not been leveraged to its full capacity (Hwang et al., 2018), especially in terms of sheathing waste minimization, in the light-frame roof construction. There is a pressing need for innovative technology and a robust tool to supplant the experience-based, as hoc approach to roof sheathing installation and effectively enable the proactive design and planning of roof sheathing for light-frame buildings, especially in the off-site construction industry.

To this end, this research explores an automated BIM-based approach to designing sheathing layouts and planning sheet material cuts (i.e., design and planning of sheathing installation) with a focus on the roof system of light-frame residential buildings. The key contributions of this research are a rule-based roof sheathing design algorithm and hybrid optimization algorithm which are capable of preserving trades know-how in the automated development of sheathing layout design for roofs while minimizing material cutting waste. Additionally, this research addresses the limitations of existing BIM practice in terms of catering to the specific needs of building trades for proactive design and planning of roof sheathing installation. A prototype system is developed and applied to two light-frame roof systems constructed by means of off-site construction methods. Test results are summarized to provide deeper insights in terms of roof sheathing waste minimization for sustainable construction.

The remainder of this paper is organized as follows. In Section 2, previous research is reviewed to clarify the research gap. Subsequently, the research methodology is illustrated in Section 3. Section 4 describes the prototype system development. The case studies, as well as their results and material waste insights, are described in Section 5. The final section concludes the paper, highlighting the research contribution.

2 Literature Review

This section reviews the existing research with respect to construction waste management and minimization (CWMM), and explores how BIM has been used to support CWMM.

2.1 CWMM

Extensive studies on CWMM have been conducted in recent decades to improve sustainability in construction. Among the five phases in the construction life cycle, i.e., (1) initial phase, (2) design phase, (3) construction phase, (4) performance and monitoring phase, and (5) closure phase, these studies have focused primarily on waste minimization in the construction phase (Osmani, 2012; Ajayi et al., 2017a). Typical examples include: (1) development of on-site waste auditing and assessment tools (Saez et al., 2013; Nagpure, 2019); (2) on-site construction waste sorting methods and techniques (Chen et al., 2002; Wang et al., 2010); and (3) reuse and recycling methods (Al-Bayati et al., 2018; Sim & Park, 2011; Zega & Di Maio, 2011). On the contrary, Ajayi & Oyedele (2018) and Ekanayake & Ofori (2004) investigated waste preventive measures using critical design factors during the design phase, including measures implemented as part of the design process (e.g., early collaborative agreement before design activities, and improved communication and coordination between various specialties) and design documentation (e.g., error-free design and detail specification) for construction waste minimization. More recently, Ajayi and Oyedele (2017b) have suggested improving the accuracy and completeness of information in design and detail specification drawings in order to reduce rework and thereby decrease material waste. Furthermore, the improvement of communication and coordination between various trades is key in preventing the generation of construction waste and improving the design process (Ajayi & Oyedele, 2018; Ikau et al., 2013; Al-Hajj & Hamani, 2011). All these efforts have been undertaken to minimize construction waste from the managerial perspective (i.e., managerial improvements).

In addition, researchers and construction practitioners alike have also been seeking to develop various mathematical models and algorithms to minimize waste in material cutting. Some building materials, including reinforcement bar and sheathing sheets, is available only in certain sizes and must be cut to the designed size for use in the given project. Cutting of these materials leads to the cutting-stock problem, which is one of the well-known problems in combinatorial optimization. Many efforts have thus attempted to improve and/or design new algorithms to solve this problem. For instance, Manrique et al. (2009) developed a combinatorial algorithm to solve the one-dimensional cutting stock problem for lumber in wood framing. Porwal & Hewage (2011) and Zheng et al. (2019) applied simulated annealing and integer programming, respectively, to minimize one-dimensional rebar waste. In terms of operational research, Del Valle et al. (2012) and Cui & Zhao (2013) developed different heuristic algorithms for two-dimensional cutting stock problems. These efforts, it should be noted, sought to address the waste minimization problem for generic material by merely formulating a cutting-stock optimization problem, but did not consider specific engineering constraints in material cutting. For example, sheathing sheets are orthotropic plates, such that a sheet is usually cut with its axis (i.e., length direction) perpendicular to the trusses, rather than in an arbitrary direction as in traditional cutting-stock optimization. In this regard, Liu et al. (2018) applied greedy algorithms to address the 2D cutting stock optimization problem for cutting of sheathing sheets. Their work primarily concentrated on optimizing the cutting plan of sheathing sheets with 2D rectangular shapes for walls and floors in residential buildings. The algorithm they presented is not applicable to roof sheathing material cutting as there are 2D irregular shape sheets on roofs. Moreover, to further build upon these efforts, the present research seeks to develop a hybrid algorithm to optimize the planning of sheathing material cuts for 2D irregular shapes for use in various types of roofs in residential buildings.

2.2 BIM for Waste Reduction

BIM has been widely used by industry and academia in CWMM, capitalizing on its capability in terms of parametric modelling, digital representation of building design, collaboration, and coordination (Hardin, 2009; Krygiel & Nies, 2008; Eastman et al., 2008). In this context, Liu et al. (2015) have proposed a BIM-based decision-making framework to minimize construction waste in the design phase. Won and Cheng (2017) have identified potential areas where this can be accomplished, such as design review, 3D coordination, quantity take-off, phase planning, site utilization planning, construction system design, digital fabrication, and 3D control and planning during the life cycle of construction projects, in order to extend the application of BIM in the CWMM. In addition to this, specific applications of BIM in CWMM are represented in the following studies: (1) BIM-enhanced coordination (Ahankoob et al., 2012) and (2) on-site waste management improvement (Hewage & Porwal, 2012). In these contributions, BIM is used to facilitate design-related tasks such as project coordination and communication. With respect to design and planning analysis, BIM can also be used to provide bills of materials for a manually pre-determined design for the purpose of material waste analysis and reduction. For instance, Porwal & Hewage (2011) leveraged BIM as an information hub and integrated the cutting optimization algorithm with BIM in order to minimize structural reinforcement waste. The BIM model in their study, though, must be developed manually with sufficient details of reinforcement. In a sense, these efforts have been undertaken on the premise that the BIM model should be developed manually to a sufficient level of detail as the input for waste analysis. However, for roof sheathing installation and material waste minimization, there is a lack of methodology and algorithms by which to automatically generate construction details (e.g., sheathing layout) based on BIM. This constrains existing BIM practice in terms of its ability to cater to the specific needs of building trades. One recent effort in this regard has been a BIM-based automated design and planning system proposed by Liu et al. (2018) which is intended to design sheathing and drywall layouts on walls and floors in light-frame residential buildings. Still, BIM-based automated sheathing design and planning for complex roof systems, incorporating comprehensive practical trades know-how and material waste minimization with 2D irregular shapes, has yet to addressed.

3 Methodology

The present research investigates a BIM-based approach to (1) automating the sheathing layout design development for light-frame roof systems; and (2) automating waste analysis (i.e., planning the sheet cutting) to reduce the material waste. Specifically, a BIM-based roof sheathing design algorithm, which incorporates trades know-how, is developed to achieve the design automation. A hybrid algorithm integrating greedy algorithm and particle swarm algorithm are applied in connection with the proposed design algorithm to optimize material cutting plans for the generated layout design with the objective of minimizing sheathing material waste. Towards this objective, a series of steps are carried out sequentially. The first step is to interpret the BIM in order to extract relevant information pertinent to roof sheathing design (e.g., truss information). The 3D geometrical information in a given BIM is transformed into a 2D local coordinate system (of roof surfaces) to ease the configuration of the sheathing sheet layout for each component in the later stage. Conceptually, the 2D roof surfaces function as a model view of a given BIM model for the sheathing layout design analysis. Afterwards, the roof sheathing layout design algorithm is developed to formulate sheathing design alternatives based on the building information extracted from the BIM. To preserve constructability in the generated sheathing design, trades know-how is interpreted as object-based machine-readable codes and incorporated into the design algorithms. Upon the completion of the sheathing layout design using the design algorithm, quantities of designed sheathing sheets are obtained. It is worthy to note that designed sheathing sheets vary in shapes from triangular, rectangular, parallelogram, trapezoid and other irregular 2D shape due to the complex geometry of roof systems. Subsequently, the material waste minimization is performed to determine the material cutting plan (i.e., waste analysis) for designed sheathing sheets. In such cases, cutting roof sheathing sheets from nominal sizes (e.g., 4′ × 12′ with the shape of rectangular) to designed sizes (with the shape of trapezoid and other irregular 2D, etc.) is formulated as an irregular shape 2D cutting stock problem. Although roof sheathing sheets are three dimensional products in rectangular shapes of varying dimensions (e.g., 4′ × 8′ and 4′ × 12′) and thicknesses (e.g., 1/2″ and 5/8″), the sheets are always cut in the direction of either the length or the width of the sheet. As a result, the optimization problem is indeed a 2D cutting stock problem. A hybrid algorithm integrating particle swarm optimization (PSO) and greedy algorithms is developed in planning the material cutting. Finally, two case studies are selected to demonstrate the feasibility and applicability of the proposed solutions.

Notably, although BIM represents the use of n-D models to facilitate the planning, design, construction, and operation of a facility, this 2D mathematical optimization problem does not discourage the use of BIM. Essentially, BIM provides a rich information repository that allows project stakeholders to easily access and share information across the project lifecycle for seamless collaboration and decision support. In this regard, BIM is crucial in this research since it provides the necessary inputs (e.g., roof and truss information) for the computational analysis (i.e., sheathing layout design analysis and sheathing cutting waste analysis). Specifically, discipline-specific 3D BIM models (i.e., architectural and structural BIM models) are taken as inputs in this research; then, the sheathing layout design algorithm automates the generation of construction design details to serve the needs of construction practitioners, while the sheathing cutting waste algorithm formulates the material cutting plan to minimize construction waste. Meanwhile, building information generically takes the form of an object-oriented representation in the BIM model, regardless of whether the visualization is 2D or 3D. Rich information and its object-oriented representation of BIM boost the efficiency of information extraction. In this research, roof and truss information required for sheathing installation is extracted and manipulated in the object-oriented form. The 3D geometrical information is merely transformed into 2D to ease the configuration of the sheathing sheet layout for each component (i.e., computational design analysis). In the following sections, the layout design analysis and waste minimization analysis are described in detail.

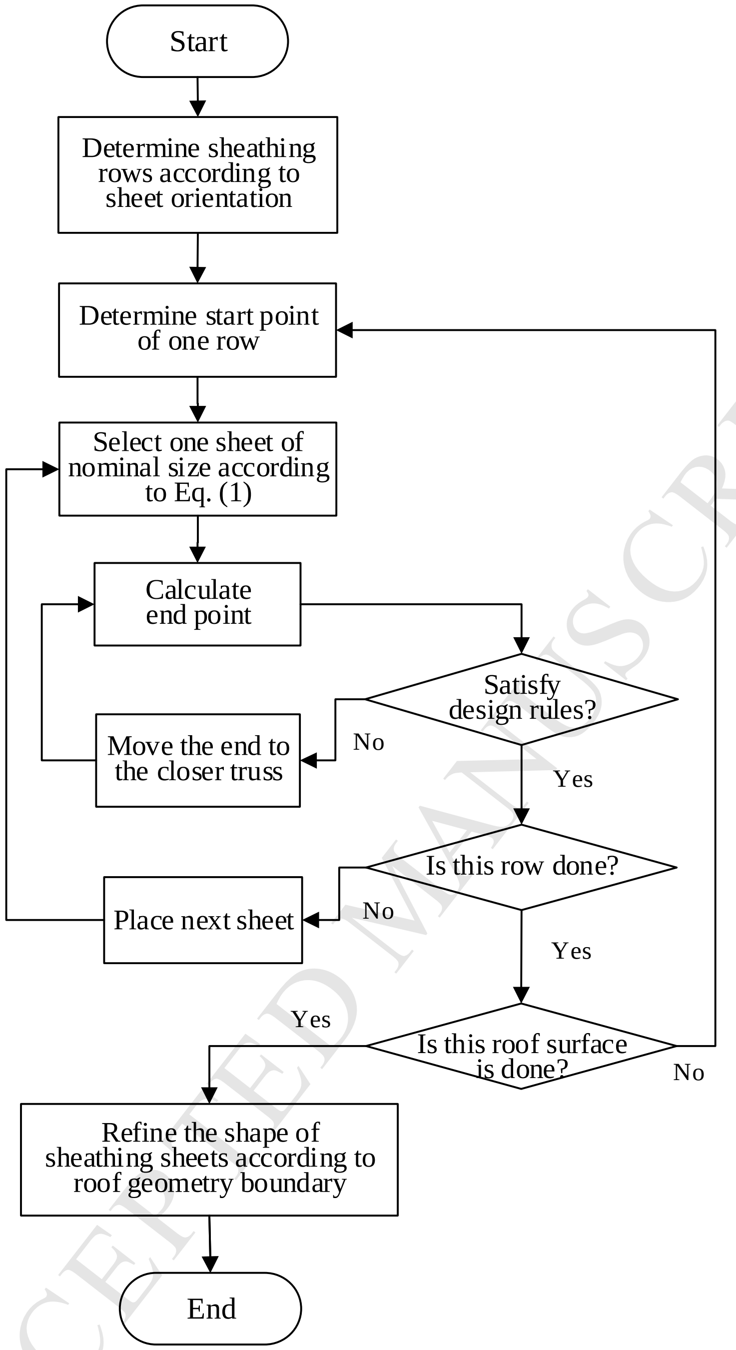
3.1 Sheathing Layout Design Analysis

In some cases, construction details are missing from discipline-specific BIM models, which means the existing BIM cannot be used to facilitate construction operations in the field, such as in the case of roof sheathing installation. As such, a sheathing design algorithm is required in order to automate the sheathing layout design generation. This algorithm is capable of detailing the construction design for the subsequent waste analysis. It should be noted that it is crucial to follow trades know-how in laying sheathing sheets on roofs to improve structural integrity and to boost operational efficiency during construction. For instance, sheathing sheet seams should always be spliced on the trusses and/or be staggered, while the sheet orientation should be perpendicular to the trusses. These rules are collected from the industry partners, translated into computer-processable codes, and encoded in the roof sheathing design algorithm to ensure the generated layout design alternative complies with trades know-how.

Figure 1 presents the flowchart of the roof sheathing design algorithm. It begins with the identification of the sheathing rows of one roof surface. For each sheet row, the algorithm begins by identifying its start point; then one sheet of the sheet of nominal size (e.g., 4′ × 8′ and 4′ × 12′) is placed perpendicular to the trusses at the identified start point. The rules of nominal size selection are expressed as in Eq. (1). Subsequently, the end point of the sheathing sheet is calculated. Next, this end point is checked against the object-based rules to ensure that formalized design rules, such as *Lay sheet edge on stud* and *Stagger sheet edge*, are satisfied. In case of any non-compliance, the sheathing sheet is cut shorter to adjust its end point, and a new end point satisfying all design rules is re-calculated by the algorithm. This end point then serves as a new start point at which to place the next sheathing sheet. The processes for one roof surface do not terminate until all sheathing rows have been placed. The same process will be applied to all other roof surfaces in the given BIM, and the design algorithm does not terminate until sheathing sheets have been placed on all roof surfaces in the BIM. Once all sheathing sheets of rectangular shape are placed on the roof, the interaction of sheet edges with roof edges is captured for the purpose of refining the shapes of the designed sheets (as shown in Figure 2). Figure 2 shows two examples of sheathing layout designs for trapezoid and irregular roof surfaces. The upper section of Figure 2 represents the initial sheathing layouts with rectangular sheets, while the lower panes in the figure show the final sheathing layouts for the given two examples. The waste for each of the generated layout designs is then determined using the hybrid optimization algorithm described in the following section.

$$L_n = \begin{cases} 12, & (L_r \, mod \, 12 < 0.01) \, or \, (8 < L_r < 12) \\ 8, & others \end{cases} \quad \text{Eq. (1)}$$

where L_n represents the length of selected nominal size; L_r denotes the length of sheathing row.



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279 Figure 1 Roof sheathing layout design algorithm

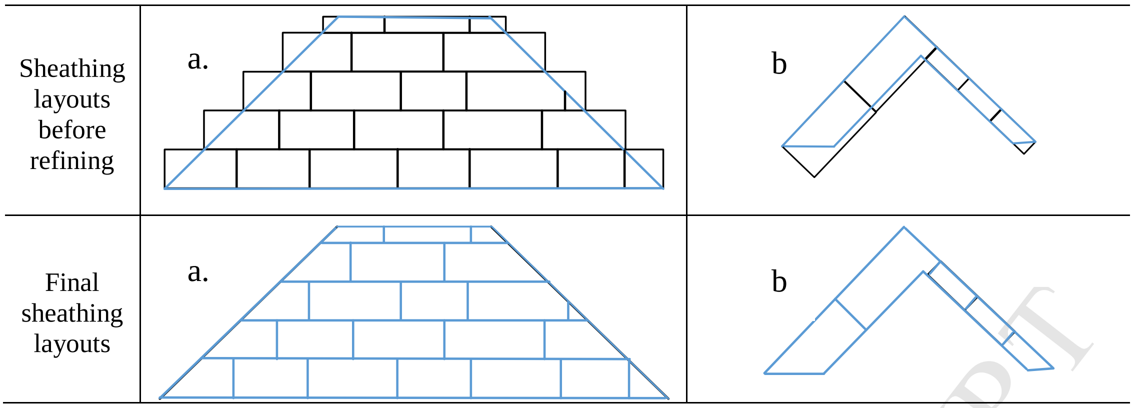


Figure 2 Sheathing layout design examples (top down view): a. trapezoid; b. irregular

3.2 Sheathing Cutting Waste Analysis

The dual objective of this research is to automate the roof sheathing layout design while minimizing material cutting waste for light-frame buildings under construction constraints. The design algorithm in the previous section takes the building information from BIM to generate a sheathing layout design. By doing this, construction design details are determined in an automated fashion, while the quantity of designed sheathing sheets can be extracted for the material cutting analysis. In this research, the cutting of roof sheathing sheets is addressed as a two-dimensional (2D) irregular shape cutting optimization problem to minimize construction material waste for the generated layout design. The rationale arises from the fact that some designed sheathing sheets are in irregular shapes due to the complexity of the geometry of roof systems of residential houses (as shown in the Figure 2). It should be noted that the 2D irregular shape cutting optimization problem is to assign a set of 2D irregular-shaped items to a rectangular object in a pattern by which we cut the rectangular object into 2D irregular-shaped items to minimize material waste. Traditionally, the width of the rectangular object in 2D irregular shape cutting optimization is fixed, while "*its length is extendable and has to be minimized*" (Shalaby & Kashkoush, 2013). In the case of roof sheathing, the width and length of the raw sheathing sheet are fixed because they are available in rectangular shapes with certain dimensions (e.g., 4′ × 8′ and 4′ × 12′), while the number of sheets of nominal size is a variable that must be minimized to achieve the maximum reduction in construction waste. The objective function is expressed as in Eq. (2):

$$O.F. = \min(\mathrm{W}) = \min(\sum_{i=1}^{n}(A_i - \sum_{j=1}^{m} A_{i,j})) \quad \text{Eq. (2)}$$

$$\text{s.t.} \qquad A_i \in \{32,48\} \quad \text{Eq. (3)}$$

$$0 \le A_{i,j} \le 48 \quad \text{Eq. (4)}$$

$$A_i - \sum_{j=1}^{m} A_{i,j} \ge 0 \quad \text{Eq. (5)}$$

where W denotes the material waste associated with the layout design alternative; A_i denotes the area of sheathing sheet stock $\boldsymbol{i}$; n is the number of stocks; $A_{i,j}$ is the area of the j^{th} designed sheathing sheet cut from the i^{th} sheathing sheet stock, determined based on the sheathing layout design; and m is the number of sheathing sheets cut from the i^{th} sheathing sheet stock.

3.2.1 Greedy and PSO-based Hybrid Optimization Algorithm

Essentially, the 2D irregular shape cutting optimization problem is nondeterministic polynomial (NP)-complete. There are two main approaches in solving this optimization problem: (1) sequence-based approach and (2) direct approach (Shalaby & Kashkoush, 2013). The Greedy and PSO-based hybrid optimization algorithm is a sequence-based approach, and is developed in this study to solve the sheathing cutting optimization model. There are two stages in this hybrid algorithm: (1) optimize the packing sequence of sheathing sheets by means of PSO and (2) place/pack the sequenced sheathing sheets, using a greedy algorithm-based placement method, into sheathing sheet stocks. In this hybrid algorithm, the material waste yielded by any packing sequence is evaluated by the greedy algorithm-based placement method and further minimized by attempting various packing sequence from PSO along a number of iterations. The greedy algorithm is used in the sequence-based approach due to the fact that it can provide an optimized solution in a timely manner (Esparza, 2003). However, the resulting solution may not represent the truly "global optimum" due to the non-deterministic polynomial-time (NP-hard) nature of this cutting-stock optimization and the limitation of the employed greedy search algorithm (e.g., search heuristics are embedded). To further minimize material waste and improve the optimization results generated by the algorithm itself, greedy algorithm is integrated with a particle swarm optimization (PSO) algorithm, which is intended to gradually reduce the material waste in each iteration during the evolution. The PSO is selected as it is superior to other evolutionary algorithms, such as genetic algorithm, in converging speed, especially for large scale, complex system optimization (Lu et al., 2006). The material waste in each iteration is minimized and calculated by means of a greedy algorithm-based sheet placement algorithm, while the PSO algorithm, although it does not guarantee an optimal solution, is capable of moving toward a better solution based on swarm intelligence. The evolutionary process of material waste, as described in Section 5.1, demonstrates the suitability and necessity of the hybrid algorithm to address the NP-hard nature of cutting-stock optimization. In the interest of brevity, the particle representation of PSO and integration between greedy and PSO algorithm are demonstrated in this paper, whereas detailed explanations of the PSO algorithms can be found in previous studies (Eberhart & Kennedy, 1995).

To achieve the greedy-PSO integration, the priority-based particle representation of PSO is employed in the present research. Originally, this representation was proposed by Zhang et al. (2006) to tackle a resource-constrained project scheduling problem (RCPSP). In RCPSP, the PSO algorithm with priority-based particle representation seeks the optimum solution by identifying a combination of priority values that are assigned to construction activities and prioritizing activities for limited resources. Analogously, in the 2D irregular shape cutting optimization, the PSO algorithm with priority-based particle representation (as shown in

Figure 3) is employed to prioritize the packing of sheets (i.e., determining packing sequences), instead of construction activities, to generate the best packing pattern that leads to the minimized material waste.

Designed Sheet ID	1	2	3	4	5	6
Position Vector:	0.64	2.68	5.85	4.05	0.86	4.98
Actual Packing Priority	1	3	6	4	2	5

Figure 3 Priority-based particle representation in PSO

In the greedy-PSO integration, the PSO algorithm feeds the greedy algorithm-based sheet placement model with packing priority of sheets (i.e., position vector) throughout iterative processes. The sheet placement model, serving as the “objective function calculator”, in turn calculates the fitness value (material waste) for the PSO model. Figure 4 illustrates the interaction of these two algorithms in detail. To begin with, the PSO initializes the particles' positions (priorities of all sheets) through random sampling; so for a given particle, the priority information of designed sheathing sheets is sent to the sheet placement model by attaching it to the designed sheathing sheets as attributes. Designed sheathing sheets assigned with priorities are then packed into the sheathing sheets of nominal size in descending order of priority number in the sheet placement model. Following execution of the placement model, the fitness value (material waste) of each particle is obtained from the placement model, and then sent back to the PSO. The PSO further identifies the global best position of all particles and the local best position for each particle in the current iteration. Afterward, each particle in the PSO updates its current state, including velocity and position (i.e., packing priority of sheets), based on the global and local best positions of particles. The next iteration is then started, and new positions of particles are evaluated in the placement model. The iteration processes do not stop until the PSO reaches its termination criteria, i.e., completing the specified number of iterations.

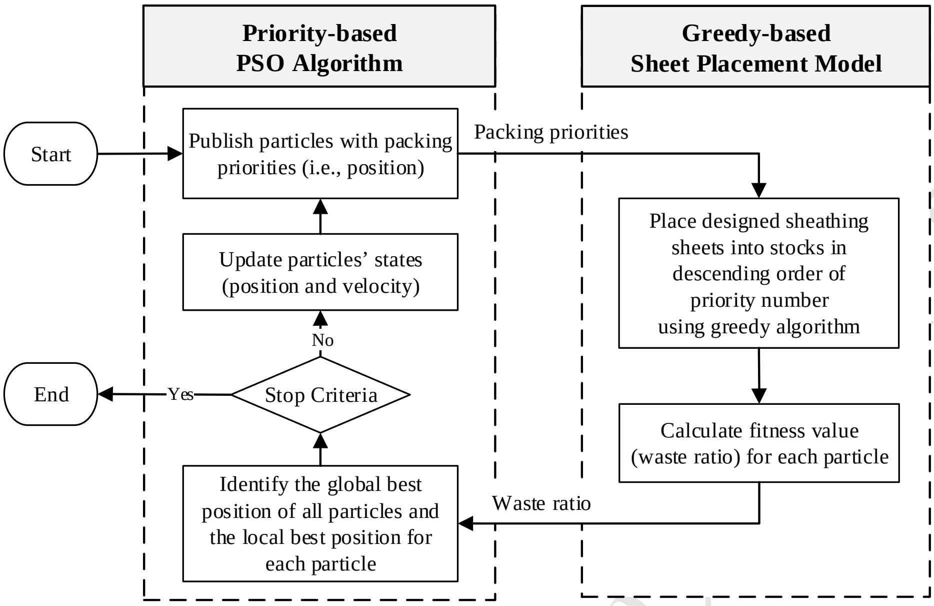
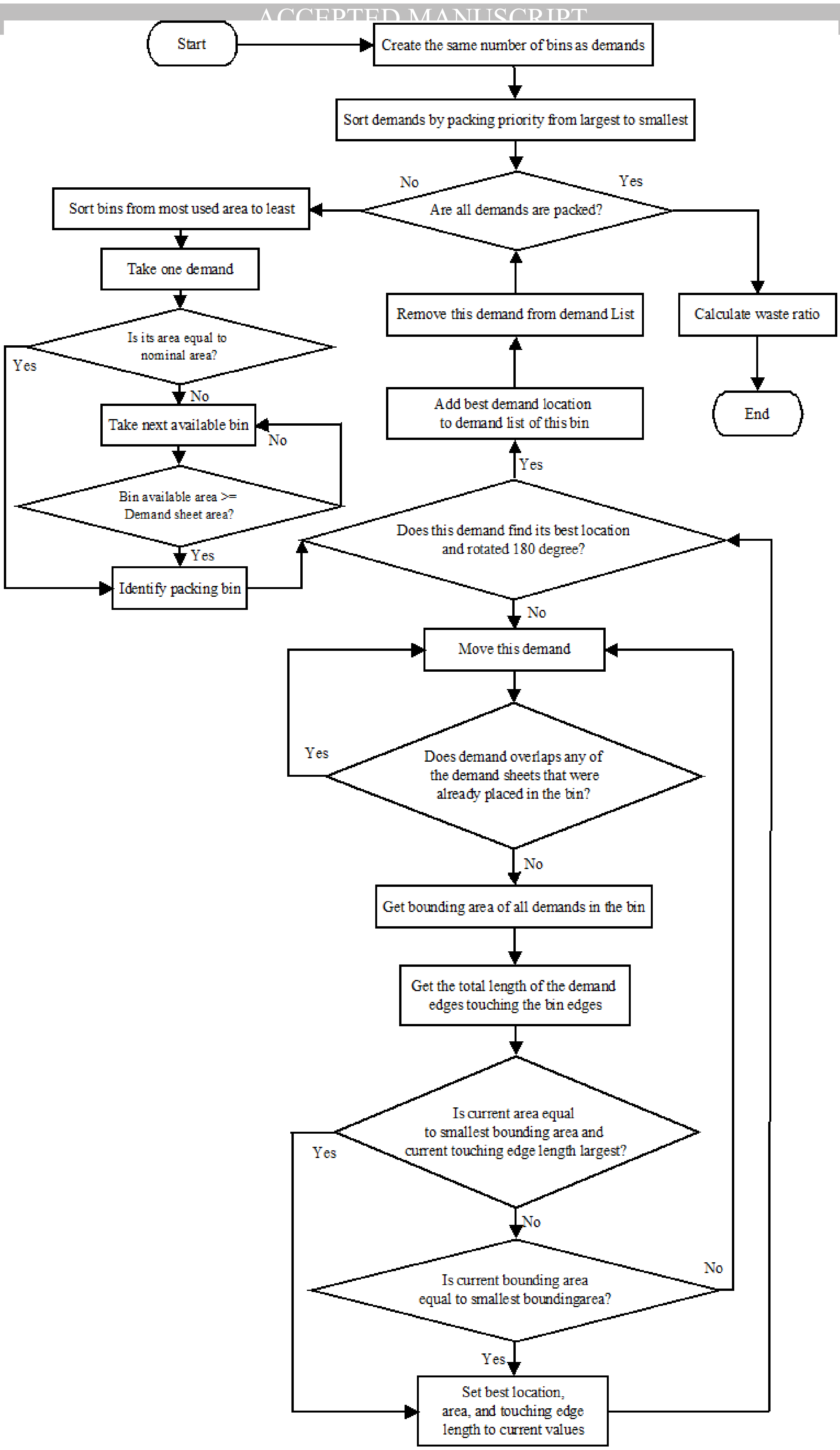


Figure 4 Integration of greedy-PSO optimization

3.2.1.1 Greedy Algorithm-based sheet placement algorithm

Greedy best algorithm is employed to pack and arrange the sequenced sheathing sheets of designed size (i.e., demands) into the sheets of nominal size (i.e., bins). *It is worthy noted that 2D irregular shape cutting of sheathing sheets differs from the traditional 2D irregular shape cutting in the cutting direction*. Sheathing sheets, such as oriented strand board, are orthotropic plates, so that a sheet is usually cut and placed with its axis (i.e., length direction) perpendicular to the trusses. The greedy algorithm-based placement method is designed to tackle this situation. The flowchart of the greedy algorithm-based placement method is presented in Figure 5. It begins with the creation of the number of bins (i.e., sheathing sheets of nominal size). Then, the demands (i.e., sheathing sheets of designed size) are sorted from largest to smallest in term of packing priority generated by PSO algorithm. Following this, the bins are sorted according to the available area from least to most. Afterward, for each demand, its area is compared with the bin area of nominal size (e.g., 4′ × 12′). This is done to exclude the demand that does not need any cutting. If the demand area is equal to or close to the bin area with the cutting tolerance (1/8″), this demand can be generated from the nominal size sheet without cutting and is assigned to the nominal size sheet. Otherwise, its area of the demand is checked against the available area of bins; if its area is greater than the available area; this algorithm then takes the next bin with larger available area in the sorted list of bins and compares demand area with its available area for the potential packing. This checking process does not terminate until the bin that can be used to cut this demand is found. Once the bin for its cutting is determined, the position of the demand sheet in its bin is further determined and refined in the following steps.



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394 Figure 5 Flowchart of greedy algorithm-based sheet placement method

Firstly, the orientations of demand are identified to ensure that the axis of demand is along with the axis of bins. Two orientations with 180 degrees between each other are determined. Then, one of these two orientations are used for a potential placement. The movement of the oriented demand is triggered in four directions including, left to right, bottom to top, right to left, and top to bottom, sequentially. The walking path for the movement is shown in Figure 6. After each movement of one inch, the demand's new position is checked by *CheckIfFitsAndBestByArea* for being a best position. Specifically, the edges of the demand are checked to determine whether or not they are interacting with any existing demands in the current bin. This is done in order to exclude the overlap relationship between this demand and existing demands in the bin. If no, the total length of the demand edges touching the edges of packed demands, along with the bounding area of all packed demands, are then calculated to determine whether or not it reaches its best position in the bin. In other words, *its best position is determined whether or not the bounding area of packed demands is reaching the bin area and the total length of the edges of current demand touching the edges of existing demands in the bin is reaching the maximum*. The movement of demand sheet does not terminate until it reaches best position criteria. Once the oriented demand finds its best position in the bin, the same process for the movement is triggered with the demand being rotated 180 degrees (i.e., the second orientation), resulting in its second-best position. Two potential best positions of this demand in two orientations are then compared and the position with smaller bounding area and longer length of touching edges is then selected as the final position of this demand in its bin. By doing so, the position of the demand is finalized in the bin. After packing the demand into its bin, the next iteration is then triggered for the next demand. The same process will be applied to all other demands, and the placement algorithm does not terminate until demands have been packed into the bins. Finally, the material waste for the sequenced demands is then calculated as the fitness value for the PSO algorithm by this greedy algorithm-based sheet placement algorithm.

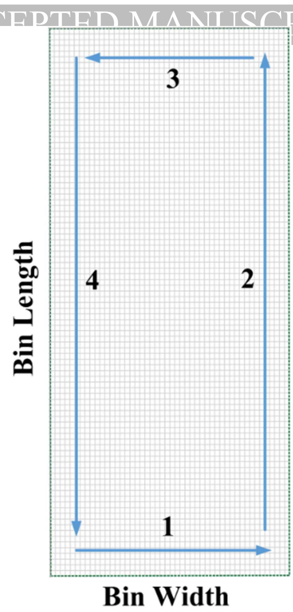


Figure 6 Walking path of demanded sheet into bin

4 Prototype System Development

To implement the abovementioned approach, an automated design and planning system is developed as a standalone application. Its graphic user interface (GUI) is shown as Figure 7. The GUI allows for the 2D visualization of roof layout, sheathing layout design, and cutting plan. BIM models of the roof system in this study need to be developed in SketchUp software. This is because SketchUp is used by our industry partner for roof design and modeling. To take the BIM data from SketchUp into the standalone application, a SketchUp add-on was developed through its application programming interface (API). The add-on is able to retrieve the roof information in the form of a text file (as shown in Figure 8) as inputs for the standalone application. Basically, the roof information such as coordinates of roof surface and trusses is exchanged between SkethUp and the prototype system. It is important to note that the proposed approach is not limited to the SketchUp platform and can be easily shifted from a vendor related SketchUp-based application to other platforms, such as a fully standardized IFC-based BIM application by means of replacing SketchUp add-on.

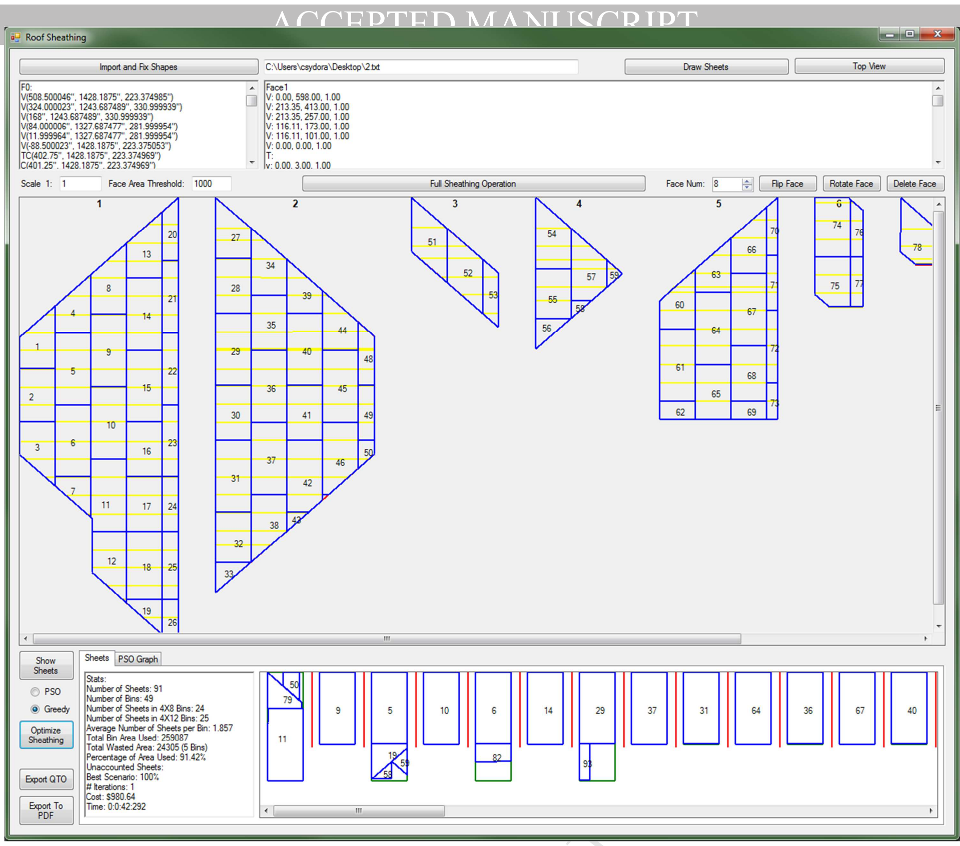


Figure 7 GUI of the prototype system

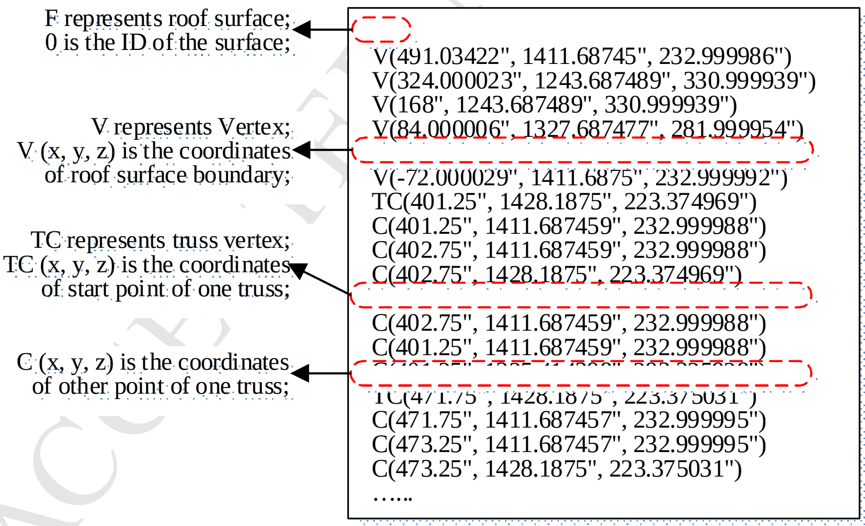
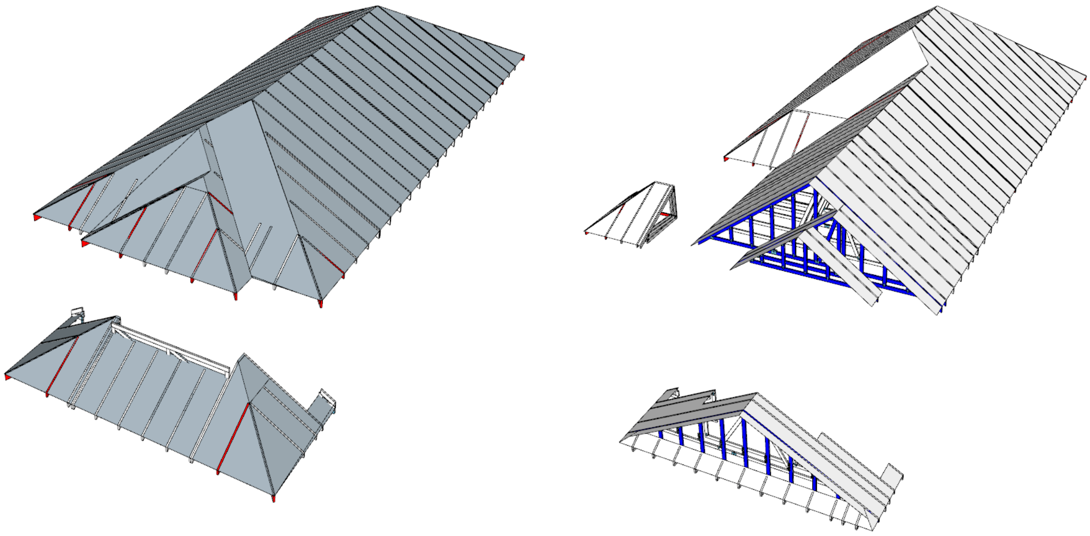


Figure 8 Sample data extracted from 3D BIM model

The sheathing layout design algorithm and hybrid optimization algorithm integrating greedy and PSO algorithms are encoded into the prototype system. To ensure the global optimal search and convergence of the PSO algorithm, its parameters are set in the consideration of previous research (Lu et al., 2008; Zhang et al., 2006). Specifically, the value of cognitive/local weight is set as 1; the value of social/global weight takes 2; the value of w is 0.9 initially, and then it linearly decreases to 0.4 at the maximum number of iterations; and swarm size is 30.

5 Case Studies

Two typical wood-framed single-family houses are selected as case studies for testing the developed prototype system. In these two case studies, one is an attached garage single family home with hip roof (roof with attached garage); the other is a detached garage single family home with hip roof (roof with detached garage). Both models also had a veranda roof on the main level. The BIM models of the framed truss roofs are shown in Figure 9. On average, the prefabricated production facility of our industry partners (see Figure 10.a) can produce around 40 single family roofs (with an average square footage of 1650) in a month. Note that, the regular steps required to build a stick framed truss roof are as follows: (1) get engineering design for the truss package; (2) estimate the roof lumber package and sheathing material based on roof square feet information provided by the roof truss supplier; (3) receive roof truss, sheathing and lumber to the site; and (4) build the roof on site. The process to build a prefabricated truss roof at our industry partners is as follows: (1) get roof truss design from the truss supplier; (2) receive roof truss at the plant; (3) build the panel roof in the plant; and (4) transport the roof panels to the site and install. During prefabrication, a quantity estimation of roof sheathing is not necessary as roof panels are built in the plant where sheathing and lumber are stock items and purchased regularly to maintain the inventory. In the case study implementation, an accurate quantity of sheets of sheathing is calculated by the prototype system and material consumption is monitored. For case studies, the truss supplier provides a 3D DWG file which is used as the input to prepare the optimal cut list of the sheathing sheets. This process was done in multiple steps: (1) import the 3D DWG file into Sketchup program; (2) create a .txt file out of SketchUp containing all the geometric information; and (3) import the text file into the prototype system to calculate the required number of sheets and cut list layout.



a. roof with attached garage b. roof with detached garage

Figure 9 3D BIM model of the roof system

a. Prefabricated production facility b. Panalized roof sytem

Figure 10 Prefabricated production facility and roof systems [image by Mohammed Sadiq Altaf]

5.1 Results

The prototype system generated roof sheathing layout design and the cutting plan (shown in Figure 11 to Figure 13) in an automated manner. The layout design results were verified by the industrial partner, revealing that the generated sheathing design preserves the design rules used in the field. It should be noted that the generated sheathing layouts of some roof surfaces (e.g., Panel 1-3 as shown in Figure 12 and Figure 13) is not stagger due to the fact that roofs system is panelized into roof panels with certain sizes such as 12′ in consideration of transportation (see Figure 10.b). The outputs in the form of 2D drawings (shown in Figure 11) significantly enhance the communication among the project participants. Based on this information, construction practitioners can manage field operations.

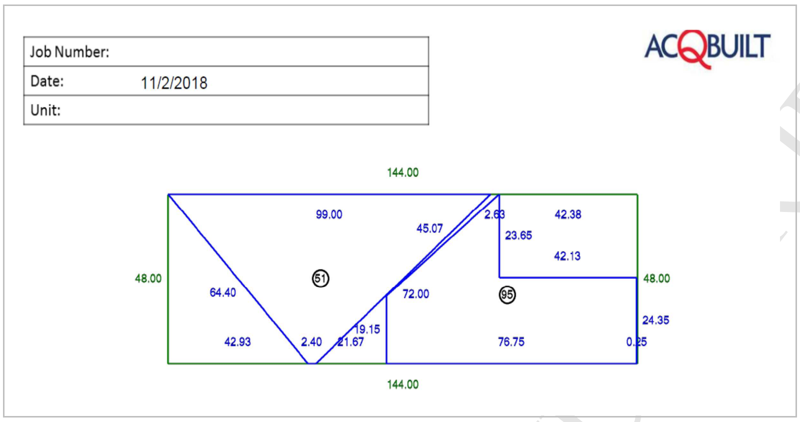


Figure 11 Outputs of the prototype system: example of material cutting drawings

The material waste pertaining to the sheathing installation generated by the prototype system is reduced to 12.1% and 12.91% for the two cases, respectively. Additionally, Figure 12 and Figure 13 show the evolutionary process of the entire PSO swarm in experiments. In the figures, the *x*-axis represents the iteration index, while the *y*-axis denotes the material waste percentage. As noted in the figures, the material waste for the roof with attached garage in the experiment gradually approaches 12.1% over 100 optimization iterations through the greedy-PSO integration. For the roof with detached garage, the material waste evolves to 12.91%. By implementing the cutting plan from the prototype system, the actual material waste for the case studies reached these expected ratios in the field. It should be noted that, at present, there is no machine available for use by our industry partner to cut angled sheets, so all the roof sheathing sheets are cut manually by a worker prior to the installation for the case studies. One worker pre-cut all the sheathing sheets based on the cutting plan generated by the prototype system. It should be noted that, in industry common practice of sheathing installation, roof sheathing sheets are cut as it gets attached to the trusses due to the lack of proactive design and planning technology. For these two specific types of roofs, the benchmarked material waste in the industry partner was found to average 20.09% and 20.73%, respectively. In comparing the waste results with these data, material waste is found to be below the company's historical levels. It reveals the prototype system reduces sheathing material waste through automating the roof sheathing design and planning processes.

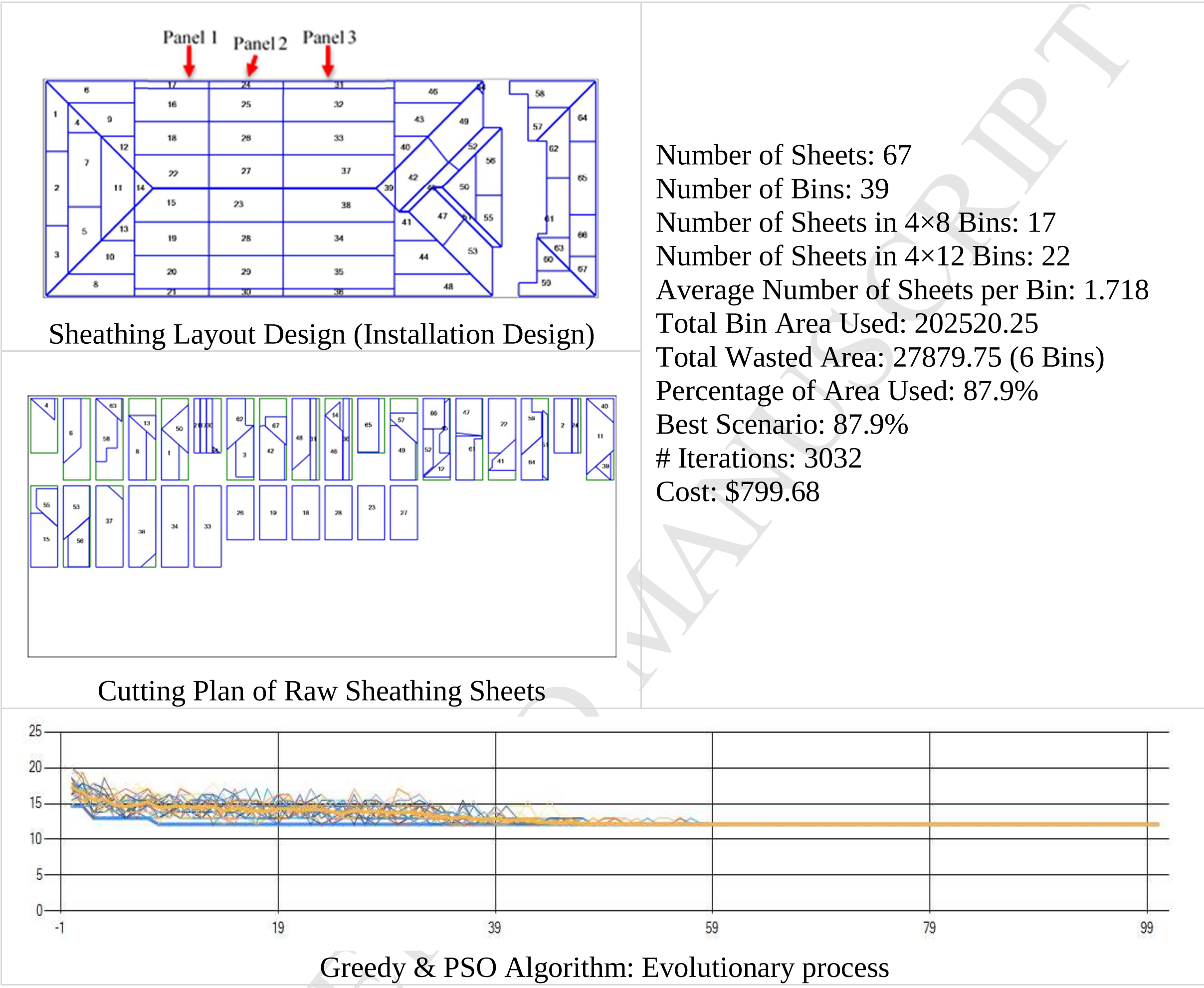
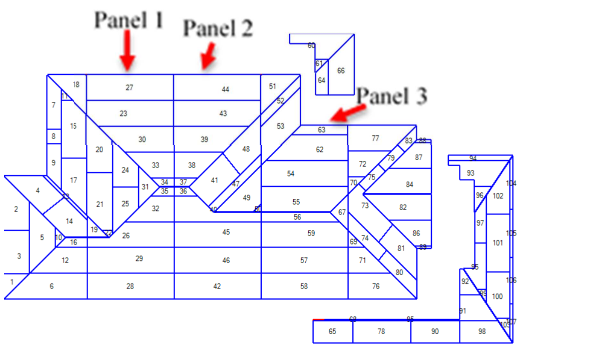
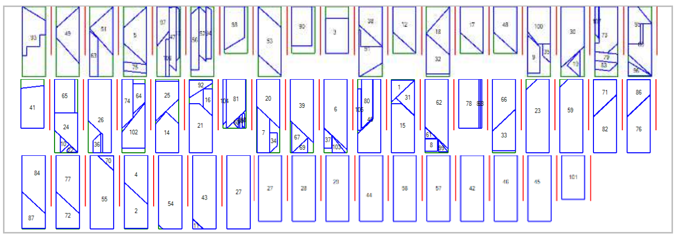


Figure 12 Outputs of the prototype system: Roof with attached garage (Model 1)

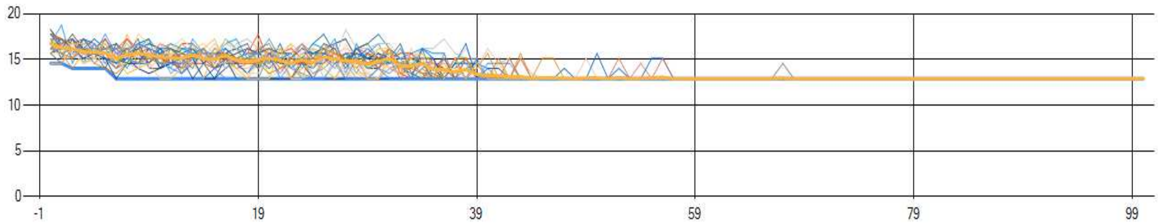


Sheathing Layout Design (Installation Design)



Cutting Plan of Raw Sheathing Sheets

Number of Sheets: 107
Number of Bins: 54
Number of Sheets in 4×8 Bins: 10
Number of Sheets in 4×12 Bins: 44
Average number of sheets per Bin: 1.981
Total Bin Area Used: 304997.08
Total Wasted Area: 45210.92 (6 Bins)
Percentage of Area Used: 87.09%
Best Scenario: 87.09%
Cost: $1230.72



Greedy & PSO Algorithm: Evolutionary process

Figure 13 Outputs of the prototype system: Roof with detached garage (Model 2)

5.2 Discussion

The proposed approach allows for construction practitioners to proactively approach construction design and planning in terms of roof sheathing installation, with the objective of waste minimization. Nevertheless, the use of the off-site construction method is recommended in order to realize the benefits of the proposed BIM-based approach. This is owing to the fact that the “perfect” installation plan demands advanced construction technologies such as those employed in off-site construction, which offer higher efficiency and accuracy in implementing the installation plan in practice. In other words, BIM provides a virtual and computational environment in which for construction practitioners to evaluate various construction plans prior to construction, while off-site construction allows construction practitioners to carry out actual construction activities in a standardized and efficient manner within a user-friendly and tightly controlled factory environment. The dual application of BIM and off-site construction maximizes the benefits of each in terms of increased sustainability in the form of construction waste reduction. In the case studies, all roof sheathing sheets are cut manually by a worker prior to the installation. Manual cutting took more time compared to the install-and-cut approach, especially for a simple gable to gable roof where there are a few angle sheets. An automated sheet cutting machine or construction robot is required to get the full benefits of the BIM-based optimization and proactive design and planning. In this regard, how to integrate the proposed approach with construction robot will be investigated in the future. The proposed approach offered the opportunity of pre-cutting roof sheathing material in order to leverage manufacturing processes, rather than merely building the product in a conventional manner but under a roof. Meanwhile, it also lays the groundwork for lean inventory management within the domain of off-site construction research for light-frame residential buildings, and provides the foundation on which advanced technologies, such as BIM, design algorithms, and off-site construction methods, can be jointly used to minimize material waste and achieve more sustainable construction.

It is also worth noting that the proposed approach, although it can reduce material waste, cannot completely eliminate the waste. The reasons partially lie in the fact that the selection of parameters described in “Prototype System Development” ensures the convergence of the PSO algorithm, but at the same time may lead the solution toward a local optimum to the NP-complete 2D irregular shape cutting optimization problem. Therefore, the minimized solution of case studies may not be the global optimum. In future work, other optimization algorithms could be further explored for such irregular shape cutting-stock optimization problem. Additionally, the raw sheathing material is available in certain sizes so that the material cutting and waste are unavoidable. Moreover, the volume of construction waste is influenced by field trades know-how in the light-frame building industry. It is because field trades know-how intends to make the size of designed sheathing sheets close to nominal size, resulting in substantial material trim waste. The authors made another experiment in which the layout design algorithm use 4′ × 12′ sheets in designing layouts, instead of the rules expressed in equation (1). The test results showed the material waste on average is 5% more compared to the case where the design layout is generated by using formalized rules in this study. In summary, the prototype system was able to reduce the construction material waste in terms of roof sheathing material and provided an analytical approach for construction practitioners to proactively plan the roof sheathing installation.

6 Conclusions

Given that improved sustainability in construction is the underlying aim, this study introduces a BIM-based approach for construction waste minimization, in particular for roof sheathing material in the light-frame building manufacturing industry. This BIM-based approach allows for proactive design of roof sheathing layout and planning of material cutting. In this research, a design algorithm is developed to formulate the roof sheathing layout design in accordance with trades know-how, while a hybrid algorithm integrating greedy and PSO algorithms was applied to solve the 2D irregular shape sheathing cutting problem and to deliver the material cutting plan with minimized material waste. An automated design and planning prototype system is developed and tested using typical wood-framed residential building projects. The field test results show that the sheathing design and installation plan generated from the prototype system ensure design constructability while reducing material waste. The prototype system has been proven to allow project managers to effectively plan field operations by eliminating the guesswork in roof sheathing installation.

The key contribution of this research is the rule-based roof sheathing design algorithm and hybrid optimization algorithm, which are capable of incorporating trades know-how in the automated development of roof sheathing layout for roofs while minimizing material cutting waste. Additionally, the proposed BIM-based approach shed light on computational BIM for engineering applications, which requires two prerequisites: 'information readiness' and 'computational algorithms' (Lu et al., 2017). In this study, 'information readiness' of the BIM is achieved by the sheathing design algorithm, while the 'computational algorithm' manipulates the information and extends the BIM with construction business intelligence (i.e., material installation plan generation).

In the research presented herein, design rules in roof sheathing are comprehensively formalized based on trades know-how and are encoded into rule-based design algorithms to preserve this trades know-how in the development of sheathing layout design. In the case that different design codes and construction rules are applied, the sheathing layout design algorithm should be modified to adapt the proposed method and prototyped system to other buildings where different design rules may apply, while construction practitioners can still rely on the greedy and PSO-based hybrid optimization algorithm to plan the sheathing material cutting. In the case of other types of building projects (other than light-frame building), both of sheathing layout design algorithm and hybrid optimization algorithm need to be modified accordingly to adapt the proposed method and prototyped system to other types of building projects.

Acknowledgments

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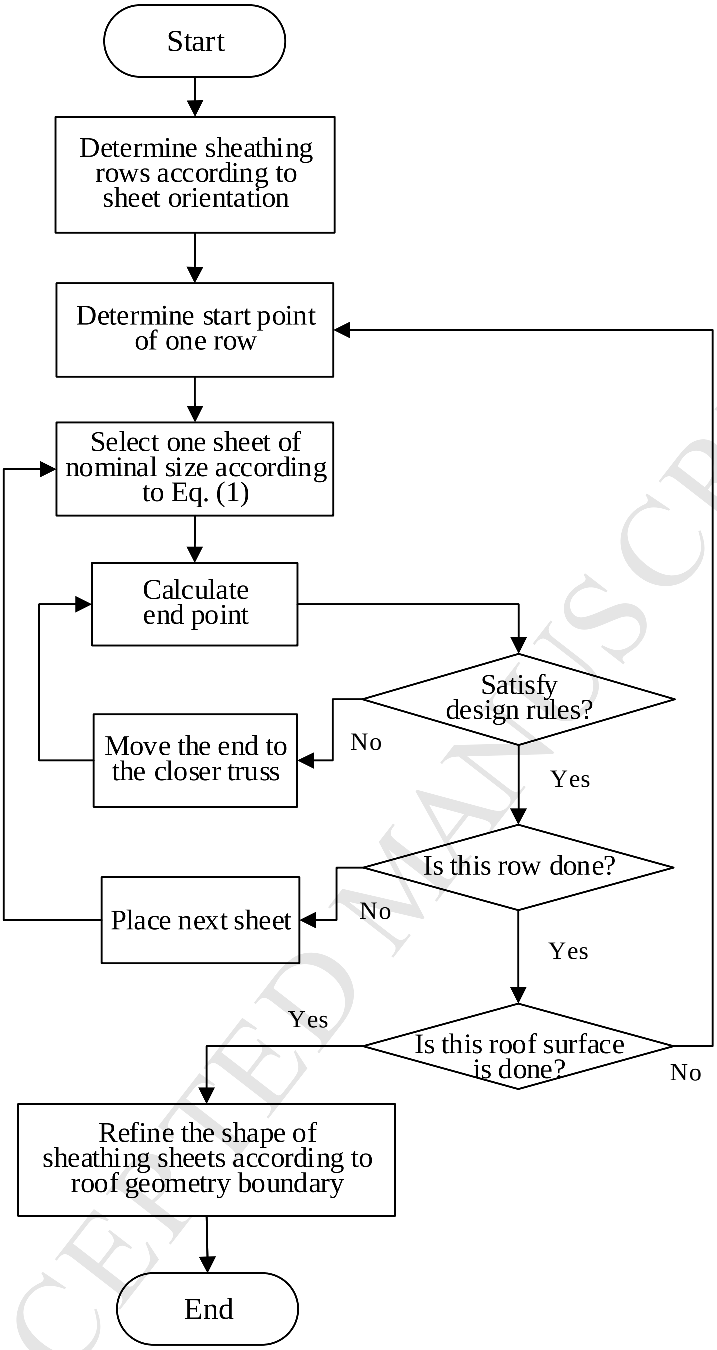


Figure 1 Roof sheathing layout design algorithm

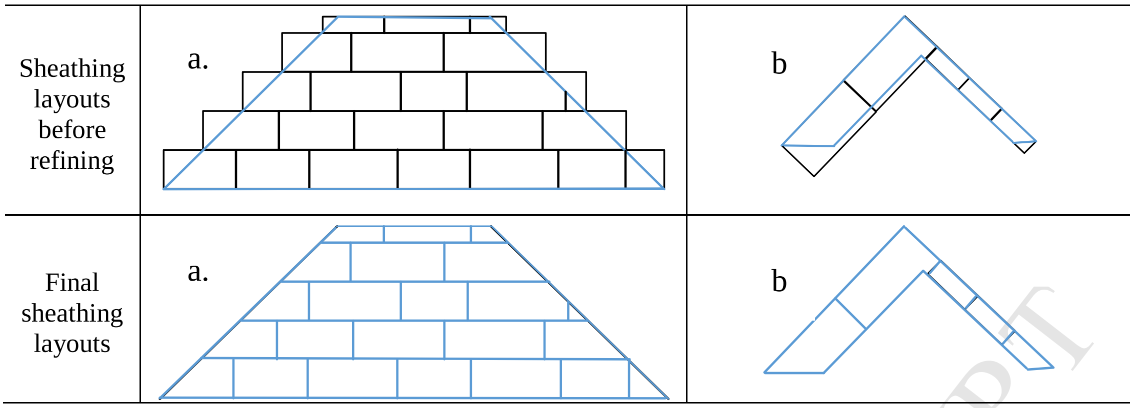


Figure 2 Sheathing layout design examples (top down view): a. trapezoid; b. irregular

Designed Sheet ID	1	2	3	4	5	6
Position Vector:	0.64	2.68	5.85	4.05	0.86	4.98
Actual Packing Priority	1	3	6	4	2	5

Figure 3 Priority-based particle representation in PSO

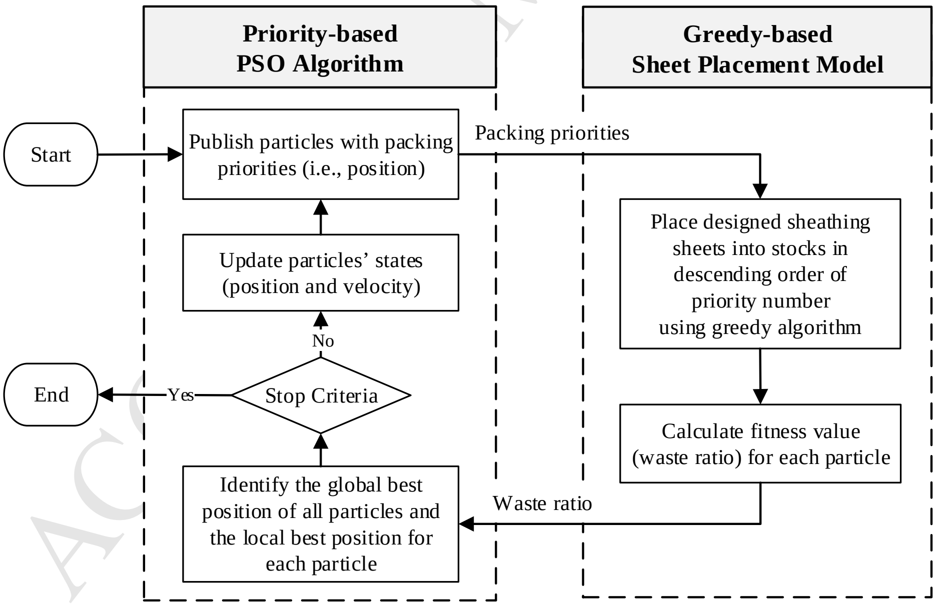


Figure 4 Integration of greedy-PSO optimization

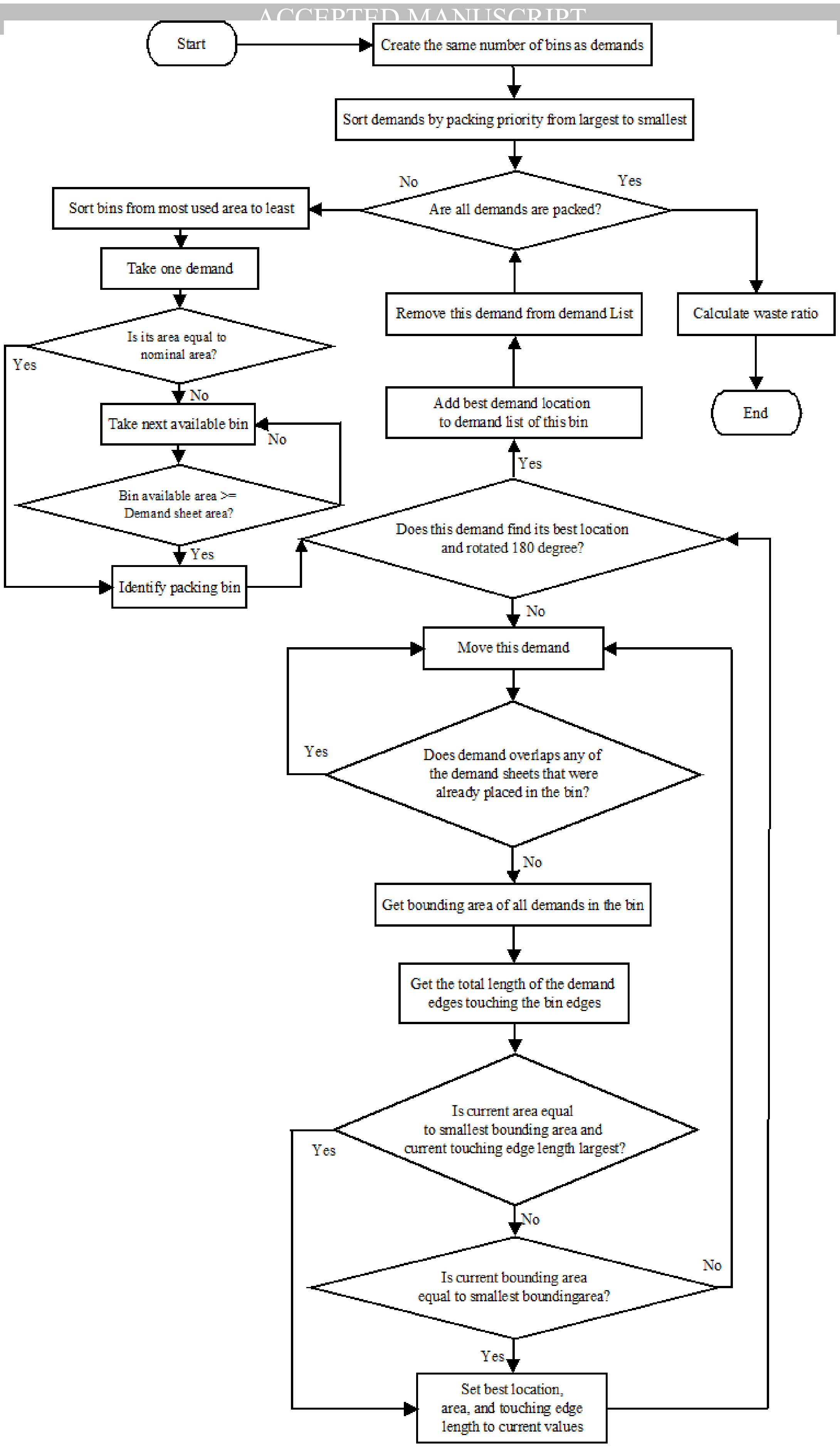


Figure 5 Flowchart of greedy algorithm-based sheet placement method

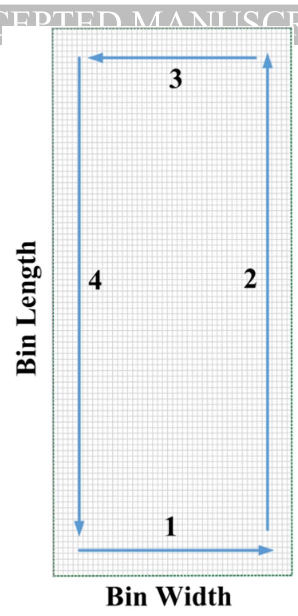


Figure 6 Walking path of demanded sheet into bin

Figure 7 GUI of the prototype system

F represents roof surface;
0 is the ID of the surface;

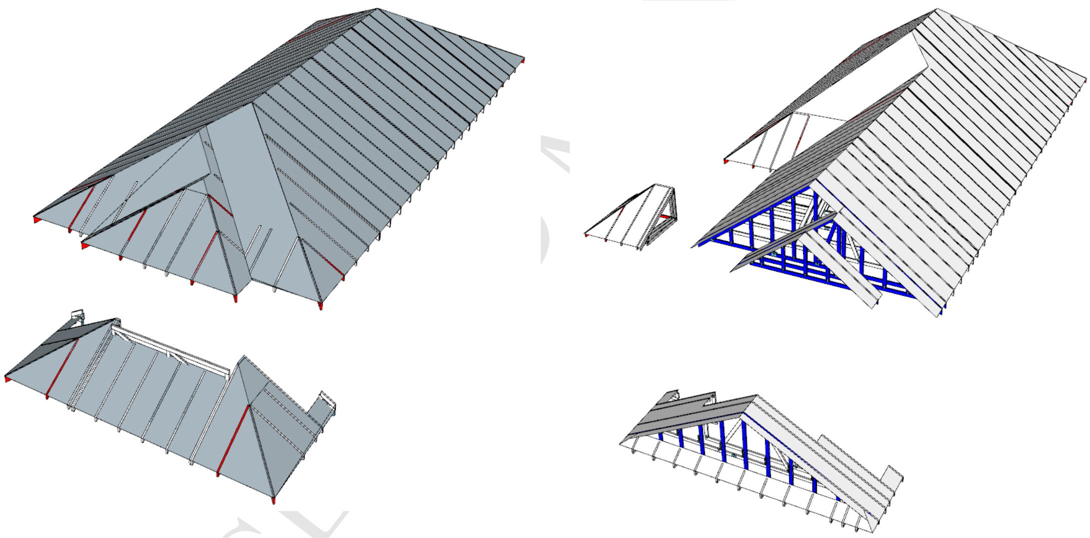
V represents Vertex;
V (x, y, z) is the coordinates of roof surface boundary;

TC represents truss vertex;
TC (x, y, z) is the coordinates of start point of one truss;

C (x, y, z) is the coordinates of other point of one truss;

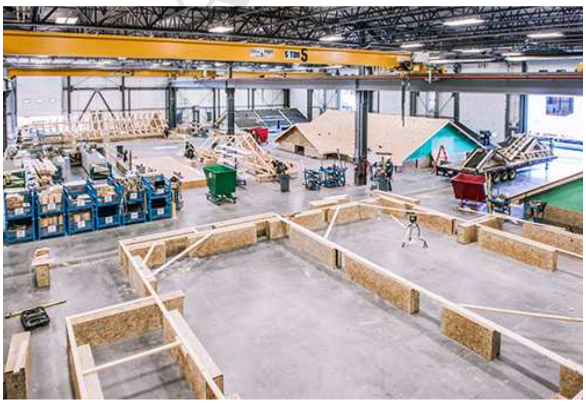
```
F0:
V(491.03422", 1411.68745", 232.999986")
V(324.000023", 1243.687489", 330.999939")
V(168", 1243.687489", 330.999939")
V(84.000006", 1327.687477", 281.999954")
V(11.999964", 1327.687477", 281.999954")
V(-72.000029", 1411.6875", 232.999992")
TC(401.25", 1428.1875", 223.374969")
C(401.25", 1411.687459", 232.999988")
C(402.75", 1411.687459", 232.999988")
C(402.75", 1428.1875", 223.374969")
TC(402.75", 1325.414398", 283.325928")
C(402.75", 1411.687459", 232.999988")
C(401.25", 1411.687459", 232.999988")
C(401.25", 1325.414398", 283.325928")
TC(471.75", 1428.1875", 223.375031")
C(471.75", 1411.687457", 232.999995")
C(473.25", 1411.687457", 232.999995")
C(473.25", 1428.1875", 223.375031")
…...
```

Figure 8 Sample data extracted from 3D BIM model



a. roof with attached garage   b. roof with detached garage

Figure 9 3D BIM model of the roof system



a. Prefabricated production facility   b. Panalized roof sytem

Figure 10 Prefabricated production facility and roof systems [image by Mohammed Sadiq Altaf]

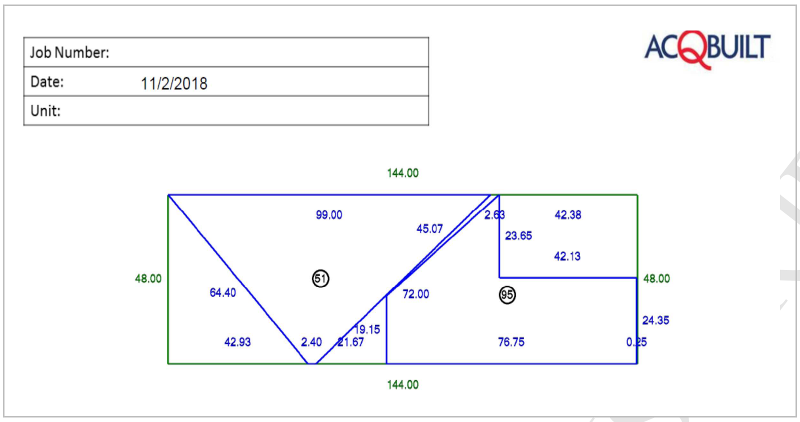


Figure 11 Outputs of the prototype system: example of material cutting drawings

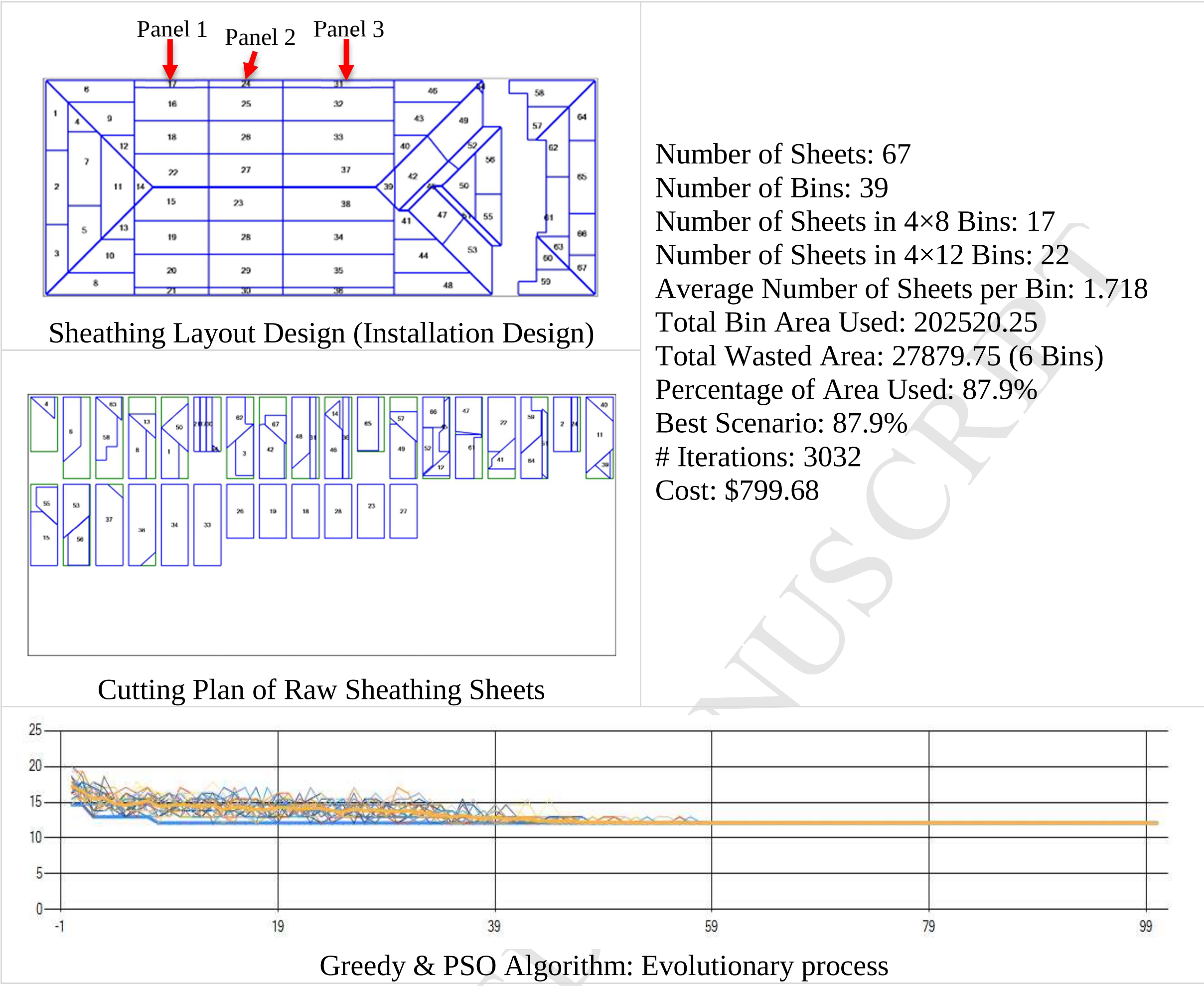
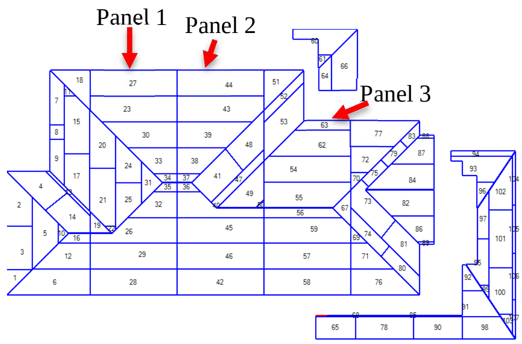
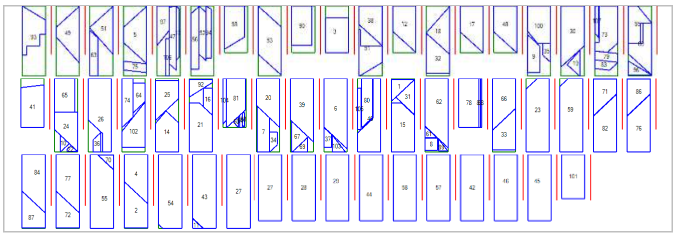


Figure 12 Outputs of the prototype system: Roof with attached garage (Model 1)

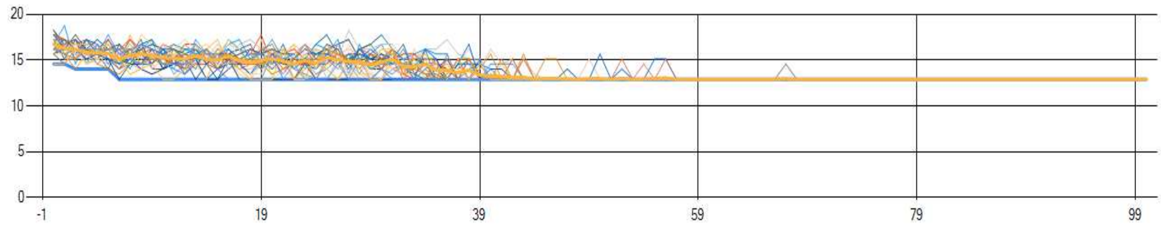


Sheathing Layout Design (Installation Design)



Cutting Plan of Raw Sheathing Sheets

Number of Sheets: 107
Number of Bins: 54
Number of Sheets in 4×8 Bins: 10
Number of Sheets in 4×12 Bins: 44
Average number of sheets per Bin: 1.981
Total Bin Area Used: 304997.08
Total Wasted Area: 45210.92 (6 Bins)
Percentage of Area Used: 87.09%
Best Scenario: 87.09%
Cost: $1230.72



Greedy & PSO Algorithm: Evolutionary process

Figure 13 Outputs of the prototype system: Roof with detached garage (Model 2)

Highlights

> Experience-based roof sheathing installation results in considerable material waste.

> BIM is used to automate layout design and waste analysis for sheathing installation.

> A rule-based design algorithm is developed for generating the sheathing layouts.

> Greedy and PSO-based hybrid algorithm is developed for material cut planning.

> The prototyped system is proven to reduce material waste for sustainable construction.