sustainability

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An Analytical Study of the Latest Trends of Free-Form Molds

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Abstract: With the development of technology, the number of free-form structures—as well as their value—is increasing. In order to construct such free-form structures, a number of studies are being conducted on free-form molds from multifaceted perspectives. However, it is difficult to identify the progress of studies related to free-form molds, as the scope of the studies is redundant or similar in many cases. Therefore, the current study focused on the identification of the trends of preceding studies on free-form molds using the PRISMA technique. The study classified the studies into three topics in order to identify the trends: 'free-form curve fabrication technology', 'free-form mold fabrication technology', and the 'analysis of free-form panel forms.' Each topic was further categorized into two tiers for more in-depth analysis. The whole process was adopted in order to suggest the trends of studies on free-form molds. The findings are expected to be used to provide fundamental data for future studies on free-form molds, and to set the directions for new studies.

Keywords: analytical study; PRISMA; free-form building; free-form mold; free-form curve surface

Citation: Youn, J.; Yun, J.; Kim, S.; Han, B.; Do, S.; Lee, D. An Analytical Study of the Latest Trends of Free-Form Molds. *Sustainability* **2022**, *14*, 3084. https://doi.org/10.3390/su14053084

Academic Editor: Antonio Caggiano

Received: 26 January 2022
Accepted: 2 March 2022
Published: 7 March 2022

1. Introduction

With the latest development in computers and information technology, many people in the construction industry have gained an interest in the realization of free-form structures, and many studies have been conducted on the ways in which to build free-form structures [1,2]. The forms of free-form structures are comprised of free curves, and are different from other structures in appearance. For that reason, free-form structures serve as urban landmarks around the world, and the value of free-form buildings is rising [3]. The exterior of free-form structures consists of unique curves, and it requires individual free-form molds. In case of the National Museum of Qatar, in fact, about 76,000 free-form concrete panels and about 3000 molds were fabricated to create the 316 discs for the structure [4,5].

A large number of free-form molds are used to construct free-form structures. Furthermore, free-form molds consume a lot of manpower and time in the process of engineering, production, and installation, raising the cost of construction. Likewise, free-form molds cannot be reused or recycled, as they are unique in shape. It takes money to handle them as disposable construction waste. Free-form molds are manually fabricated by manpower, consuming much time for production and losing precision of form over time.

Currently, studies on free-form molds are conducted for different purposes, and are limited to the fundamental stage, not the commercialization stage. They are not enough to suggest substantial solutions to the aforementioned limitations of free-form molds. Furthermore, it is difficult to identify the progress of studies as their scope is redundant or similar in many cases. The current study adopted the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) technique to summarize the trends of the preceding studies on free-form molds in order to suggest the trends.

2. Application of the PRISMA Technique

PRISMA was used to identify the trends of studies on free-form molds. PRISMA identifies and analyzes the studies selected based on the standards of systemized review and meta-analysis. The current study applied the PRISMA technique in the following order: (1) the selection of the search engine; (2) the selection of the keywords; (3) the selection and exclusion of studies; and (4) the PRISMA Flow Diagram.

2.1. Step 1: Selection of the Search Engine

In order to implement PRISMA, the search engine which was suitable for the data collection was selected. Among the many search engines—such as Scopus, PubMed, WOS, and Google Scholar—the study chose to use Google Scholar. Google Scholar allows auto-searching and inclusive literature searching. In order to collect enough studies related to free-form molds, 'OR' was used instead of 'AND' for an inclusive search of the data.

2.2. Step 2: Selection of the Keywords

Keywords related to free-form molds were selected and entered into Google Scholar. The following were the conditions of the selection of the keywords: (1) kinds and use of free-form panels, (2) realization of free-form panels, and (3) free-form molds. The keywords satisfying the above conditions are given in Table 1. The keywords related to the kinds and use of free-form panels gather publications related to the fabrication of free-form panels and the structures built using them. The keywords were 'Free-form concrete panel', 'Free-form panel', 'Free-form construction', 'Free-form building', and 'Free-form panels and CNC'. The keywords related to the fabrication of free-form panels were used to search for publications on the curves and curvature of free-form panels. The keywords were 'Free-form curved surface', 'Single curved panel', 'Double curve panel', and 'Free-form shape'. The keywords on free-form molds were used to gather publications on the types of molds. The keywords used to search were 'Free-form recycling mold', 'Flexible mold', and 'Adaptive mold'. The word 'mold' in the keywords can be used as 'mould' or 'formwork' in some studies, so all of the variations were searched additionally.

Table 1. Keywords selected for free-form molds.

Selecting Keywords	Search Keywords
Free-form Panels	Free-form concrete panel Free-form panel Free-form construction Free-form building Free-form panel & CNC
Realization of Free-form Panels	Free-form curved surface Single curved panel Double curved panel Free-form shape
Free-form molds	Free-form recycling mold (formwork) Flexible mold (formwork) Adaptive mold (formwork)

2.3. Step 3: Selection and Exclusion of the Studies

In the process of collecting the publication, there were publications which were not related to free-form molds. Therefore, the publications related to the keywords were classified based on the selection and exclusion standards in Table 2. Among the publications collected, the publications from academic seminars and journals were selected, and the books, R&D reports, and dissertations with redundant contents or fundamental information were excluded. Publications on EPS molds, CNC molds, and other free-form molds, and publications on technological development for related equipment were selected. Publications on the FCP (Free-form Concrete Panel) production process, FCP mixing ratio, algorithms, and equipment which is not related to free-form molds were excluded. In order to analyze the trends of the latest studies, publications written within 10 years from 2021 were selected, and any publications written before 2011 were excluded.

Table 2. Categorization of the publications collected.

Selected Categories	Excluded Categories
Publications from Academic Seminars	Books and R & D Reports
Publications from Journals	Dissertations
Non-fundamental Publications	Fundamental Studies
Publications on Free-form molds (EPS Molds, CNC Molds, Wooden Molds, etc.)	Publications Not on Free-form molds (FCP Production Process, Free-form Panels, FCP Mixing Ratio, Algorithms, etc.)
Publications on Mold Equipment Technology Development	Publications Not on Mold Equipment Technology Development
Publications after 2011	Publications before 2011

2.4. Step 4: PRISMA Flow Diagram

The keywords were entered into Google Scholar in order to collect 34 Korean publications and 47 international studies, for a total of 81 publications. (1) Books, reports, special articles, and dissertations were excluded because books, reports, and special articles are not logically written literature, and dissertations may be redundant with publications from journals. In that process, 13 publications were excluded and 68 publications from academic seminars and journals were excluded. (2) In the case of the FCP production process, free-form panels, the FCP mixing ratio, and algorithms, publications on the fabrication of free-form panels that are not related to free-form molds and publications that were not on free-form molds were excluded. In that process, nine publications were excluded, and 59 publications remained. (3) In order to identify the latest trends of studies related to free-form molds, four publications written before 2011 were excluded, and 55 publications written between 2011 and 2021 were included. (4) Publications on the equipment used to fabricate free-form molds, publications not on technological development, and fundamental studies were excluded. In that process, 17 publications related to development and seven fundamental studies—for a total of 24 publications—were excluded. Finally, 31 publications on CNC equipment for the fabrication of free-form members and publications on technological development were included. In that process, the PRISMA Flow Diagram in Figure 1 was completed.

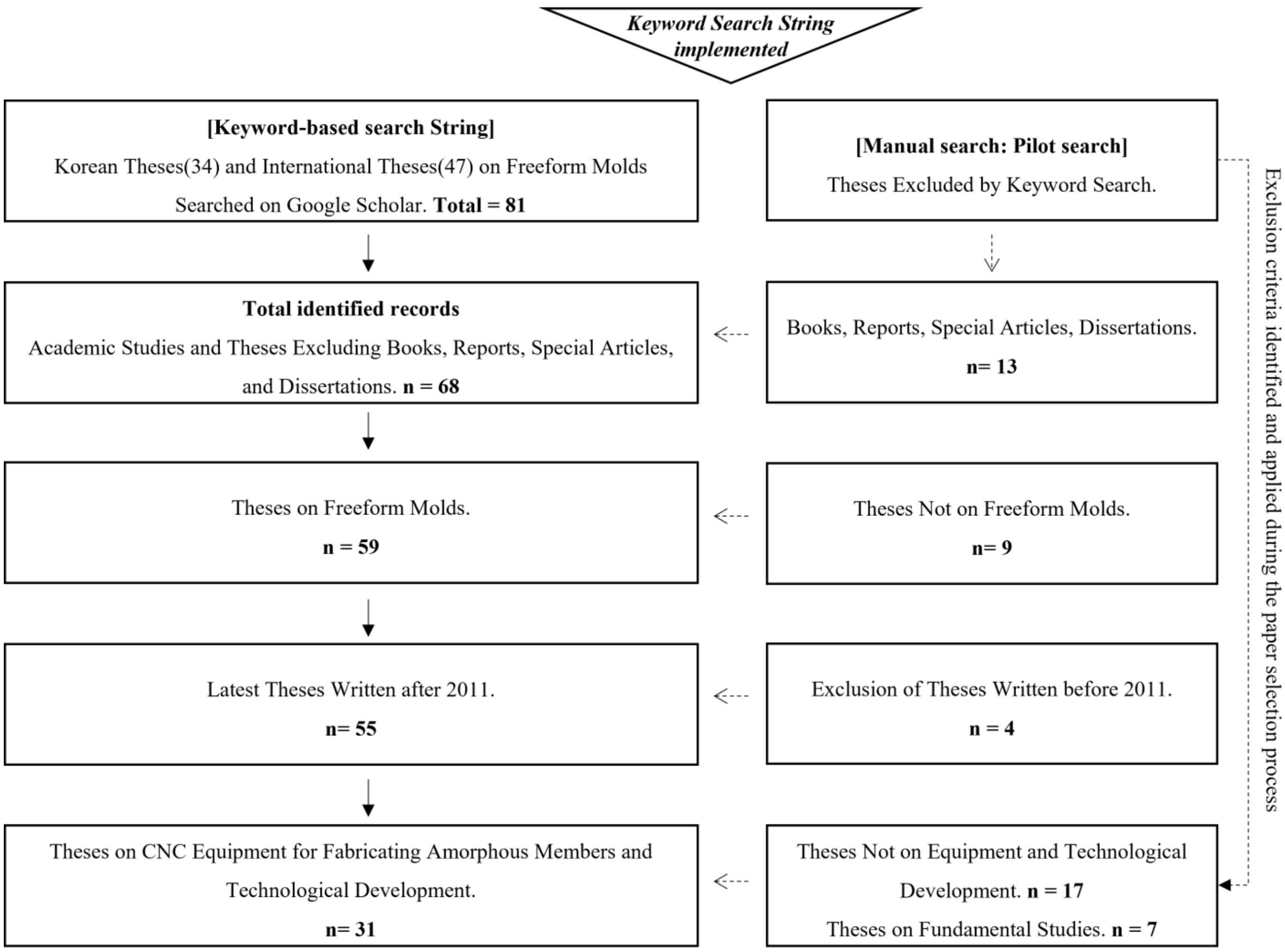

Figure 1. PRISMA flow diagram.

3. Categorization and Analysis of the Selected Publications

The 31 publications selected through PRISMA were classified into 'Free-form curve fabrication technology', 'Free-form Mold fabrication technology', and 'Free-form panel analysis.' As the contents of some publications fell into multiple categories, the sum total of publications categorized was 45. The publications selected from the PRISMA are listed in Table 3.

Figure 2 shows the number of publications written in each year, using images. There were 11 publications on free-form curve fabrication technology, and they took up 23.9%. There were 27 publications on free-form mold fabrication technology, and they took up 58.6%. There were eight publications on free-form panel analysis, and they took up 17.5%. A total of 31 publications were selected by PRISMA, but some publications were redundantly categorized into two or three categories, for a total of 46 publications in the categories.

Table 3. Categorization of the publications collected [6–36].

No	Author	Free-Form Curve Fabrication Technology	Free-Form Mold Fabrication Technology	Free-Form Panel Analysis
1	Kim, Ki-Hyuk et al. (2018)		√	
2	Cho, Chul Min et al. (2016)	√	√	
3	Sim, Joon Hyeok et al. (2020)		√	
4	Ahn, Hee Jae et al. (2020)		√	√
5	Seo, Junghwan and Hong Daehie (2017)			√
6	Kim, Ki Hyuk et al. (2019)		√	
7	Lim, Jian Hui, et al. (2020)		√	
8	Raun, C., and P. H. Kirkegaard. (2015)	√	√	
9	Lim, Jeeyoung, and Sunkuk Kim (2018)		√	√
10	Hayashi, Sei, and Tomoyuki Gondo. (2021)		√	√
11	Donghoon Lee et al. (2017)		√	
12	Schipper, H. R., and B. Janssen. (2011)	√	√	
13	Raun, Christian, Mathias K. Kristensen, and Poul Henning Kirkegaard. (2011)	√		
14	Jeong, K., et al. (2020)	√		
15	Yun, Jiyeong, et al. (2021)	√		√
16	Kim, Sunkuk et al. (2021)		√	√
17	Schipper, H. R., and Bas Janssen. (2011)	√	√	
18	Schipper, H. R., and P. Eigenraam. (2016)	√	√	
19	Schipper, H. R., et al. (2014)		√	
20	Asut, Serdar, Peter Eigenraam, and Nikoletta Christidi. (2018)		√	
21	Borhani, Alireza, and Negar Kalantar. (2017)		√	
22	Oesterle S. et al. (2012)		√	
23	Palikhe, Shraddha et al. (2015)	√	√	
24	Kwen, Soon-Ho et al. (2011)	√	√	√
25	Mayencourt, Paul, et al. (2015)		√	
26	Tang, Gabriel. (2012)	√	√	
27	Orr, John. et al. (2016)		√	
28	Costanzi, C. Borg, et al. (2018)		√	
29	Sitnikov, Vasily. (2019)		√	
30	Ji-Yeong, Yun, et al. (2021)		√	
31	Oh, Young-Geun et al. (2020)			√
	Totals	11	26	8

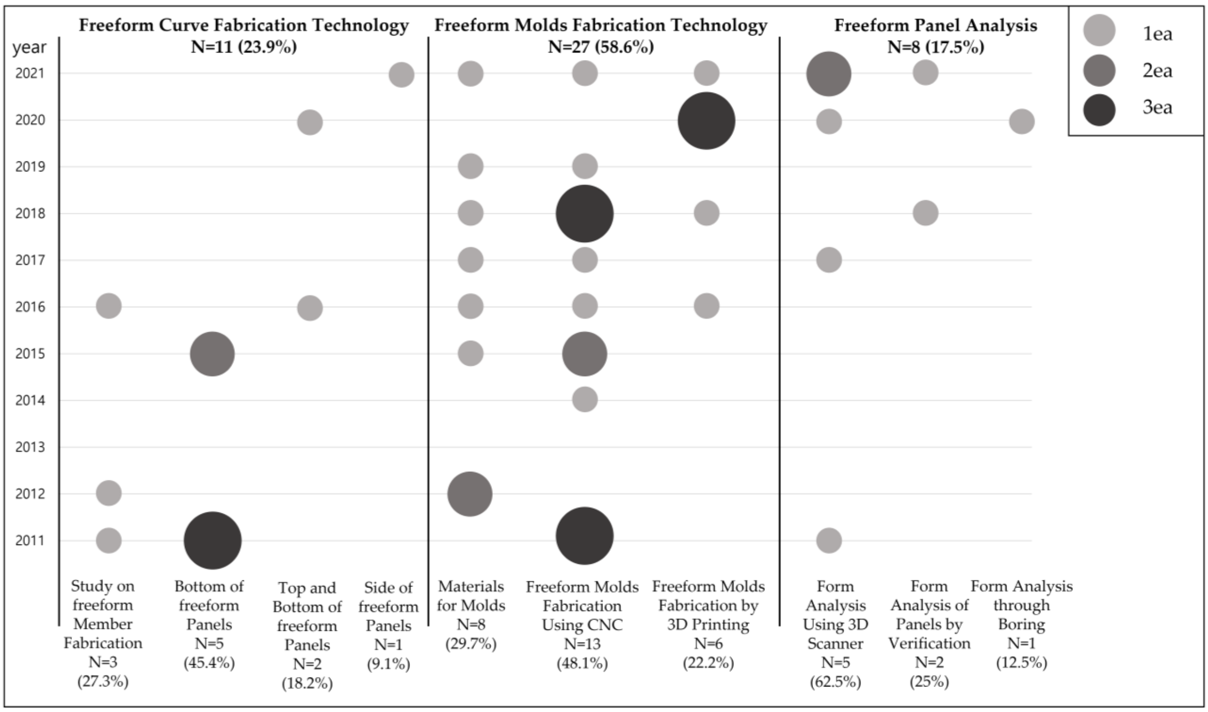

Figure 2. Free-form Mold study trends.

3.1. Analysis of Free-Form Curve Fabrication Technology Research

Free-form panels consist of a top part, a bottom part, and a side part. They form different shapes and curvatures of curves according to the place of use. Much time and manpower is consumed in the process of forming the curves of free-form molds, and frequent errors make it impossible to assemble some of the panels. Therefore, free-form panels require the swift formation of curves and precise fabrication technology. The publications were classified into those on free-form panel forms and those on free-form members. For the accurate identification of the research trends, the publications were further categorized into those on free-form members and others on the bottom, top and bottom, and side of free-form panels. A total of 11 publications were selected among the 31 publications.

- Publications on the fabrication of free-form members (three studies) (Schipper, H. R. 2016; Kwen, Soon-Ho et al. 2011; Tang, Gabriel. 2012).
- The bottom of the free-form panels (Raun, C. and P. H. Kirkegaard. 2015; Schipper, H. R. and B. Janssen. 2011; Schipper, H. R. and Bas Janssen. 2011; Raun, Christian, Mathias K. Kristensen, and Poul Henning Kirkegaard. 2011; Palikhe, Shraddha et al. 2015).
- The top and bottom of free-form panels (two studies) (Cho, Chul Min et al. 2016; Jeong, K., et al. 2020).
- The side of free-form panels (one study) (Yun, Jiyeong, et al. 2021).

There were three publications on free-form members. In order to realize a double-curve form on the 2D plane using shearing deformation, the development of a mapping algorithm, i.e., a parameter algorithm, was suggested. This method measures the 3D space on CAD in order to find and realize the coordinates of the target curve [24]. A reverse engineering technique was used to draft a panel on Digital Project, a BIM tool for free-form structures, and to achieve the optimization of the panels. The panels were classified into flat members with no curves, single-curve panel members, and double-curve panel members, in order to fabricate the mock-ups. The mock-up panels were fabricated out of aluminum and GFRC [30]. In order to make thin concrete shell structures, 5-mm holes were bored into the end of the pine wood in the form of a grid to connect to a longer member using nuts and bolts. The joints used joining bolts to form revolving joints. When the grids are completed, the braces are usually bored in order to fix them using bolts. This improves the fabrication of the free-form concrete shell [32]. The study aimed at the fabrication of free-form members using algorithms, BIM, and fabric molds.

There were five studies on the bottoms of free-form panels. Adaptive molds were developed in order to realize double-curve structures. The bottom of the molds was fixed using membrane pistons. The curvature of the bottom of the free-form structures was determined by adjusting the position of the pistons [14]. Flexible molds were developed to fabricate the double-curve panels. These installed pins on a 6 × 11 pin bed, and the double-curve elements were set on the 3D plane. Then, strip molds were used to set the vertically adjusted vertical lines and intersecting single-curve splines. The strips raise the pins to the accurate positions according to the shape of the panels in order to form the bottom of the free-form shape [18,19]. Similarly, CAD was used to control the actuator and realize the bottom of the free-form structure [23]. The methods applied to fabricate the free-form concrete panels are expensive and time-consuming; as such, they are improved with rod-type molds. Those molds replace the rubber panels on top with rods in order to realize the curves on the bottom of free-form panels. However, the end of the rod is flat, causing errors compared to the engineered forms. Therefore, the end of the rod was deformed into a semi-circle in order to improve the precision of the curvature on the bottom of the panels [29]. The actuator or rod was elevated in order to deform the bottom of the panel and realize the bottom of the free-form panels.

There were two studies on the top and bottom of free-form molds. Recycling formwork is a new method of fabricating free-form molds. It makes holes on a 800 mm × 1200 mm ×

12 mm steel sheet to fix 25 pins. Each pin can be moved up and down. The end of each pin is a sphere. It can be connected to a casing, such that the ball joint can revolve freely within the casing. The outside of the casing has bolts to fix it at the desired angle. Each casing is connected to a rubber panel with a bolt, and the top and bottom free-form forms are created by adjusting the angle of the casing and the position of the pins. In the case of sides, the exterior steel sheets are used to form a 2D form [8]. FCP (Free-form Concrete Panel) developed a two-sided multi-point press for production. This equipment realizes the top and bottom forms of an FCP. It combines the top and bottom molds of an FCP with rods and silicon rubber [20]. The equipment that forms the curvature of the top and bottom uses pins or rods to deform the rubber panel for the top and bottom.

There was one study on the sides of free-form forms. Among the equipment that can fabricate FCP automatically, side mold control equipment was developed. It can produce various forms of FCP, and can adjust the angle for the side of panels. Therefore, the molds are deformed according to the curvature and form of the side of the panel [21].

Among the 11 studies on free-form curve fabrication technology, there were five studies on the bottom curve of free-form panels: three from 2011 and two from 2015. The number of studies on the bottom was the greatest, but no study has been conducted since 2015. This means that the studies on bottom curves were conducted before other curves, and that the progress of studies was extensive. The studies on the top and bottom curvature of free-form panels were conducted in 2016 and 2020, and there was one study on the sides of free-form panels conducted in 2021. There were only a few studies, but the studies were conducted recently, showing that the studies are currently on-going. Most of the studies are various studies on rod-type equipment. In the case of sides, mold equipment has been developed to adjust to the curvature and form of the sides of panels. The studies for the realization of the curvature of free-form panels and the development of equipment are expected to persist. It is also anticipated that equipment would be developed for the fabrication of all of the sides of free-form panels.

3.2. Trends of the Studies Related to Free-Form Mold Fabrication Technology

Free-form molds have unique shapes of panels, and require customized molds. Used molds cannot be reused. They generate construction waste and lead to costs and environmental pollution. The technology for the curvature of free-form molds is insufficient, such that the molds are currently fabricated by manpower. It takes a long time to complete the fabrication and lowers the precision of the molds. There are studies being conducted on free-form mold fabrication technology to resolve these issues. Among the 31 studies, 26 studies have been conducted and categorized into three topics.

- Studies on the materials used to fabricate free-form molds (eight studies) (Kim, Ki-Hyuk et al. 2018; Donghoon Lee et al. 2017; Oesterle S. et al. 2012; Orr, John. et al. 2016; Sitnikov, Vasily. 2019; Hayashi, Sei, and Tomoyuki Gondo. 2021; Mayencourt, Paul, et al. 2015; Tang, Gabriel. 2012).
- Studies on the fabrication of free-form molds using CNC (13 studies) (Schipper, H. R. et al. 2014; Costanzi, C. Borg, et al. 2018; Borhani, Alireza, and Negar Kalantar. 2017; Palikhe, Shraddha et al. 2015; Lim, Jeeyoung, and Sunkuk Kim 2018; Kim, Sunkuk et al. 2021; Kim, Ki Hyuk et al. 2019; Kwen, Soon-Ho et al. 2011; Asut, Serdar, Peter Eigenraam, and Nikoletta Christidi. 2018; Schipper, H. R., and B. Janssen. 2011; Schipper, H. R. and Bas Janssen. 2011; Raun, C., and P. H. Kirkegaard. 2015; Schipper, H. R., and P. Eigenraam 2016).
- Studies on equipment that fabricates free-form molds automatically using 3D printing technology (six studies) (Kim, Ki-Hyuk et al. 2018; Cho, Chul Min et al. 2016; Sim, Joon Hyeok et al. 2020; Ahn, Hee Jae et al. 2020; Lim, Jian Hui, et al. 2020; Ji-Yeong, Yun, et al. 2021).

FCP free-form molds are difficult to fabricate and recycle due to their nature. They cause a massive quantity of construction waste, and are expensive to fabricate. Therefore, paraffin, a type of PCM (Phase Change Material), is used for the molds. Paraffin coagulates in high temperatures; as such, the forms of free-form molds are fabricated using 3D printing technology and a cooling machine for the instant coagulation and continuous fabrication of molds. This is expected to contribute to many environmental and economical effects by recycling FCP molds and reducing the cost of labor [7]. It satisfies the variation of free-form molds, and uses PCM to produce concrete panels for less money within a short period of time. PCM liquefies at a temperature higher than the temperature that liquefies water. The coagulated PCM has strength and viscosity, and can be reused for the mass-production of molds and rapid fabrication. Various materials were mixed to develop compound PCM in order to improve the crystallization of paraffin and reduce shrinkage upon coagulation. This delays crystallization in order to save the cooling energy and time by over 50% and reduces shrinkage by over 95%. Therefore, PCM molds improve the productivity of free-form concrete members and reduce the cost of production [17]. Furthermore, recyclable wax molds were developed using wax. This technology uses free-form wax molds that are recyclable in order to reduce construction waste. However, it is necessary to develop ways to resolve issues related to the hardening time, strength, cracks, and crystallization of wax. As a result of the fabrication of a panel using a wax mold for analysis, the precision of the free-form concrete member was poor, and further studies are required for commercialization [28]. Fabric molds can be used to produce concrete panels. Fabric can be reused in order to easily create new forms. Fabric can easily produce variable section fabric-molded beams that are hollow in the middle. It can also circulate exposed air. In the case of fabric molds, the CNC fabrication process can be used to construct double-curve concrete. However, it consumes great costs and time, and is suitable for cases where more than one identical unit is needed [33]. CNC milling molds based on ice are used to produce concrete. When ice is used for molds, it resolves various issues related to the sustainability of the production of free-assembled concrete elements, including the waste of materials. When concrete is structurally hardened, ice molds melt naturally, reducing all of the manual work in the production cycle [35]. Wood was once used to make the molds for free-form roofs. This method of wooden architecture was combined with digital fabrication technology to develop a new method. This was analyzed in relation to the production, practicality, and realization of wooden free-form molds. As a result, they consume a considerable amount of time and limit the strength of materials. Furthermore, wooden molds generate a lot of waste, which makes them not very sustainable. Therefore, they can be used with steel pipe bearings. In actual fabrication, the error may be greater due to accumulated errors. Therefore, wooden free-form molds are not very usable [16]. The existing mold construction technology makes it difficult to create free-form concrete, and consumes great costs. Therefore, wooden panel connection technology and CNC milling technology are combined for the construction of wooden panels. UHPFRC (Ultra-High Performance Fiber Reinforced Cement-Based Composite) is a high-strength cement material reinforced with steel fibers. The material has outstanding compression strength and tensile strength, along with hardening and softening behaviors to change the tensile strength. Screws are used to fix the gaps between panels, and UHPFRC is poured into the side. This means that mechanical connection makes it relatively easy and quick to construct the molds [31]. A lot of labor cost is consumed to produce concrete shells. Wooden grid shells can be deformed, and can easily realize double-curved structures. Wooden molds are used to create thin concrete shells [32]. Eight studies have been conducted on the materials used to fabricate free-form molds.

In order to resolve the issues related to free-form construction, flexible molds have been developed. These use CNC to combine silicon forms and molds on top of bearings. The height of the bearing can be altered to change the silicon panels for the curvature of free-form panels. This allows the reuse and flexibility of the curvature, but it is only good for thin panels [25,34]. Transformative formwork is a mold for various free-form panels. It contains an array of vertical bars that can be adjusted using CNC, and combines the bars with the membranes or the interpolation layer on top of them. It moves the bars to create double curves, but it requires the use of flexible materials. Transformative formwork is applied in two manners. First, hardening materials such as concrete are poured into a mold and cured. Second, softening materials can be used to form the molds after cooling [27]. Rod-type molds have been developed based on CNC using the equipment for [29]. CNC equipment has been developed to produce PCM molds for the economic fabrication of FCP. It can produce free-form panels quicker than the manual method. Silicon rubber is attached onto the CNC machine, and the bars move up and down to form the free-form shape [15,22]. In order to fabricate various forms of FCP, CNC equipment has been improved in order to develop the side form control system. It consists of a side mold conveyor, rails, and fixtures. The number of side molds is controlled in order to fabricate an FCP that is not rectangular. A conceptual drawing has been suggested to install a side panel conveyor with rails to adjust the angles and sizes of polygons [12]. CNC is used to fabricate the aluminum panels and GFRC panels for the mock-up [30]. A variable mold has been developed with individually adjustable vertical units, such as pistons or actuators, that are equally spaced based on the CNC. Vertical units can be moved up and down automatically or manually and adjust the molds according to the digitally engineered forms. This allows the creation of single or double curves for free-form panels [26]. Schipper and Bas Janssen studied how to produce free-form molds that use CNC equipment for reusability and flexibility [14,18,23,24]. There were 12 studies that fabricated free-form molds using CNC.

Manually produced free-form molds are not precise. For improvement, studies have been conducted on equipment that fabricates free-form molds automatically using 3D printing technology. There is a technology that uses cooling machines and 3D printing to resolve the problems related to free-form mold production. Therefore, a method was suggested to fabricate free-form molds using the low melting point of paraffin [7]. When free-form concrete structures are constructed, enormous manpower and time are consumed to fabricate the molds. In order to construct various free-form forms of structures, the recycling of formwork has been developed in order to fabricate the concrete module blocks. At that time, a Concrete 3D Printer was used to develop the technology to fill in the gap between the concrete modules. The technology behind assembly using 3D printers saves time [8]. The existing CNC milling technology consumes too much time when fabricating free-form molds. In order to resolve this, the S-LOM process—3D printing technology for the swift formation and free-forming of 3D shapes—was developed in order to fabricate free-form molds. As it is based on 3D printing technology, it saves time, and it improves precision compared to the existing method [9,10]. A new technology has been developed to use 3D printing technology to extrude concrete into an Adaptable Membrane Formwork. This secures the accuracy of curves and quality according to the engineered forms [13]. Furthermore, a 3D concrete extruding nozzle has been developed for FCP production. It consists of molding equipment and a 3D printer. The 3D printer is used to extrude concrete into the mold that matches the FCP shape, and the mold is removed after the concrete has been poured and cured to complete the FCP. It can be moved on the 2D plane or down, and it retains the shape of the concrete [36]. There were six studies on the development of equipment that fabricates free-form molds using 3D printers.

The studies on the materials of molds continued from 2012 to 2021. In 2012, studies were conducted on wooden molds with improved precision, and reusable wax molds. In 2015, a hinged wooden panel structure was constructed by combining wooden panel technology and CNC milling technology. Fabric molds were studied in 2016, PCM molds were studied in 2017, paraffin molds in were studied 2018, ice molds were studied in 2019, and a combination of wooden molds and digital production technology were studied in 2021. In the future, it will be necessary to develop mold materials that are usable and free-form. Further studies would be conducted to fabricate free-form molds by combining the materials that satisfy the requirements.

Among the technologies for the development of free-form molds, the studies on CNC took up 48.1% and the studies on 3D printing technology took up 22.2, with a difference of seven studies. Free-form molds can be fabricated either manually or automatically. When free-form molds are fabricated manually, they mainly use CNC.

Schipper conducted two studies in 2011 and one study each in 2014, 2015, and 2016. The studies applied CNC equipment to flexibly adjust the free-form molds. The bearing of silicon panels and molds is moved to adjust the curvature of the free-form panels. A follow-up study was conducted to fabricate a thin free-form panel using the technique. In addition, a mock-up was fabricated in 2011, and free-form molds have been fabricated by adjusting the vertical units using CNC since 2017. In 2018, CNC-based adjustable molds were developed to move the molds up and down automatically according to the digitally engineered forms. In 2019, CNC equipment was improved in order to develop a side form control system. In 2021, new equipment was developed in order to use the CNC equipment for free-form forms.

In 2016, a study was conducted to adopt 3D printing technology to construct free-form structures in 2016. In 2018, a cooling machine, a 3D printer, and paraffin were used to fabricate free-form molds. In 2020, a study was conducted to improve the mold fabrication time and precision, and concrete extrusion technology was developed. In 2021, a 3D printer nozzle was developed in order to extrude concrete for FCP fabrication.

CNC was studied from 2011 to 2021, but the studies were active between 2011 and 2018. The studies on 3D printing were conducted from 2016 until recently. CNC is used as fundamental equipment for the fabrication of free-form molds, and it is more advanced than 3D printing technology. Further studies are expected to combine CNC with various other technologies. Currently, 3D printing technology is combined with CNC to fabricate free-form molds. However, the current level is limited to the discussion of the technological concept and simple testing, and further studies are required in order to develop and test the equipment for free-form mold fabrication.

3.3. Analysis of Trends of Studies on Free-Form Panels

Free-form molds require forms that are different in all sizes and should match the engineered shapes. In case of errors, the completed free-form panels cannot be assembled, increasing the amount of construction waste and the cost of construction. Therefore, it is essential to conduct studies on the analysis of forms in order to ensure that the free-form molds match the engineered shapes. Form analysis can include various processes, and eight out of 31 studies were classified into this topic of study.

- Studies on form analysis using 3D scanners (five studies) (Ahn, Hee Jae et al. 2020; Seo, Junghwan and Hong Daehie 2017; Yun, Jiyeong, et al. 2021; Hayashi, Sei, and Tomoyuki Gondo 2021; Kwen, Soon-Ho et al. 2011)
- Studies on the form analysis of panels through statistical verification (two studies) (Lim, Jeeyoung, and Sunkuk Kim 2018; Kim, Sunkuk et al. 2021)
- A study on form analysis by boring panels (one study) (Oh, Young-Geun et al. 2020)

The 3D scanners are usually used to analyze the precision of free-form panels. For the comparative analysis of the precision, life-sized models were fabricated using the S-Lom method and the CNC milling method. A 3D scanning technology using lasers was applied to compare the precision. Stereoscan Neo was used to adjust the color and brightness according to the errors in the shapes. The data from a measured shape are applied to engineering, and are converted to a 3D CAD file. Then, it is compared to the 3D CAD engineering drawing in order to calculate the errors [10]. A 3D scanner is used to extract the height information from the surface of the EPS foam, and to gather its vector data. The gathered data are compared to the modeling data of EPS foam using the CAD program. When the surface distance between the two compared targets did not exceed 1 mm, it was expressed in green. Red means that the EPS foam is less cut than the CAD model, and blue means that it is more cut than the CAD model. The CNC milling machine was compared to the EPS foam processing machine based on the range of errors [11]. Furthermore, a 3D laser distance meter was used to calculate the errors on the surfaces of the assembled molds. The errors were measured from a 100-mm distance in order to secure the 3D coordinates and measure the errors between the 3D models for the analysis of accuracy [16]. Free-form molds have different curvatures at each side, such that they are hardly reused after completing the panels. Therefore, side mold control equipment was developed for the fabrication of reusable free-form molds. It automatically creates various forms, but it needs to be tested to see if there are any errors compared to the engineered forms. A 3D scanner can scan the fabricated panels and enter the data into VXInspect, a quality inspection program. Then, the scanned data are compared with the engineered shapes in orderto analyze the errors [21]. In order to fabricate the GFRC (Glass Fiber Reinforced Concrete) free-form panels, a special mold was fabricated. The 3D laser scanning technology and superposition method were used to compare the precision of the 3D modeling data of the mock-up and the actual member. The superposition method overlaps the BIM data of an actual member from laser scanning and the BIM data of the engineering in order to compare and measure the errors [29]. There were five studies that used the superposition equipment to analyze the forms of free-form molds.

One of the studies applied the statistical method of foam analysis. FCP (Free-form Concrete Panel) is a member that uses concrete panels on the exterior of free-form structures. As it was not very effective in terms of productivity and cost, a PCM (Phase Change Material) mold was developed based on CNC for the more economical production of FCP. The errors of FCP forms were verified for commercialization. The method of measuring the errors was the conversion of the coordinates of engineered models into graphs or charts in order to compare the members with the engineered shapes. ANOVA analysis was conducted based on the average of the errors in order to test the reliability of the error analysis [15]. Furthermore, free-form concrete panel production technology was developed using CNC machines. A test was conducted in order to verify the forms and quality of the free-form panels. The *t*-test was applied to the engineered form and the panel fabricated using CNC equipment in order to ensure that the errors did not exceed 3% of the thickness of the walls, which is the difference allowed by architectural law [22]. There were two studies that adopted ANOVA analysis or a *t*-test; they identified the errors between free-form molds and engineered shapes.

In addition to the aforementioned methods, there were studies that analyzed the forms by boring the free-form panels. They used CNC equipment to fabricate free-form panels, and analyzed the errors to indicate the difference in the deflection of the panels. Forty-nine holes were bored on the panels in order to measure the thickness of each zone. The thickness was measured using a laser leveler to analyze the error of each zone using the measurements gathered from the 49 holes. The error is the difference between the set value and the measured value, divided by 100 for the percentage. The precision of the panels was verified using this method [36].

The free-form panels were compared with the engineered shapes for the error analysis. The studies of the form analysis of free-form panels were classified by the method of comparison. There were eight studies related to the analysis of free-form forms; these only took up 17.5% of the studies, which was the lowest percentage. The analysis of free-form forms is only possible after the fabrication of the free-form molds using a certain technology. Therefore, the number of such studies of analysis is limited, as they were performed relatively recently.

There were five studies that analyzed the forms of panels using 3D scanners. In 2011, 3D laser scanning technology was used to compare the precision between 3D modeling data and the actual member. From 2017 to 2021, 3D scanners were used to scan the free-form panels in order to compare them with the engineered shapes, and to identify the accurate errors or precision.

Form analysis through statistical testing expresses the coordinate values of models on charts in order to test the reliability of error analysis through ANOVA or *t*-test. In 2020, the panels were bored to analyze the forms. The 3D scanners can easily analyze the errors of free-form panels, and they make it easy to secure the data of free-form molds and panels. The data are used to compare the free-form molds with the engineered shapes in order to identify the accuracy errors and the precision of the shapes. As there are on-going studies on the fabrication of free-form molds, the studies on the analysis of free-form panels are expected to continue in order to analyze them, and 3D scanners will be used in most cases.

4. Conclusions

The current study analyzed the multifaceted studies on free-form molds using the PRISMA method to identify and analyze the trends of the studies. The keywords related to free-form molds were selected and entered into Google Scholar in order to collect the publications. The publications were classified based on the standards of selection and exclusion, and 31 studies on free-form molds were used to complete the PRISMA Flow Diagram. The process of the analysis of the studies on free-form molds is as follows.

First, there were 11 studies on the technology for the fabrication of the free-form curves, which took up 23.9%. They were further categorized into studies of free-form members and studies of the bottom, top and bottom, and sides of free-form panels. The studies on the fabrication of members and the bottom took up 27.3% and 45.4%, respectively, and were conducted between 2011 and 2016. The studies on the top, bottom, and sides of free-form panels were conducted within the latest five years, and further studies would be needed, as there are only few.

Second, there were 26 studies on the technology behind the fabrication of free-form molds, and they took up 58.6%. The studies were further categorized into the materials of molds, the method of fabricating free-form molds using CNC, and the fabrication of free-form molds using 3D printing. The studies on the materials of molds have constantly been conducted, in order to fabricate free-form molds that are recyclable. There were 13 studies that used CNC to fabricate the free-form molds, and they took up 48.1%. They applied CNC to the equipment used for the fabrication of the free-form molds; however, the fabrication process was mostly manual, as the technology behind CNC equipment is still insufficient. There were six studies on automatically fabricated free-form molds using 3D printing between 2016 and 2021. Therefore, more studies on the technology behind the fabrication of free-form molds should be conducted in order to construct the automation equipment.

Third, there were eight studies on the analysis of the precision of free-form panels completed through studies on free-form molds, and they took up the least 17.5%, as the analysis of form involves follow-up studies. There were five studies that compared the files of free-form panels from 3D scanners to the engineered shapes, in order to measure the precision. There were two studies that used *t*-tests and ANOVA to measure the precision, and one study that analyzed the shapes through boring. Form analysis is essential for the studies on the fabrication of free-form molds, and 3D scanners are suitable for the measurement of the precision, showing that further studies should be conducted using 3D scanners. The analysis of the trends of studies on free-form molds organized the multilateral studies on free-form molds. The current study is expected to resolve the redundancy of studies on free-form molds, and to provide the standards of studies on free-form architecture, in order to contribute to the development of free-form molds in the future.

Author Contributions: Conceptualization, J.Y. (Jongyoung Youn), S.K. and J.Y. (Jiyoung Yun); methodology, J.Y. (Jongyoung Youn); formal analysis, J.Y. (Jongyoung Youn) and J.Y. (Jiyoung Yun); writing—original draft preparation, J.Y. (Jongyoung Youn), S.K. and D.L.; writing—review and editing, D.L., S.D. and B.H.; supervision, D.L.; project administration, J.Y. (Jongyoung Youn) and S.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. 2020R1C1C1012600).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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