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Production Technology of Free-form Concrete Panels using 3D Carving Techniques

Ki-Ho Kim[a], Jeeyoung Lim[b], Oum-Joong Oh[c] , Sunkuk Kim[d]*

[a] Dept. of Architectural Engineering, Kyung Hee University, Suwon, Republic of Korea

[b] Dept. of Architectural Engineering, Kyung Hee University, Suwon, Republic of Korea [c] Dept. of Architectural Engineering, Kyung Hee University, Suwon, Republic of Korea

[d] Dept. of Architectural Engineering, Kyung Hee University, Suwon, Republic of Korea

Abstract: ***Production technology of free-form concrete panels (FCP) using PCM (Phase Change Material) molds was developed for free-form building construction. PCM is a substance that changes phases from liquid to solid depending on temperature changes and it is economical since the mold is reusable. However, crystallization occurs when the PCM mold transforms into solid state and its volume shrinks, making it unable to secure preciseness of the mold. Accordingly, it is difficult to produce quality FCPs. Therefore, a production technology of accurate PCM molds regardless of phase changes needs to be developed. The purpose of the study is to propose an FCP production technology using 3D carving techniques. To do so, problems of existing technologies are analyzed and an innovative production technology that has been improved from the existing ones is suggested. In the academic aspect, these study results will be used for development of algorithms used for efficient 3D carving techniques, and in the practical aspect, free-form buildings will be built using a high-quality panel production.***

Keywords: **free-form, concrete panel, PCM, production technology, carving technique.**

I. INTRODUCTION

Owing to development of 3D digital technologies, a wide range of free-form buildings are being newly built [1].

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Although a tremendous amount of capital and various techniques are applied for construction of free-form buildings, there is still not technology advanced enough to economically produce high-quality free-form panels [2, 3].

In particular, it impossible to reuse molds that are adopted for free-form concrete panel (FCP) production, laying a burden in terms of cost [10, 11, 12, 13]. This is because free-form finish panels have various curvatures (free form surfaces), including plane, single curved and double curved types [3, 4, 5].

To solve this problem, there have been various studies regarding development of variable molds for FCP production using wax, paraffin and fiber [5, 6, 7, 9]. Among these, a PCM (Phase Change Material) mold, a substance that changes phases from solid at room temperature to liquid at a certain temperature, was developed [8]. FCPs produced with PCM molds can be reused infinitely and it is more innovative and economical than existing methods.

Crystallization occurs when the PCM mold transforms to solid and its volume shrinks, making it unable to secure preciseness of the mold [6, 7, 10, 12]. Accordingly, it is difficult to produce quality FCPs [11]. It is necessary to ensure FCP production technology to improve PCM liquefaction and solidification properties which generates such problem. In other words, a production technology for precise PCM molds, regardless of phase changes, is required. Therefore, the purpose of the study is to propose a production technology of free-form concrete panels using 3D carving techniques.

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Firstly, existing FCP production technologies that apply PCM molds are analyzed by reviewing previous studies. Then, problems of the existing technologies as well as their advantages/disadvantages are identified.

Secondly, improvements and solutions to existing PCM technologies are analyzed. Based on these, performance requirements and conditions of the technology proposed in the study are deduced.

Thirdly, the concept of 3D carving techniques using solid PCM reflecting the above is proposed. Then, high-quality FCPs can be economically produced.

The developed technology will dramatically reduce time in producing PCM molds, which is a problem of existing FCPs and it is an innovative technology that may improve preciseness and accuracy of molds. Academically, the study results will be used for development of algorithms for efficient 3D carving techniques, and practically, it will make possible to economically produce high-quality FCPs.

II. PRELIMINARY STUDY

A. FCPs Production Technology of using PCM

A lot of studies have been conducted for economic production of high-quality free-form concrete panels (FCP) [6, 7, 10, 11, 12]. In particular, various materials and methods were applied to solve a problem on reusing molds. Lee et al. (2017) conducted a study on developing a variable mold that uses PCM (Phase Change Material), a phase-changing substance [10, 11, 12].

The production technology proposed by Lee et al. (2017) is to produce FCPs with free-form molds using liquid PCM. As shown in Fig. 1, the production technology is arranged into a PCM production process and FCP production process. During the PCM production stage, liquid PCM is prepared as illustrated in Fig. 1 [10, 11, 12]. The prepared PCM is injected into a CNC machine, and the rod height is controlled to manufacture free forms [11, 12]. Liquid PCM with the manufactured form is cooled to maintain its shape. The solidified PCM is separated from the CNC machine and a form board is attached to its sides to produce a PCM mold. During the FCP production stage, concrete mixed into the PCM mold is poured and cured to manufacture FCPs. When the concrete strength reaches a certain point, the removed PCM is melted into liquid for reuse. As explained above, the PCM and FCP production processes are repeated for FCP production [12].

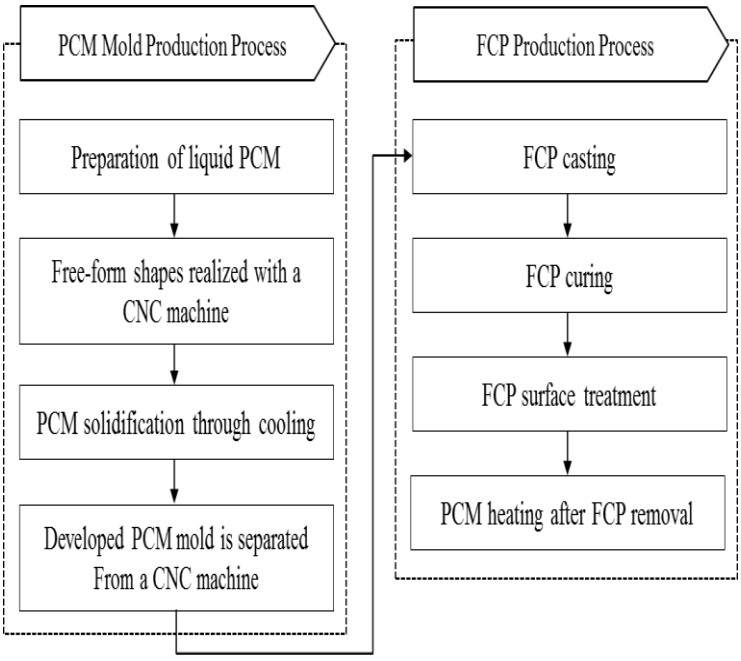

Fig. 1: Process of FCP Production Technology [11]

B. PCM Problems

The PCM mold process that solved the exclusivity of molds is as illustrated in Fig 2. Although exclusivity of molds is secured by minimizing PCM cooling which is one of the biggest problems of FCP production technology, a problem occurs during the PCM mold production process. Several advantages of PCM include less quality degradation and chemically stable characteristics even when solidification and melting procedures are applied. Additionally, it is easy to purchase materials and they are inexpensive [12]. Despite the above advantages, a specific time is required for cooling and solidifying PCM when producing molds. Furthermore, crystallization generated during the process causes its volume to partially shrink, making it difficult to secure preciseness of molds [12]. In addition, cooling techniques or additional cooling devices are required for quick solidification. To solve these

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problems, there were studies proposing the concept of PCM molds and its development. However, production time and mechanical problems remain unsolved [14].

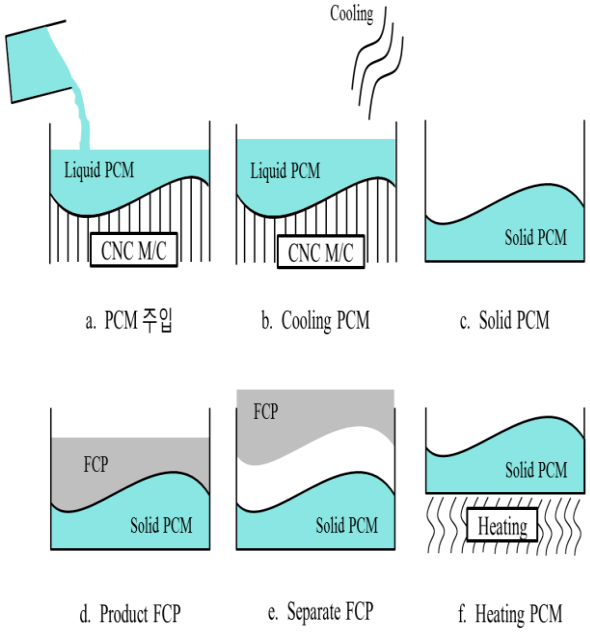

Fig. 2: PCM Mold Production Process [11]

Lee et al. (2017) secured FCP production and management technologies. Based on this, Lee intended to produce optimized molds with free-form shapes [14, 15]. However, the study only introduced the FCP production method and its superiority. Therefore, more innovative technological studies are required to solve problems related to materials and time during the production process.

III. REQUIREMENT ANALYSIS

A. Analysis on Performance Requirements of 3D Carving Techniques

Any solutions and improvements to existing production technologies should be drawn to secure an innovative production technology with improved productivity and economic feasibility [13 & 14]. For this, 3D carving techniques are adopted, and the related equipment needs the following functions as shown in Table 1: Carving, Plastering, Troweling and Grinding. Each function should be installed onto a horizontally-moving device of the 3D carving machine to produce FCPs. The 3D carving machine should have the head of a vertically-moving device with each function as described in Table 1. In other words, 4 different equipment units should be operated to produce FCPs.

Table 1. 3D Carving Machine's Performance Requirements

Main Function	Details
Carving	- PCM molding for molds for FCP production
Plastering	- Materials such as GFRC and HPC applied for FCP production
Troweling	- Surface treatment for FCP surface finish - When functions are added to the 3D carving machine, it is included in CP (Critical Path)
Grinding	- When cutting the corners of PCM, pieces may be cut off; thus, PCM should be 5mm larger than the required size considering for cutting errors; - PCM cut larger than the required size is grinded to its original size; - When functions are added to the 3D carving machine, it is included in CP (Critical Path)

B. Analysis on Performance Requirements of PCM Mold and FCP Finished Products

The performance requirements of PCM molds and FCP finished products are analyzed in terms of quality, cost and construction period as described in Table 2. PCM requires productivity, economic-feasibility, convenience, variability, and exclusivity and finish ability. Performance requirements of PCM molds are largely analyzed in terms of quality, construction period and cost. Fine finished surface in terms of quality; production speed in terms of construction time; and the economic-feasibility of mold materials in terms of cost should be reviewed. Materials, including GFRC (Glass Fiber Reinforced Concrete) and HPC (High Performance Concrete) are applied for FCP finished products, and their constructability durability, curing speed, economic-feasibility, water-tightness and insulation properties are required. When it comes to quality, shape, thickness, fine finished surface and uniformity should be reviewed. Likewise, in construction period,

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curing speed should be taken into account; and when it comes to cost, economic-feasibility of concrete materials should be reviewed.

Table 2. Performance Requirement of PCM Molds and FCP Finished Products

Type	Material	Requirements	Consideration Points
PCM Mold	PCM (Phase Change Material)	- Productivity, economic-feasibility; - Convenience, variability; - Exclusivity, finish ability	- Quality: Fine finished surface - Construction period: Production speed - Cost: Economic-feasibility of mold materials
FCP Finished Product	GFRC (Glass Fiber Reinforced Concrete) HPC (High Performance Concrete)	- Constructability, durability strength - Curing speed, economic-feasibility - Water-tightness, insulation	- Quality: Shape, fine finished surface, uniformity of materials - Construction period: Curing speed - Cost: Economic-feasibility of concrete materials

If 3D carving techniques satisfy performance requirements according to the analysis, it is likely that PCM molds will consistently produce quality panels with less production error and dependable production time for mass production.

IV. 3D CARVING FCP PRODUCTION TECHNOLOGY

A. 3D Carving Techniques

The proposed technology uses a 3D carving machine to automatically cut solid PCM (Phase Change Material) and produce FCPs using PCM as a variable mold. The FCP production process is shown in the pictures below. 3D carving technology is categorized into the following stages: PCM preparation, PCM mold production, FCP production and equipment return. First of all, a solid rectangular PCM is prepared.

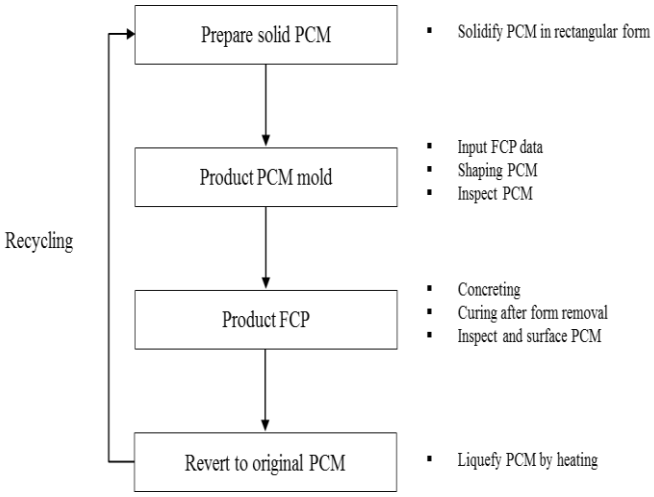

Fig. 3: 3D Carving Production Technology

When it is ready to be used, the solid PCM is placed on the 3D carving machine for zero-point adjustment and get ready for PCM cutting. Here, panel design data are inserted into the 3D carving machine based on BIM (Building Information Modeling). When the zero-point adjustment of the machine is completed, PCM molding is implemented. The Shaping Cutter chooses a blade considering production time and FCP's curvature. The completed PCM is moved onto the next process, and the 3D carving machine is initialized for the next molding job.

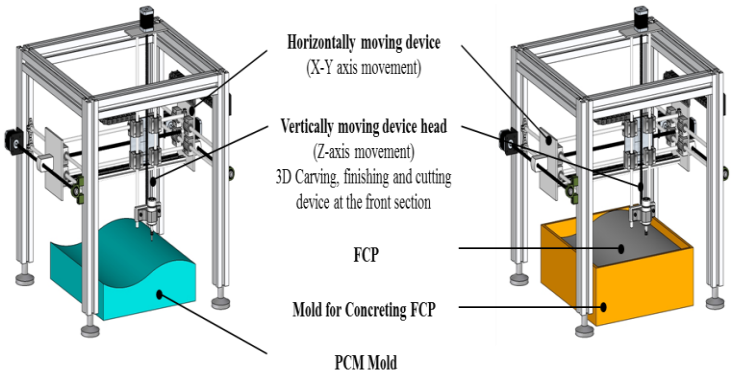

Fig. 4: 3D Carving Machine concept

Fig. 5 shows the FCPs production process. A mold is prepared for carving to produce a PCM mold. After applying panel materials such as GFRC and HPC, surface treatment is performed. The produced FCP is 5mm larger than the designed FCP, so its corners should be cut to produce a final FCP that can be installed. Here, the 3D

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carving machine returns to its initial state for the next process, and the above procedure is continuously repeated for FCP production. As shown in Fig. 4, this 3D carving machine is composed of devices for X, Y and Z-axis movement, and a head is attached to the vertically-moving device for FCP production.

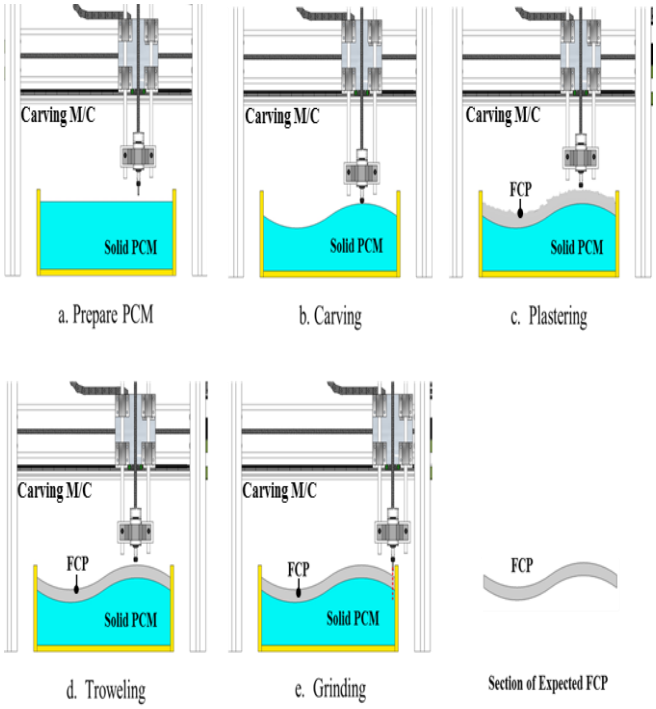
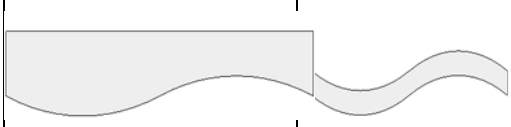
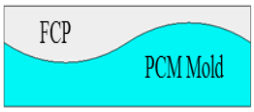
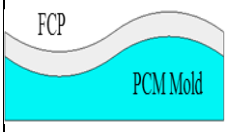


Fig. 5: FCP Production Process

Table 3. Performance Requirements of PCM Mold and FCP Finished Product

	Single Curved	Double Curved
FCP		
FCP + PCM mold		
Material cost	Expensive	Inexpensive
FCP weight	Heavy	Light
Production time	Short	Long
Constructability	High	Low

When FCPs are produced with the above technology, the single-curved and double-curved process methods can be used. The characteristics of each production type are stated as below in Table 3. That is, they are analyzed in terms of material cost, FCP weight, production time and constructability. The materials' cost and weight for single-curved processing were found to be expensive and heavy. However, when considering production time and shipment as well as in-situ construction, the efficiency of double-curved processing declines. Thus, it can be concluded that single-curved FCPs are more advantageous in terms of productivity and constructability.

B. Pros and Cons of the Existing Technology and 3D Carving Technology

Two major differences between the existing technology and 3D carving technology are detailed in Table 2.

First is a phase change during the mold production process. The existing technology injects liquid PCM into a CNC machine to produce free-form molds. After the mold is shaped, its outer part is cooled faster than the inner part during PCM cooling. It takes time for the inner part to solidify and it is difficult to secure preciseness of the mold due to crystallization. However, 3D carving technology uses solid PCM mass that has no phase changes during the production process to shape a free-form, solving problems related to quality and time.

Second is the need of related equipment. The existing production technology requires separate equipment to solidify free-form shapes and molds. However, 3D carving technology only needs a carving machine for free-form shapes. This reduces additional equipment cost and improves the complicated production process, ultimately solving problems related to manpower and cost.

Table 4. Differences between Two Production Technologies

Main Category	Sub-category	FCP Tech.	3D Carving Tech.	Excellence of the technology
Phase Change	Number of Processes	Relatively a lot	Less than the existing technology	Improved productivity

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	Impact of making PCM mold on process	Having an impact	Having no impact	Improved productivity
	Mold shaping process	Impacting the physical characteristics during PCM solidification	Carving without the solidification process	Quality secured
Equipment (Machine)	Mold's error range	Slightly generated	Barely generated	Improved precision
	Realization of mold shapes	Separate equipment needed	No separate equipment needed	Cost reduction

When the proposed technology is applied, it will be an innovative FCP production and hold a dominant position in the production market. However, further studies on production and equipment plans are required to meet the increased demand as economic feasibility and productivity grow.

V. CONCLUSION

The existing production technologies of FCPs cannot solve problems regarding quality and time. They have a lot of limitations related to production, like increased construction period and cost. Accordingly, the study proposed a production technology that has improved the existing production technology using 3D Carving Machine, and the problems were resolved. The study results are described below.

Firstly, the existing FCP production technologies were reviewed and problems that needed to be addressed were analyzed. Then, the direction to take to improve the technology was deduced.

Secondly, the technology direction and performance requirements to solve problems of the existing technologies were drawn. Based on these findings, an innovative production technology for FCPs production was proposed.

Thirdly, the concept of 3D carving technology without phase changes during the production process considering the above was suggested. With these techniques, and efficient production and management technology were established so as to produce FCPs with improved productivity and economic feasibility.

The study proposed an efficient production technology of free-form concrete panels. Academically, the study results will be the basis to develop algorithms for efficient 3D carving techniques, and in practice, it will make possible to economically produce high-quality FCPs and dramatically reduce time and cost.

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REFERENCES

[1] Beatriz Plaza (2006). The Return on Investment of the Guggenheim Museum Bilbao, International Journal of Urban and Regional Research, 30(2), 452-467. doi:10.1111/j.1468-2427.2006.00672.x.

[2] James Payne(2003). The Sydney Opera House, Inside and Out, New South Wales, Sydney: Interview with author. 247-277. Retrieved fromhttps://ses.library.usyd.edu.au/bitstream/2123/1415/8/08 chapter7.pdf.

[3] Mandl, P., winter, P. & Schmid V. (2009). Stahlbau. Hybride Strukturen freige formt - Das Haus für Musik und Musiktheater in Graz. doi:10.1002/stab.200910065.

[4] Yuosre F. Badir, M. R. Abdul Kadir, Ahmed H. Hashim (2002). Industrialized Building Systems Construction in Malaysia, Journal of Architectural Engineering, 1(19), 19-23. doi:10.1061/(ASCE)1076-0431(2002)8:1(19).

[5] Charles M. Eastman, Rafael Sacks (2008). Relative Productivity in the AEC Industries in the United Sates for On-site and Off-site Activities, Journal of Construction Engineering and Management, 134(7), 517-526. doi:10.1061/(ASCE)0733-9364(2008)134:7(517).

[6] Lee, D. H.(2014). Production Technology of Free-form concrete Segments using Phase Change Material,

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ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 8, Issue 9, November 2018

International conference on Advances in Civil and Structural Engineering. doi: 10.15224/ 978-1-62348-006-4-100.

[7] K. Kim, C. Lim, S. Kim(2013). A basic study of manufacturing technology of free-form concrete segments, Proceedings of the Conference of the Korea Institute of Building Construction, 13 (1), 12-13. Retrieved from http://www.auric.or.kr/User/Rdoc/DocRdoc.aspx?returnVal=RD_R&dn=296999#.Wo1BO6hl-Uk.

[8] K. Kim, K. Son, E.D. Kim, S. Kim(2015). Current trends and future directions of free-form building technology, Archit. Sci. Rev., 58(3), 230-243doi:10.1080/00038628.2014.927751.

[9] D.H. Lee(2015). A Study of Construction and Management Technology of Free-form Buildings, (Doctoral dissertation, Department of Architectural Engineering, Kyung Hee University). Retrieved from http://dcollection.khu.ac.kr/jsp/common/DcLoOrgPer.jsp?sItemId=000000164730.

[10] D.H. Lee, W.K. Hong, J.T. Kim, S. Kim(2015). Conceptual study of production technology of free-form concrete segments, Int. J. Eng. Technol., 7(4), 321. doi:10.7763/IJET.2015.V7.812.

[11] Lee, D., Lee, S. G., & Kim, S. (2017). Composite Phase-Change Material Mold for Cost-Effective Production of Free-Form Concrete Panels, Journal of Construction Engineering and Management, 143(6), doi:10.1061/(ASCE)CO.1943-7862.0001300.

[12] D.H. Lee, S. Kim (2017). Development of PCM-enabled atypical concrete segment production process, J. Archit. Inst. Korea, 17 (1), 219–224. Retrieved from http://www.earticle.net/Article.aspx?sn=241701.

[13] Bruckman, A.(1997). Moose Crossing: Construction, community, and learning in a networked virtual world for kids (Doctoral dissertation, Massachusetts Institute of Technology). Retrieved from http://www.static.cc.gatech.edu/~asb/thesis/.

[14] J.Y. An(2017). A Study on the Lessons Learned for Improving Efficiency of Freeform Façade Construction, (Master thesis, Seoul National University of Science & Technology) Retrieved from http://snut.dcollection.net/common/orgView/000001105968.

[15] S.H. Son, L.Y. Lim, S.K. Kim (2018). Planning algorithms for in-situ production of free-form concrete panels, Automaton in Construction, 91, 83-91.doi:10.1016/j.autcon.2018.03.006