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Article

Utilizing CNC Router Machine to Construct a Prototype Incorporation Principles of Solid-based Rapid Prototyping Process and Interlocking Brick Design

Suchada Rianmora[a,*], Nutthamon Samorhom[b], and Worapong Chaidilok[c]

School of Manufacturing Systems and Mechanical Engineering (MSME), Sirindhorn International Institute of Technology, Thammasat University, Pathumthani, 12121, Thailand
E-mail: [a,*]suchada@siit.tu.ac.th (Corresponding author), [b]nutthamon.sam@gmail.com, [c]w.chaidilok@hotmail.com

Abstract. Integrating user-friendly concepts into product design fosters innovation, addressing design thinking gaps and minimizing the risk of overinvestment in trial-and-error prototypes. Driven by a "technology-push platform," manufacturers often prioritize product identity over universal design. However, a shift towards standardization promotes user autonomy and reduces costs. This approach empowers future generations to develop or enhance products efficiently through a do-it-yourself (DIY) approach. Upholding environmentally conscious manufacturing, strategic waste reintegration aligns with environmental goals and reduces costs. In CNC Router operations, repurposing unused material promotes sustainable practices. The main objective of the proposed research is to revolutionize rapid prototyping through the innovative use of interlocking brick design, addressing traditional prototyping challenges. This method eliminates the need for adhesives, simplifying assembly and enhancing structural integrity. The proposed research explores solid-based rapid prototyping and interlocking bricks, utilizing a CNC router. Designers optimize bricks through CAD and FEA analysis, facilitating rapid, adhesive-free prototyping. Emphasis on FEA analysis of mechanical properties, 3D slicing, tool selection, and material choice ensures the creation of functional prototypes. Key parameters, including FEA analysis of mechanical properties, slicing the 3D virtual model into layers matching the brick's thickness, appropriate tool selection, and material choice, are critical in achieving the desired outcomes. This comprehensive strategy aligns with a waste-to-wealth concept, illustrating the seamless integration of sustainable practices into innovative manufacturing processes, revolutionizing contemporary design and production. By adopting this approach, manufacturers can streamline production processes, reduce material waste, and enhance product adaptability, ultimately promoting user autonomy and cost reduction.

Keywords: Solid-based rapid prototyping, layer manufacturing process, CNC router machine, interlocking bricks, studs, finite element analysis.

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1. Introduction

The trend of ready-to-assemble (RTA) furniture is rapidly expanding in global manufacturing, significantly affecting both customers and producers. Prototyping techniques such as injection molding, metal casting, and additive fabrication play crucial roles in reducing production time and accommodating complex designs [1]-[4]. Injection molding, for instance, melts materials like plastic or metal to create molds, allowing for high-volume production but is costly and unsuitable for modifying intricate designs [5] – [10].

Reverse engineering (RE) techniques generate 3D CAD models from existing objects, facilitating the efficient production of complex shapes and surfaces. RE is crucial for design modification, recreation, or troubleshooting [11] – [13]. Finite element analysis (FEA) further supports verifying the structural robustness of these models by simulating forces and ensuring compliance with safety criteria before prototyping [14] – [15]. Rapid prototyping (RP) technologies, such as Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM), enable the quick fabrication of prototypes layer by layer from 3D CAD models. While efficient, these processes are often more expensive, making them suitable for unique, low-volume applications. Decision analysis assists in selecting the most appropriate RP process based on cost, considering factors like material and machine expenses [16] – [24].

In this research, a CNC router is utilized for prototype fabrication, commonly applied in woodworking and decorative applications. CNC routers operate with a multi-motor system to enhance speed and accuracy, performing milling and drilling tasks [25] – [28]. By converting 3D virtual models into toolpaths, the CNC router accurately cuts materials, ensuring high surface finish quality. Incorporating user-friendly concepts into product design encourages innovation and reduces design barriers. Over-investing in trial-and-error prototypes can lead to compromised customer satisfaction due to a "technology-push" approach. Conversely, standardizing parts with a universal design platform promotes DIY solutions, reducing costs and time while enhancing product development efficiency. This strategy supports environmentally conscious manufacturing by reintegrating waste materials for reprocessing, recycling, or reuse, contributing to both cost savings and sustainability.

This research explores innovative techniques such as solid-based rapid prototyping and interlocking brick designs for efficient prototype creation. By using a CNC router to cut solid materials into brick shapes, with studs designed through CAD and FEA for optimal structural integrity, easy assembly without adhesives is achieved. This approach not only offers a cost-effective and efficient method for creating functional prototypes but also ensures they meet required loads and stresses.

For "strengthening importance and impact", these following key considerations are revealed:

- *Highlight the novelty:* This research addresses the critical gap in efficiently creating structurally sound prototypes using innovative, cost-effective, and environmentally conscious methods. By integrating solid-based rapid prototyping and interlocking brick designs, this study presents a novel approach to prototype development. The application of CAD and FEA for designing studs ensures optimal load-bearing capacity and stress distribution, while the precision cutting of the CNC router facilitates intricate designs.
- *Quantify the impact:* The findings can significantly reduce manufacturing costs and waste, promoting sustainability and economic efficiency in the engineering sector. The innovative use of interlocking brick designs for easy assembly without adhesives accelerates the prototyping process while minimizing material waste.
- *Target the audience:* The introduction is crafted to resonate with engineers facing challenges in rapid prototyping and sustainable manufacturing, emphasizing practical solutions and industry relevance. By addressing the specific needs and constraints of modern manufacturing processes, this study offers actionable insights and innovative methodologies that meet current industry demands.

2. Related Works

To effectively implement the proposed "waste-to-wealth" concept, where the unwanted raw materials left from the cutting process can be reused and applied to create a new product or purposed in support of start-up businesses or industries employing classic cutting operations such as material removal machines, it is crucial to consider foundational concepts and related research. A review of the definitions of material removal processes, interlocking bricks, and ready-to-assemble products has been undertaken, revealing key insights. These findings serve as essential groundwork for the subsequent implementation and guidelines in this study.

2.1. Material Removal Process

Material Removal Process (MRP) is a broad term used to describe various manufacturing processes that involve the removal of material from a workpiece to achieve the desired shape or size. This process is commonly used in industries such as automotive, aerospace, and medical device manufacturing. Here is a more detailed overview of the information provided in the statement: MRP involves the use of a cutting tool to remove material from the workpiece in the form of chips. The cutting tool is selected based on factors such as the workpiece material, the required accuracy, and the desired surface finish. There are several types of cutting tools used in MRP, such as drills, milling cutters, and grinding wheels. *Milling* is a type of MRP process where the cutting tool rotates and removes material from the workpiece by cutting with its edges. The tool can move in different directions to produce complex shapes. *Drilling* is a process that creates a round hole in the workpiece by using a drill bit. The drill bit rotates and advances into the workpiece, cutting a cylindrical hole in the material. *Turning* is another MRP process where the workpiece rotates and the cutting tool removes material from the workpiece. The cutting tool moves along the length of the rotating workpiece, producing cylindrical shapes. *Grinding* is a process where a grinding wheel rotates and removes material from the workpiece by cutting with abrasive particles. The grinding wheel can be used to produce a smooth surface finish on the workpiece. *Electrochemical machining (ECM)* is another type of MRP process where an electrolyte and an electric current are used to remove material from the workpiece. ECM is commonly used to produce complex shapes and fine surface finishes. MRP is a family of manufacturing processes that involves the removal of material from a workpiece using cutting tools to achieve the desired shape or size. The choice of cutting tool and the cutting parameters depend on several factors, such as the workpiece material, the required accuracy, and the desired surface finish. These processes are widely used in various industries, including automotive, aerospace, and medical device manufacturing [29] – [33].

2.2. Interlocking Brick

Interlocking bricks for built-in furniture are modular units engineered to connect tightly without the use of mortar or adhesives, offering a versatile solution for constructing shelves, cabinets, and walls. These bricks are valued for their ease of assembly and disassembly, making them ideal for customizable furniture designs that can adapt to different spaces and needs. The bricks have demonstrated strong mechanical properties, including excellent compressive strength, resistance to water absorption, and low shrinkage, which make them well-suited for durable and long-lasting furniture. Moreover, interlocking bricks are increasingly recognized for their sustainability. They can be manufactured from eco-friendly materials, reducing the environmental impact of furniture production. The modular nature of these bricks also contributes to waste reduction during both the manufacturing and construction processes. Additionally, their ability to be reused and reconfigured extends the lifespan of the furniture, aligning with principles of sustainable design. Recent research highlights the need for further exploration into the use of interlocking bricks beyond furniture, potentially expanding their application to broader construction projects. The combination of their mechanical robustness, sustainability, and adaptability positions interlocking bricks as a promising material for innovative and eco-conscious design solutions in both residential and commercial settings. [34] – [39].

2.3. Ready-to-Assembly Product

The benefits and limitations of Ready-to-Assemble (RTA) products, along with the importance of considering factors like design and consumer satisfaction during creation and evaluation, have been thoroughly examined to serve as guidelines for the proposed design. A comprehensive review focused on the diverse range of RTA products, emphasizing their advantages—cost-effectiveness, ease of transportation and storage, and reduced environmental impact [40] – [47]. These benefits guide users and designers toward the promising application of this concept. Conversely, the limitations, such as potential quality issues and the requirement for end-user assembly, were underscored. Various types of RTA products, including furniture, cabinetry, and modular housing, were meticulously planned for assembly under specific conditions. The design and usability of RTA products necessitate careful consideration of factors like material selection, assembly methods, and user experience. Additionally, a novel geometric parameter for self-centering connections, crucial in the design of RTA products, has been introduced. Self-centering connections, known for their intricate geometries, pose design challenges, and the proposed parameter optimizes their design, demonstrated through computer simulations that showcased enhanced performance. As RTA furniture gains popularity for its affordability and convenience, consumer satisfaction became a focal point. A survey targeting end-users investigated into factors influencing satisfaction, revealing that product quality, assembly instructions, and ease of assembly played pivotal roles. Further insights were derived from a usability study utilizing eye-tracking technology, exploring the intricate assembly process. The findings, influenced by factors like assembly instructions, process complexity, and user familiarity, offer valuable insights to enhance the overall design and usability of RTA products.

3. Research Concept

Since the proposed approach for creating a ready-to-assemble product involves the analysis of solid-based layer manufacturing process and interlocking bricks, with the key component being the brick which consists of cylindrical studs and rectangular blind holes. The 3D virtual model is sliced into layers with the thickness of each layer equal to the thickness of the brick. The accuracy of the obtained prototype depends on the size and thickness of the brick and studs, and Finite Element Analysis (FEA) is used to analyze the appropriate design of the studs. The appropriate cutting tool and raw material are then determined based on the simulation results.

The key considerations of the proposed approach are FEA analysis of mechanical properties, slicing 3D virtual model, selection of appropriate cutting tool and raw material, and generation of toolpaths.

To accomplish the goal of the proposed approach, a

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classic cutting machine, specifically the CNC router machine in this case study, is repurposed to generate alternative designed parts from unwanted raw materials, establishing a “waste-to-wealth” platform. This involves a comprehensive analysis of the solid-based layer manufacturing process and interlocking bricks concepts, identifying relevant parameters to align with the desired cutting conditions and stud shapes.

The key component of this approach was the brick, which consisted of round cylindrical studs (on the top portion) for holding another part above it and rectangular blind holes (at the bottom portion) for locking the studs of another brick. When each brick was stacked up together, the prototype was obtained. The material used for producing the brick was acrylic sheet. In the design process, the 3D virtual model was sliced into layers with each layer’s thickness equal to the thickness of the brick.

One layer might contain more than one brick, depending on the scale and shape of the desired model. For the initial stage of the research, a simple rectangle shape of the brick was analyzed and applied. The overall process of the proposed approach was shown in Fig. 1 The precision of the prototype produced using the proposed technique was determined by the size and thickness of the brick and studs. Since adhesive material was not required for the technique, the size of the stud was a crucial factor to consider before designing the brick and slicing the 3D virtual model. Finite element analysis (FEA) was used to analyze the appropriate stud design quickly, and mechanical properties such as force, stress, or strain occurring during the holding process were determined. The simulation results influenced the selection of the cutting tool and raw material. Hence, the appropriate cutting tool and raw material were chosen accordingly. After slicing the 3D CAD model to the appropriate brick thickness, a set of toolpaths was generated and ready for the actual cutting operation. Moreover, the yield strength of acrylic plate materials used in this study can be considered from the suggestions of various sources [48] – [52].

Key Contents: this comprehensive approach enhances prototype development efficiency, sustainability, and economic viability in the engineering field.

- *Research Focus:* Exploring solid-based rapid prototyping and interlocking brick designs for efficient, cost-effective prototype creation. Using CAD and FEA ensures studs’ structural reliability, allowing easy assembly without adhesives.
- *Injection Molding:* Melts materials to form high-volume units but is costly and unsuitable for reshaping intricate master designs.
- *Innovation and Sustainability:* Integrating easy-to-use concepts in design fosters innovation and reduces barriers. Standardizing parts with a universal design platform support DIY approaches and environmentally conscious manufacturing.
- *RTA Furniture Trend:* The rise of ready-to-assemble furniture impacts global manufacturing, necessitating efficient prototyping methods.
- *Reverse Engineering (RE):* Creates 3D CAD models from existing objects, aiding in modifying, recreating, and troubleshooting designs.
- *Finite Element Analysis (FEA):* Simulates forces to verify structural reliability, ensuring models meet safety criteria before prototyping.
- *Prototyping Techniques:* Injection molding, metal casting, and additive fabrication are essential for creating complex designs quickly.
- *Rapid Prototyping (RP):* Techniques like Fused Deposition Modeling (FDM) and Laminated Object Manufacturing (LOM) fabricate prototypes layer by layer from 3D CAD models. Decision analysis selects the most cost-effective RP process.
- *CNC Router Machines:* Used for prototype fabrication, converting 3D models into precise toolpaths for accurate milling and drilling operations.

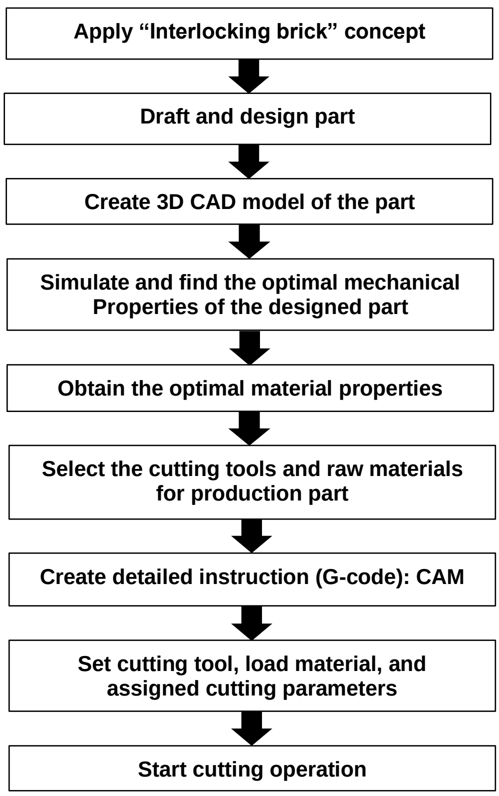

Fig. 1. The overall process of the proposed approach.

Explanation of Chosen Methodology: the proposed methodology, which involves solid-based layer manufacturing and interlocking brick design, is the most suitable for achieving the research objectives for several reasons:

- *Alignment with Objectives:* The goal of creating a ready-to-assemble product relies on precise fabrication and structural integrity. This methodology directly supports those objectives by ensuring that each brick is designed for optimal interlocking without the need for adhesives.
- *Integration of Finite Element Analysis (FEA):* Utilizing FEA allows for thorough evaluation of the mechanical properties of the studs, enabling the design to withstand the required loads and stresses during assembly. This analysis is crucial for ensuring the robustness of the final prototype.
- *Layered Manufacturing Process:* By slicing the 3D virtual model into layers that correspond to the brick's thickness, the methodology enhances precision in prototyping. This approach is essential for producing intricate designs and maintaining the structural integrity of the interlocking system.
- *CNC Router Utilization:* Repurposing a CNC router for this application facilitates the transformation of unwanted raw materials into valuable components, aligning with sustainability goals through a "waste-to-wealth" platform.

Comparison to Alternative Approaches:
For traditional manufacturing methods:

- *Limitations:* Conventional methods like injection molding are expensive and often not suitable for low-volume production or complex designs.
- *Benefits of Chosen Method:* The proposed approach is more adaptable to rapid prototyping needs and allows for easy modifications to the design without incurring high costs.

For other additive manufacturing techniques:

- *Limitations:* Techniques such as Fused Deposition Modeling (FDM) can be slower and may not achieve the same level of surface finish or structural detail required for interlocking designs.
- *Benefits of Chosen Method:* The solid-based approach allows for the creation of smoother surfaces and more complex geometries essential for interlocking functionalities.

For traditional joining methods:

- *Limitations:* Traditional methods often rely on glue or screws, which can make assembly complicated and reduce design options.
- *Benefits of Chosen Method:* The interlocking design eliminates the need for extra materials, making assembly easier and creating a stronger connection.

Benefits of the Chosen Methodology: these following benefits can be obtained.

- *Customization and Flexibility:* The methodology allows for rapid design iterations and customizations to meet specific project requirements while maintaining high production quality.
- *Sustainability:* By incorporating a waste-to-wealth strategy, the approach not only reduces material waste but also promotes sustainable practices in manufacturing.
- *Efficiency in Prototyping:* The combined use of FEA, CNC routing, and solid-based prototyping significantly shortens the development cycle, enabling quicker transitions from design to physical prototype.

Additionally, the chosen methodology effectively aligns with the research objectives by leveraging advanced design and manufacturing techniques that offer precision, sustainability, and flexibility, making it superior to alternative approaches in the context of ready-to-assemble product development.

3.1. Obtaining the Proper Size of Stud

For this study, a reference design of a 4x2 brick was selected due to its complexity in having eight cylindrical studs, as compared to designs with two or four studs. The choice of this reference design was also made based on the need to minimize the amount of material that needed to be removed during the manufacturing process, in order to reduce the time required. The mechanical properties of the reference design were analyzed by varying the height of the cylindrical studs. The CAD model of the brick can be seen in Fig. 2 and Fig. 3. In the FEA analysis, the mechanical properties such as force, stress, and strain of the 8-stud design were evaluated by varying the height of the studs. The simulation results showed that the height of the studs had a significant impact on the mechanical properties and the tightness of the interlocking bricks. The optimal thickness of the studs was found to be 2.5 mm, which provided the required tightness for re-assembly. After determining the optimal thickness of the studs, the design process was initiated to create a series of interlocking bricks. The 3D CAD model of the brick was sliced into layers, with each layer having a thickness equal to the thickness of the brick. The slicing process was based on the optimal thickness of the studs, and the number of bricks in each layer was determined based on the scale and shape of the desired model.

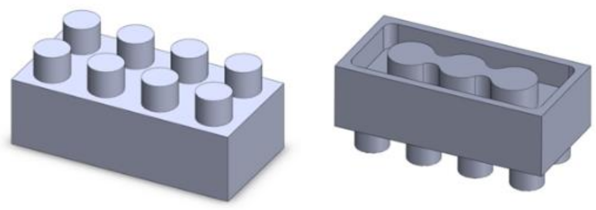

Fig. 2. Top (left) and bottom (right) view of the brick.

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The design of the studs plays a crucial role in ensuring that the assembled parts remain securely interlocked without the need for adhesive materials. Similar to LEGO bricks, the cylindrical studs on the top portion of each brick are designed to fit precisely into the rectangular blind holes on the bottom portion of another brick. This interlocking mechanism ensures that once the bricks are assembled, they do not separate easily, providing stability and robustness to the assembled structure. Moreover, the advantages of the proposed method can be expressed as:

- *No Need for Adhesive Material:* The primary advantage of the proposed method is the elimination of adhesive materials. The interlocking mechanism of the studs and holes ensures a tight fit, holding the bricks together securely. This not only simplifies the assembly process but also reduces the environmental impact associated with adhesive use.
- *Reduction in Material Removal:* The design of the interlocking bricks minimizes the amount of material that needs to be removed during the manufacturing process. By optimizing the stud design through Finite Element Analysis (FEA), we ensure that the bricks are both strong and material-efficient. The simulation results indicated that a stud thickness of 2.5 mm provides the required tightness and strength, allowing for efficient material use.
- *Minimized Production Time:* The interlocking design and the use of a CNC router facilitate rapid production. The precise slicing of the 3D CAD model into layers matching the brick thickness ensures consistency and accuracy in manufacturing. This method reduces the overall production time compared to traditional assembly techniques that require adhesives or complex fastening methods.

The material used for producing the interlocking bricks was acrylic sheet, selected based on the simulation results and the cutting tool used for the material removal process. The selection of acrylic was justified through simulation (FEA) results from the FEA analysis, which assessed the mechanical properties of various materials under the stress conditions expected in the brick design. Acrylic was chosen due to its favorable properties, such as adequate yield strength, ease of machining, and cost-effectiveness, ensuring the bricks maintain structural integrity while being cost-efficient and easy to produce. The appropriate cutting tool and raw material were determined based on the results obtained from the simulation software. The set of toolpaths was generated, and the real cutting operation was performed.

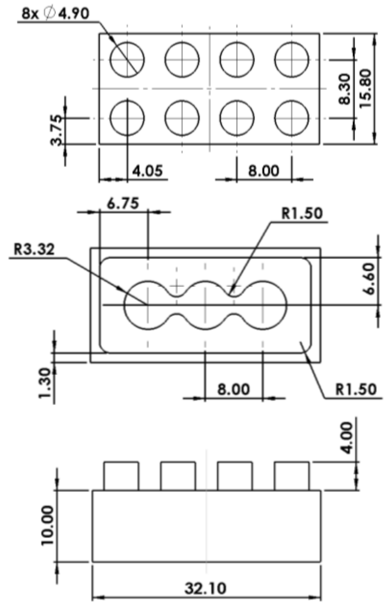

Fig. 3. Drawing of the master model-in mm unit: 2x4 brick in top, bottom, and side views.

For key considerations, additionally, the size and thickness of the brick and studs are important factors that affect the accuracy of the obtained prototype. The use of acrylic sheet as the material for producing the brick is also a consideration. The 4x2 brick is chosen as the reference design due to its complex 8-stud design and for minimizing the amount of material removal during the manufacturing process. The tightness assumption of the 8-stud design is also a key consideration for re-assembly purposes. The results of the FEA simulation are used to determine the appropriate thickness of the studs, which directly affects the design of the bricks and the slicing of the 3D virtual model. The approach provides the advantage of not requiring adhesive material, reducing the amount of material removal, and minimizing the time required for production. The proposed approach requires careful consideration of various parameters and factors to achieve the desired results.

3.2. Simulation

The size of the studs is determined using finite element analysis (FEA) to analyze the mechanical properties of two stacked bricks and determine whether the connection between them is strong enough to create a functional prototype. To conduct the analysis, the simulation software is used to assign material properties (such as medium-high impact acrylic plate), and mechanical properties such as mass density, tensile strength, and elastic modulus. The software also assigns the types of contacting areas between the upper and lower brick to be a shrinking fit with a coefficient of friction of 0.35. The contacting areas and fixed position with mesh model are shown in Fig. 4 to Fig. 7, respectively.

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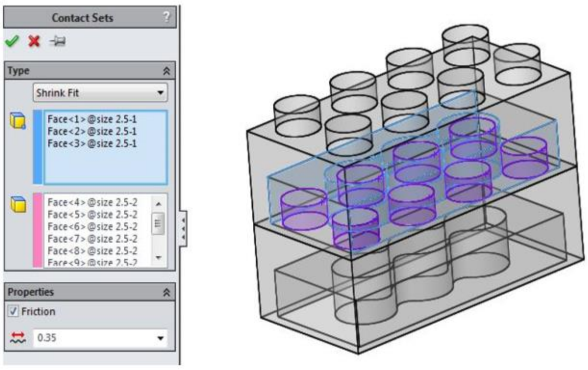

Fig. 4. Contact Sets (Shrink Fit and No – Penetration).

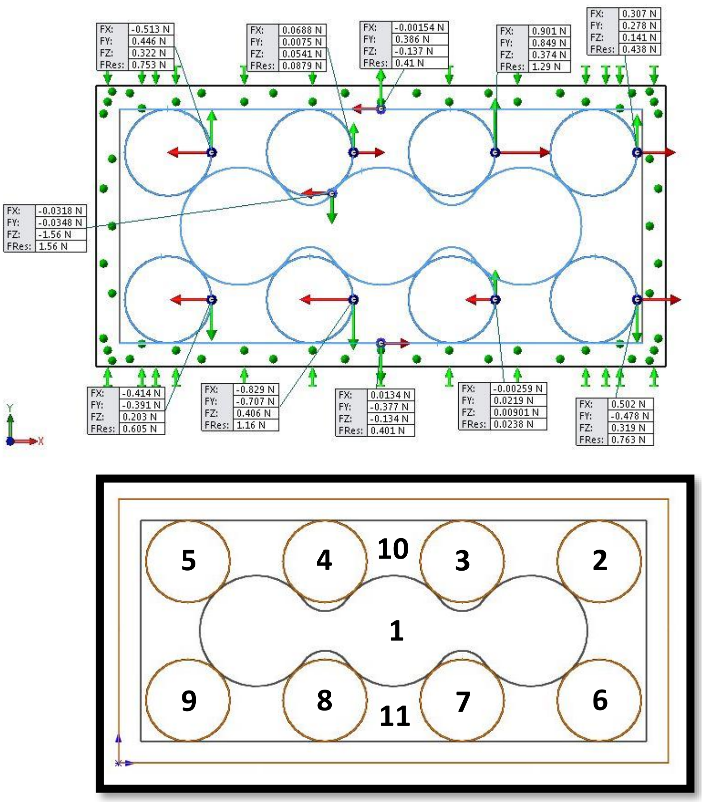

Fig. 5. Selecting views and contact areas.

This process allows for the determination of the appropriate size of the studs to ensure a tight fit between the bricks and a structurally sound prototype. The subsequent step involves fixing the top and bottom areas of the brick to avoid any translations and rotations that might occur when forces are applied. Meshes are then created to construct the geometric shape's structure, which is used to analyze the load distribution. A smaller mesh size leads to a more accurate analysis, but it also takes longer for the program to analyze the model.

In this case, a mesh size of 1.5 mm is deemed appropriate for analyzing the model because of its simple geometric shape. The simulation results are presented in both graphical (Fig. 8) and tabular (Table 1) forms. Table 1 lists the total forces at each contact point for stud heights ranging from 1.8 to 4 mm, with each height represented by a different line in the graph. The maximum force occurs at the contact point when the upper and lower bricks attempt to separate from each other. Figure 8 demonstrates that increasing the stud height leads to an increase in the force required to separate the bricks.

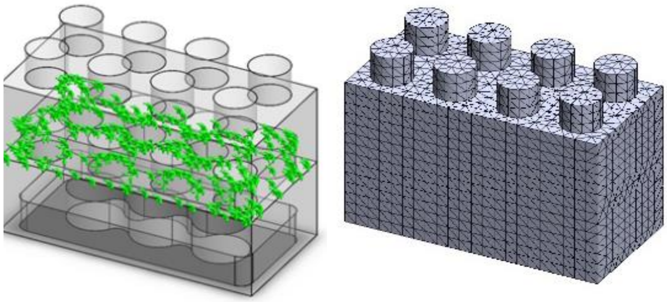

Fig. 6. Fixing Model (left) and creating mesh (right).

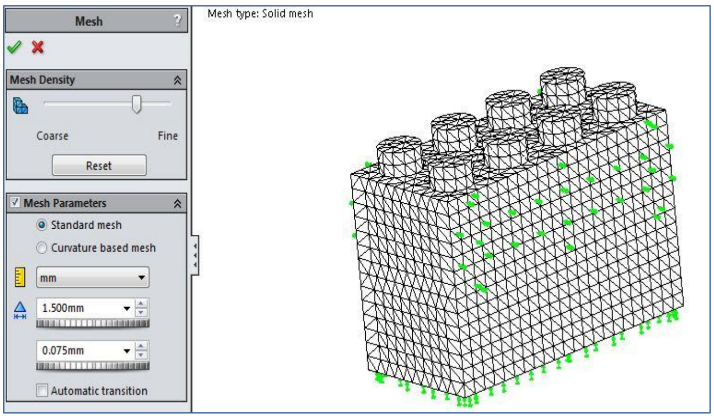

Fig. 7. Mesh creation in software.

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Table 1. Total force on each pair of contact points with various thicknesses of the studs

Contact Points	Total force (N)					
	Thickness of Stud (mm)					
	1.8	2.0	2.5	3.0	3.5	4.0
1	1.5150	1.7400	1.8400	1.7450	1.8650	2.055
2	0.4390	0.4590	0.5760	0.5140	0.4135	0.6055
3	1.2850	1.0300	1.2300	1.0400	1.2150	0.9855
4	0.0915	0.1550	0.0241	0.0194	0.1140	0.0772
5	0.7530	0.8570	0.9060	0.8585	0.9135	1.085
6	0.7550	0.7150	0.9115	0.9890	0.9330	1.11
7	0.0241	0.0668	0.0504	0.0761	0.0863	0.0812
8	1.1800	1.5400	1.5900	1.2900	1.4500	1.125
9	0.6075	0.5330	0.5470	0.4755	0.4945	0.6515
10	0.3975	0.3380	0.4965	0.6850	0.9525	1.165
11	0.4080	0.5750	0.8235	1.0200	1.2300	1.365

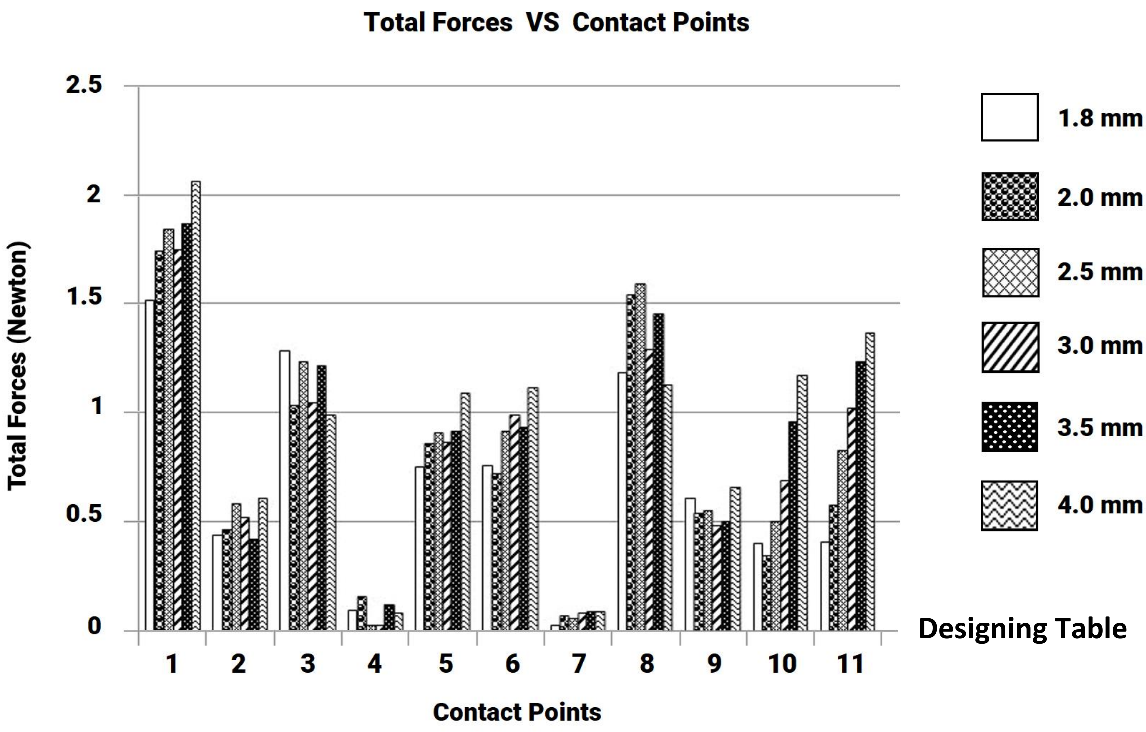


Fig. 8. Graph of the total force with contact points.

Therefore, a 4-mm-height stud is deemed suitable for use in various sample prototype designs, such as portable tables, chairs, and wall showcases, since the stacked parts (i.e., two consecutive bricks) can hold each other more rigidly at the contact point than at other stud heights. These results aid in the creation of interlocking brick-based prototypes that can be assembled and disassembled. The implementation of this approach is discussed in the following section.

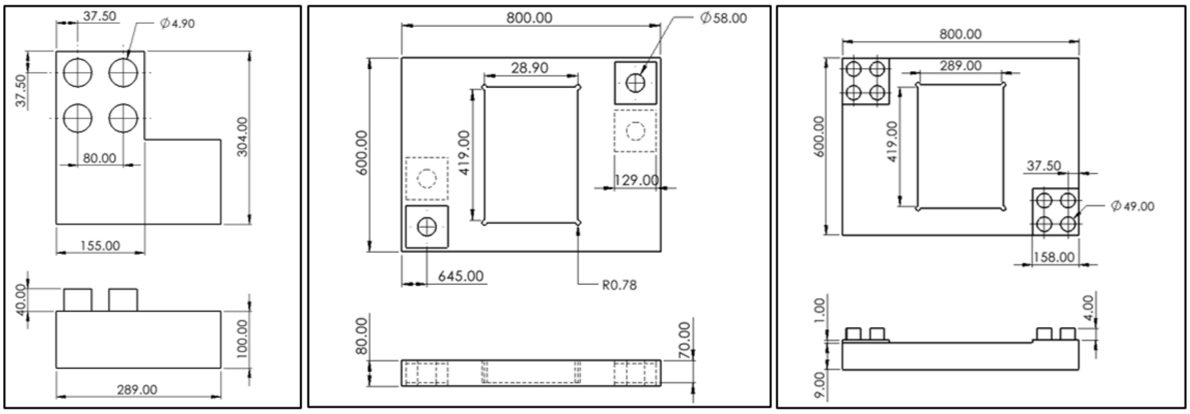
Generate a mesh consisting of various geometric shapes for use in analyzing the model. The accuracy of the analysis increases with a smaller mesh size, but the program will require more time for analysis. For the analysis of this model with simple geometric shapes, a mesh size of 1.5 mm is deemed appropriate.

4. Implementations of the Proposed Approach

This section outlines the three key steps involved in designing and creating a prototype using the interlocking brick approach. These include creating a 3D CAD model of the desired design, assigning cutting parameters for the CNC-router machine, and generating a prototype.

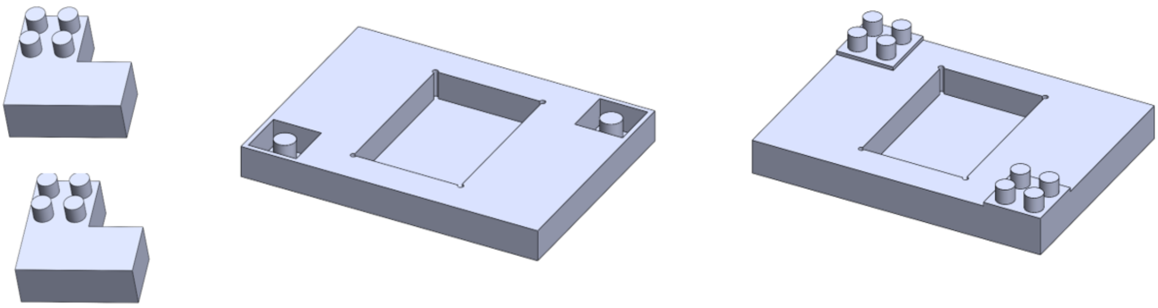
4.1. Creating a 3D CAD Model of the Desired Design

To demonstrate the proposed approach, a portable table with 90-degree corners and geometric shapes was created using commercial CAD software. The physical characteristics of the table were identified by using a simulation platform, where an external load was assumed to be uniformly distributed on the table's surface. The simulation was run repeatedly until the table collapsed, to check the amount of reaction force around the connecting areas between the studs. The table comprises three main components: two legs, one base, and one cover, as shown in Fig.9 and 10. The 3D CAD model of the table is depicted in Fig. 11. In the implementation stage of the design process, the preliminary design of the brick was considered. It was found that the previous design of the brick did not meet the main assumption of the 8-stud design, which is tightness for easy re-assembly. The brick was found to loosen and not fit firmly together. Therefore, the bottom side of the brick needed to be redesigned while keeping the stud design the same. After applying a force of more than 500 N on the surface of the table as shown in Fig. 12, the area most likely to collapse first was identified. The figure above indicates that the Von Mises stress around the collapsed area had a value of approximately 47.953 N/mm^2 which exceeds the yield strength of the material (45.000 N/mm^2). To select the cutting tool, high-speed steel (HSS) is a commonly used tool material in manufacturing and is easy to order at a moderate cost. Table 2 are the yield strength of the material – Acrylic material [48] – [52].



(a) 2 Legs **(b) 1 Base** **(c) 1 Cover**

Fig. 9. Dimensions of each component (millimeter).



(a) 2 Legs **(b) 1 Base** **(c) 1 Cover**

Fig. 10. 3D CAD model of each component of the table.

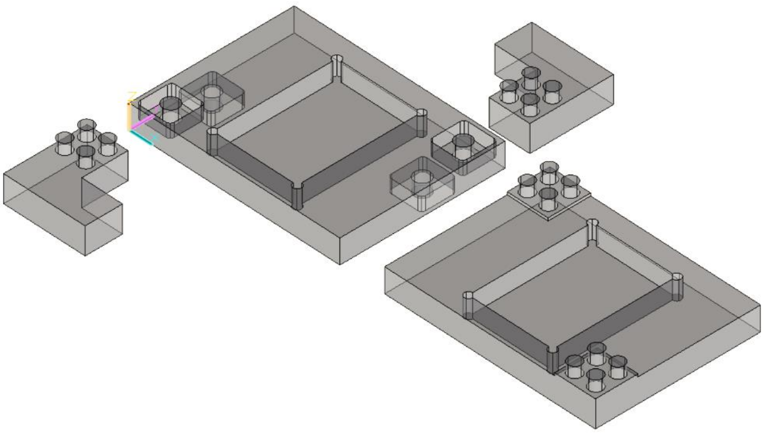


Fig. 11. 3D CAD model of the designing table.

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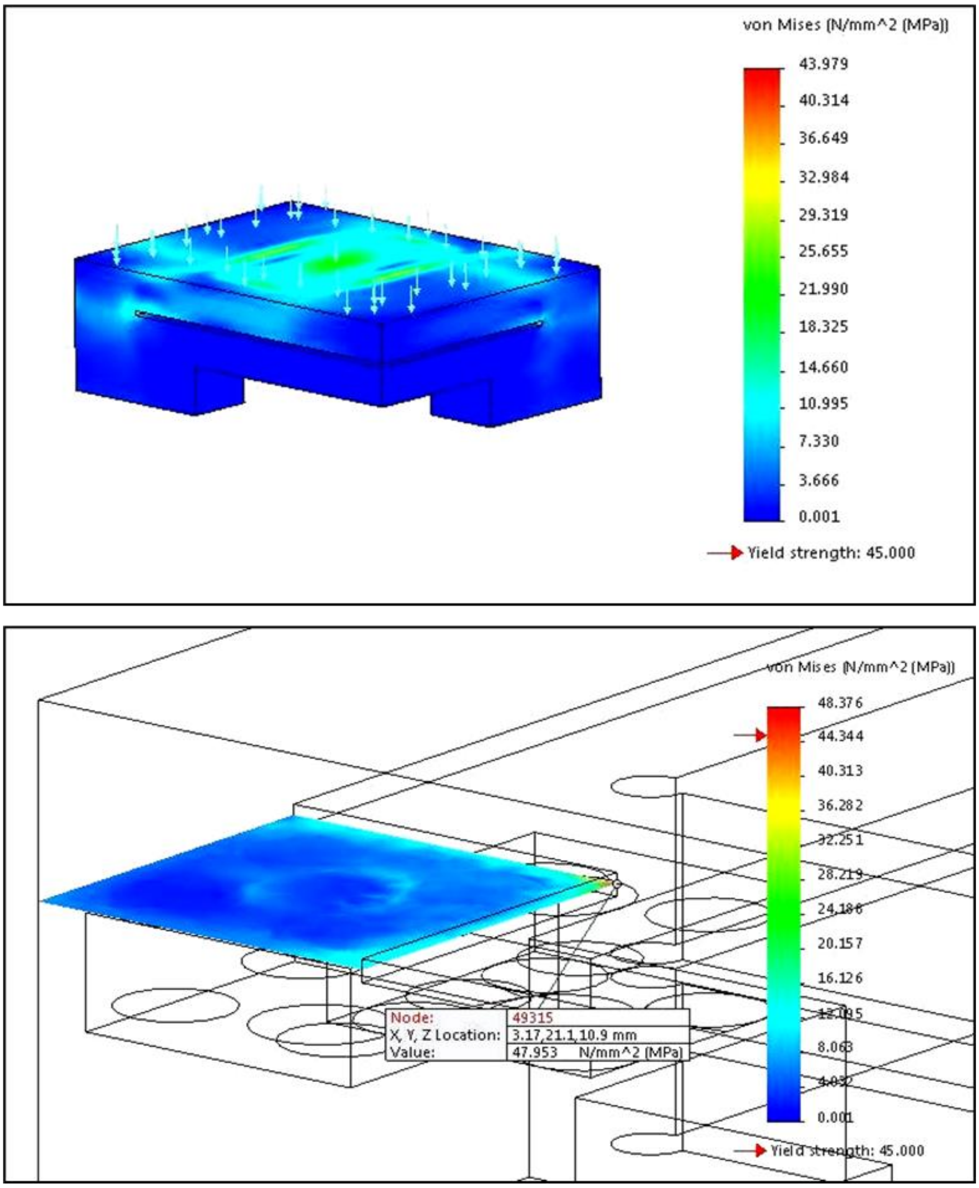

Fig. 12. Simulation with force.

Table 2. A table of yield strength of acrylic plate materials in N/mm^2.

Acrylic Material	Yield Strength (N/mm^2)
Acrylic Glass	75 - 95
Cast Acrylic	70 - 90
Extruded Acrylic	50 - 65
Impact Modified Acrylic	80 - 100

4.2. Assigning the Cutting Parameters of the CNC-Router Machine

To demonstrate the proposed approach, acrylic sheet was selected as the raw material and was processed using a CNC-router machine based on the designed cutting conditions. Table 3 lists the cutting heads of different materials, and high-speed steel was selected for this demonstration [53] – [56]. Due to the flute's height of the cutting head (as shown in Fig. 13), the thickness of the acrylic sheet cannot exceed 15 mm. Acrylic cubes (Fig. 14) were used as the raw material for creating a conceptual prototype that can be applied further for built-in furniture (Fig. 15-18).

Table 3. Allowable cutting speed of different tool materials.

Tool Material	Year of initial use	Allowable cutting speed			
		Non-steel Cutting		Steel Cutting	
		m/min	(ft/min)	m/min	(ft/min)
Plain carbon tool steel	1800s	Below 10	(Below 30)	Below 5	(Below 15)
High-speed steel	**1900**	**25-65**	**(75-200)**	**17-33**	**(50-100)**
Cast cobalt alloys	1915	50-200	(150-600)	33-100	(100-300)
Cemented carbides (WC)	1930	330-650	(1000-2000)	100-300	(300-900)
Cermets (TiC)	1950s			165-400	(500-1200)
Ceramics (Al_2O_3)	1955			330-650	(1000-2000)
Synthetic diamonds	1954, 1973	390-1300	(1200-4000)		
Cubic boron nitride	1969			500-800	(1500-2500)
Coated carbides	1970			165-400	(500-1200)

Fig. 13. Cutting tool materials with their allowable cutting speeds.

Fig. 14. Raw material applied for this proposed approach: (a) Acrylic cube (52x68.5x80.5 mm), and (b) Acrylic sheets (300x300x15 mm).

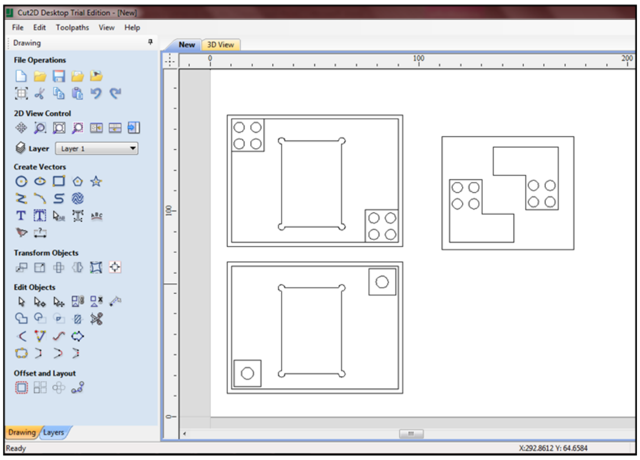

Fig. 15. Sketching the geometric shapes of the prototype.

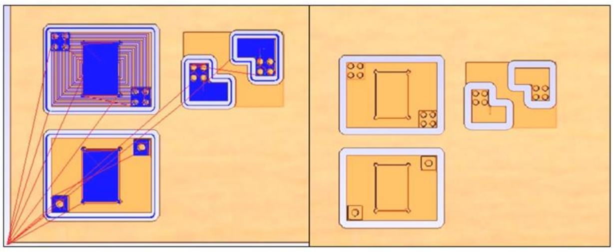

Fig. 16. Previewing all toolpaths before cutting the prototype.

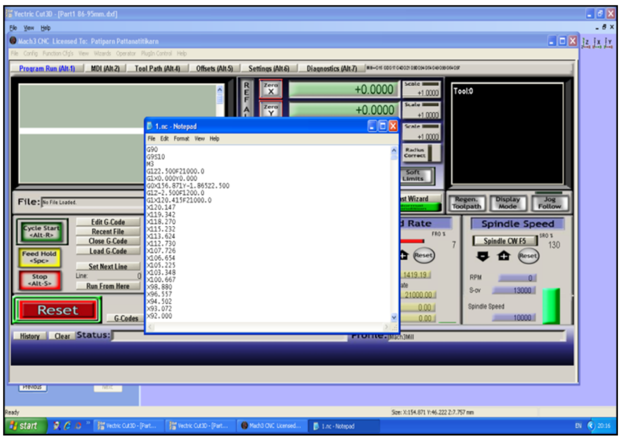

Fig. 17. Uploading and Editing G-Code in CNC software.

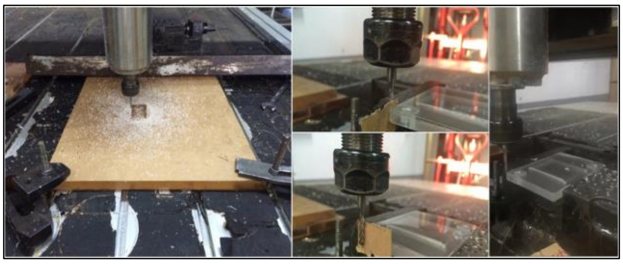

Fig. 18. Adjusting the cutting head along the x-axis and y-axis to be zero – starting point.

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5. Recommendation for the future work

5.1. Applying Laser Cutting

Laser cutting is a popular technique used in various industries for precision cutting of materials [57] – [62]. It involves using a high-powered laser beam to melt, burn or vaporize the material, resulting in a smooth, precise cut. This technique is often used for cutting acrylic plates, as the material can be easily cut and engraved using a laser. In the context of interlocking brick concept, laser cutting can be used to create precise and intricate cuts on acrylic plates for the purpose of interlocking brick assembly. The interlocking brick concept involves creating bricks with unique shapes that can interlock with one another without the need for mortar or adhesive. By using laser cutting to create these unique shapes, the precision of the cuts can ensure a tight and secure fit between the bricks. This can lead to a more stable and durable structure, as well as a more aesthetically pleasing design. Additionally, laser cutting can allow for the creation of complex designs and patterns on the surface of the bricks, further enhancing their visual appeal. There some pros and cons of laser cutting applied to cut acrylic plates for supporting interlocking brick:

Pros:

1. *High precision:* Laser cutting is a highly accurate cutting method that produces clean and precise cuts. This precision ensures that the acrylic plates fit the interlocking brick perfectly, which enhances the overall stability and durability of the structure.
2. *Versatile:* Laser cutting can be used to cut acrylic plates into any shape or size, making it a versatile method for creating supports for interlocking bricks of various sizes and shapes.
3. *Efficient:* Laser cutting is a fast and efficient cutting method that can produce large quantities of supports in a short amount of time.
4. *Smooth finish:* Laser cutting produces a smooth and polished edge on the acrylic plates, which can enhance the overall appearance of the structure.

Cons:

1. *Cost:* Laser cutting can be an expensive cutting method, especially for small-scale projects. The cost of the laser cutting machine and the maintenance required can add up quickly.
2. *Limited thickness:* Laser cutting has a limited cutting depth, which means that it may not be suitable for thicker acrylic plates. This can limit the size and strength of the supports that can be created.
3. *Safety hazards:* Laser cutting produces fumes and emits radiation, which can be hazardous to human health if proper safety measures are not taken.
4. *Fragility:* Acrylic is a relatively fragile material, and laser cutting can create stress points that can weaken the structure of the support. This can make the support more prone to cracking or breaking over time.

5.2. CNC Router versus Laser Cutting on Acrylic Plate

One benefit of using CNC router for cutting acrylic plates is that it offers greater precision and accuracy compared to laser cutting. CNC routers use mechanical cutting tools that can create sharp and detailed cuts with a high degree of accuracy. On the other hand, laser cutting uses a focused beam of light to melt or vaporize material, which may not always produce clean and precise cuts, especially on thicker materials like acrylic plates. Another benefit of using CNC router is that it can handle a wider range of materials compared to laser cutting. While laser cutting is best suited for materials like wood, plastic, and metal, CNC routers can cut through a variety of materials including foam, composites, and even some metals. This makes CNC router more versatile and suitable for a wider range of applications. In terms of cost, CNC routers may be more affordable than laser cutters for small-scale production. Laser cutters can be expensive to purchase and maintain, while CNC routers are generally more affordable and require less specialized training to operate.

For the key points, while both CNC router and laser cutting can be used for cutting acrylic plates for interlocking brick concept, CNC router offers greater precision, versatility, and affordability, making it a more viable option for some applications.

5.3. Generating a Prototype by CNC Router and FDM-RP

After ensuring all necessary parameters for the cutting operation, such as adjusting the cutting head and starting position, the zero setting for the Z-axis is recorded when the cutting head first touches the object's surface. Acrylic plate is used as the raw material, and the feed rate is set low to reduce heat and friction during cutting. The upper and lower parts of the final prototypes are assembled to check their positions and alignment, as shown in Fig. 18. These prototypes serve to demonstrate the proposed approach, with their contribution explained by the ratio between the size of the stud and the desired part area, as shown in Table 4.

The CNC router provides an efficient and cost-effective approach for creating prototypes, as it minimizes material cost and operational time compared to the fused deposition modeling (FDM) rapid prototyping process. While the amount of material used in RP prototypes may be lower than that used in CNC router applications, the material cost of RP is typically more expensive and difficult to maintain and preserve over time. The slicing model (i.e., base part) fabricated by the RP machine is shown in Fig. 19. This model is created using the FDM-RP process (Fig. 20) with specific properties assigned as follows: layer resolution of 0.254 mm, sparse-high density model interior, SMART support fill, 1 copy, and STL units and scale of millimeters and 1.0, respectively. Table 5 presents a comparison of the time and material spent between the CNC router and the FDM-RP machine for prototyping. This table can be used to determine which method is more suitable for a particular project based on factors such as cost, time, and complexity.

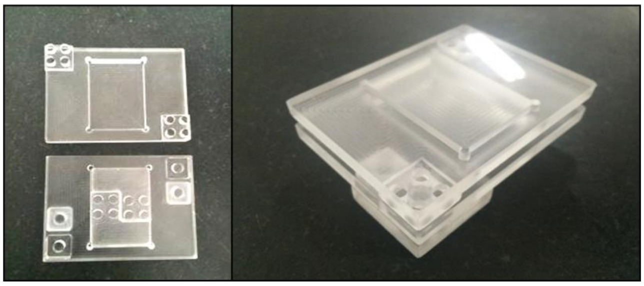

Fig. 19. Prototype of the designing table.

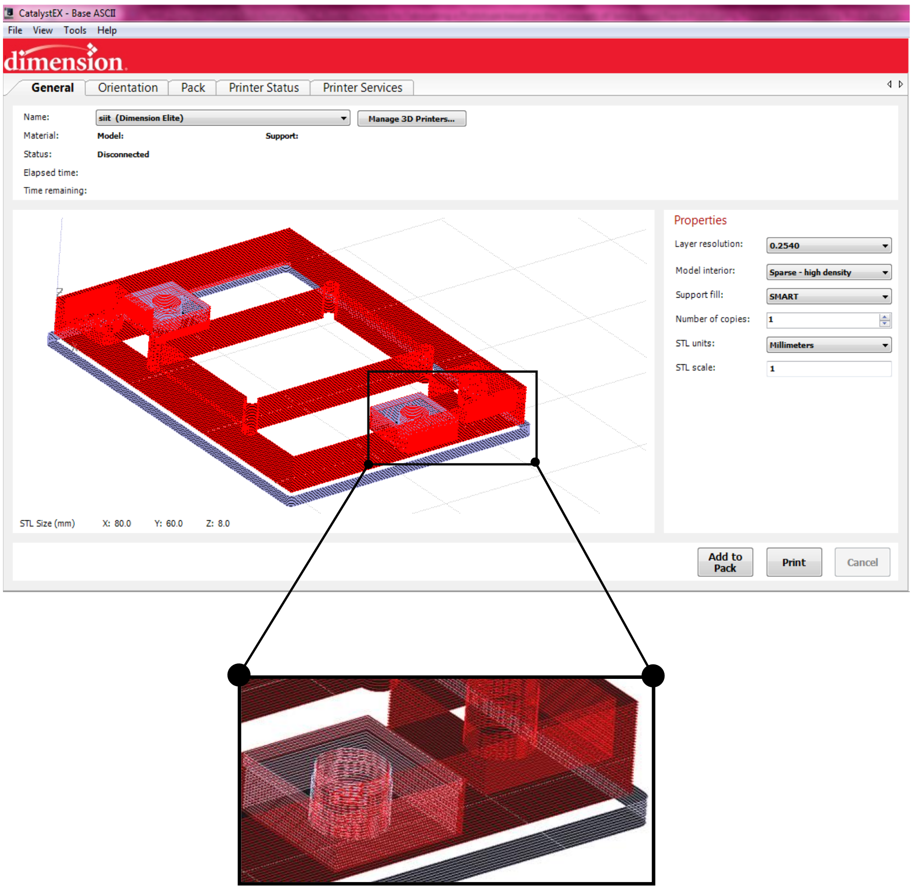

Fig. 20. Slicing file of the base model created by FDM machine.

Table 4. The recommendation of the proposed approach.

Pressure (N)	Part dimension (mm)		Size of stud (mm)		Guidelines	
	Length	Width	Ø	Height	No. of studs	Brick pattern
≤ 500	15.8 ~ 158	15.8 ~ 158	4.9	4	8	1 pair (2x2) at the diagonal corners
	+100 (every)	+100 (every)	4.9	4	8+(2)*	• 2 pairs of (2x2) at the diagonal corners • *Adding 1 pair of (1x2) at every 100-mm interval
> 500	15.8 (min)	15.8 (min)	4.9	4	8	1 pair (2x2) at the diagonal corners

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Table 5. The comparisons of time and material spent between the CNC router and the rapid prototyping machine.

Parameters \ Methods	CNC router	RP (FDM)
Set up time	40 min	20 min
Processing time (all components)	76 min	254 min
Material used	10.94 inch^3	3.94 inch^3
Support material used	-	0.64 inch^3

5.4 Finished Prototypes

To support the proposed concept of utilizing a CNC router machine for constructing prototypes that integrate solid-based rapid prototyping and interlocking brick design, several prototypes made from acrylic plates have been developed. These prototypes are scaled at approximately 1:20 relative to the actual product. The design team aims to evaluate the CNC router's performance in cutting small-diameter and geometric shapes, resembling a "Lego-like design" that is both compact and intricate. Fig.21 to 23 illustrate the furniture examples produced by the CNC router machine, reinforcing the connection between the research objectives and the tangible outcomes achieved through this innovative prototyping method.

- *Deeper Interpretation*

The prototypes exhibit innovative designs that reflect the design team's vision, incorporating trendy curved surfaces and compact dimensions. This exploration enables a thorough understanding of the CNC router's capabilities in managing intricate details and smaller components, as shaped by the team's insights and experiences. Analyzing the performance of the CNC router reveals its proficiency in producing complex geometries, highlighting the potential for further applications in rapid prototyping.

- *Relate to Objectives*

The findings align with the research objectives of assessing the CNC router's effectiveness in achieving detailed prototypes and understanding the interlocking brick design's functionality. For example, the "tabletop surface" functions as a stable and horizontal upper area of a table, while the "rectangle-chair set" provides versatile seating arrangements for 1-2 people. This modular design can be conveniently stored beneath the tabletop surface, showcasing the prototype's practical application and adaptability.

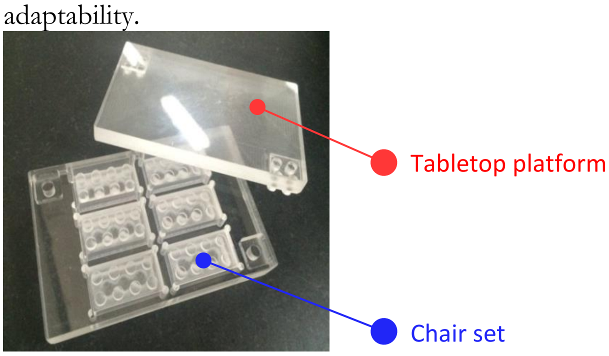

Fig. 21. An alternative design for a table and chair set.

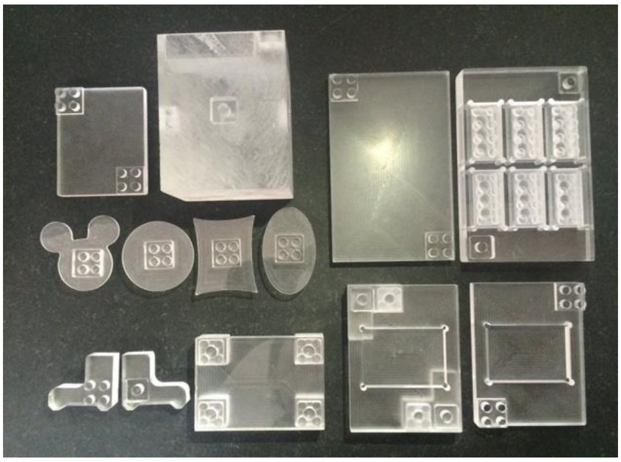

Fig. 22. Finished prototypes - components.

Fig. 23. Finished prototypes – assembled parts.

6. Conclusion

The proposed method for creating a ready-to-assemble product focuses on solid-based layer manufacturing and interlocking brick designs. Central to this approach is the brick, featuring cylindrical studs and rectangular blind holes, which ensure structural integrity and easy assembly. The 3D virtual model is sliced into layers matching the brick' thickness for precise fabrication.

- *Unique Contributions:* This research significantly advances the field by using Finite Element Analysis (FEA) to optimize stud design for interlocking bricks, guiding the selection of cutting tools and materials, thus enabling complex prototype creation without adhesives.

• *Theoretical Implications:* The findings enhance the understanding of additive manufacturing and modular design, showcasing the efficacy of solid-based rapid prototyping in achieving intricate geometries.

• *Managerial Implications:* This approach can aid engineering and manufacturing decisions by streamlining production, reducing waste, and promoting product adaptability. Interlocking designs allow for customizable solutions while minimizing assembly time.

• *Limitations and Future Directions:* While the method is promising, limitations remain. Future research should explore scalability for larger prototypes and diverse materials, as well as assess the long-term performance of interlocking bricks in various applications.

In summary, the project aimed to develop a method for fabricating interlocking bricks without adhesives. The innovative brick design enables secure connections and supports versatile assembly.

Key Design: The design of a 4x2 brick with eight cylindrical studs enhances stability and interlocking capabilities. Each stud's thickness was optimized using FEA to ensure strength while keeping the brick lightweight. This careful design led to a series of bricks suitable for slicing from the 3D model. The goal was to create interlocking bricks that operate without adhesive. This was achieved through a stud-and-hole mechanism that promotes easy assembly. The studs not only support the structure but also ensure precise alignment during assembly, simplifying the construction process and reducing environmental impacts. Additionally, the brick's design is crucial for the prototype's functionality, allowing for versatile configurations and empowering users to construct complex structures easily. This modular design aligns with current trends in sustainable manufacturing and consumer preferences for adaptable products.

7. Contribution

The method involved combining workpiece simulation with various variables, including tensile strength, modulus of elasticity, coefficient of friction, and gravitational force. The results demonstrated the feasibility of producing a real product using this method, and prototypes were successfully fabricated using this approach. The study also investigated cutting parameters such as feed rate and rotational speed, which determined the surface quality of the prototypes. If the parameters were set too high (over 8000 rpm), chatter occurred on the prototypes resulting in rough surfaces. The proposed method showed promising results for fabricating interlocking bricks without adhesive materials, and further research can be done to explore the potential of this approach in other areas of manufacturing.

To support manufacturing processes and today's competitive industrial strategies, particularly in transportation (logistics and supply chain management), mold and die making, storage arrangement, and material handling frameworks [63] – [66], this proposed approach offers space-efficient packing for lightweight items, even when the material is rigid and solid. The studs-and-stacks design minimizes the risk of product damage during transportation, as the small pieces fit together to maintain the original shape of the desired part.

Author Contribution

Conceptualization, literature review, methodology, formal analysis, investigation, data validation, supervision, and writing—review and editing S.R.; literature review, methodology, writing—original draft preparation, data validation, data collection and primary analysis, N.S. and W.C. All authors have read and agreed to the published version of the manuscript.

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Suchada Rianmora is a lecturer in School of Manufacturing Systems and Mechanical Engineering (MSME), Sirindhorn International Institute of Technology, Thammasat University, Thailand. She received her D.Eng. from Asian Institute of Technology, Thailand. Her research interests are reverse engineering, rapid prototyping, image processing, industrial instrument and controlling system, design and development, design for manufacture and assembly, maintenance engineering, and manufacturing processes.

Nutthamon Samorhom received her B.Eng. from the Industrial Engineering Program at the School of Manufacturing Systems and Mechanical Engineering (MSME), Sirindhorn International Institute of Technology, Thammasat University, Thailand. Currently, she is a student in Master of Science (Engineering and Technology) from the same institute. Her research interests are reverse engineering, rapid prototyping, manufacturing process design, and instrument process and control.

Worapong Chaidilok received his B.Eng. with second-class honors from the Industrial Engineering Program at the School of Manufacturing Systems and Mechanical Engineering (MSME), Sirindhorn International Institute of Technology, Thammasat University, Thailand. He also completed a Master of Engineering in Logistics and Supply Chain Systems Engineering (LSCSE) from the same institute. His research interests include manufacturing systems design, 3D prototyping, supply chain management, project management, and data analytics.