Master of Science in Engineering

The Offset Factors of Learning Curve Effect in High-rise Constructions

by

Bogyeong Lee

Department of Architecture & Architectural Engineering

The Graduate School

Seoul National University

February 2014

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Bogyeong Lee

A thesis submitted in partial fulfillment

of the requirements for the degree of

Master of Science in Engineering

Seoul National University

2014

The Offset Factors of Learning Curve Effect in High-rise Constructions

지도교수 박문서

이 논문을 공학석사 학위논문으로 제출함

2013 년 10 월

서울대학교 대학원

건축학과 건축공학전공

이 보 경

이보경의 공학석사 학위논문을 인준함

2013 년 12 월

위 원 장 이 현 수 (인)

부위원장 박 문 서 (인)

위 원 강 현 구 (인)

The Offset Factors of Learning Curve Effect in High-rise Constructions

December, 2013

Approved by Dissertation Committee :

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Hyun-Soo Lee

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Moonseo Park

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Thomas Kang

Abstract

The Offset Factors of Learning Curve Effect in High-rise Constructions

Bogyeong Lee
Department of Architecture and Architectural Engineering
The Graduate School
Seoul National University

Focusing on repetitive works of construction, many research have been conducted about the application of the learning curve effect. However, it is still controversial, especially on the high-rise project, since the productivity improvement from the learning curve effects are hard to prove. In the previous research, the applicability of the learning curve was mainly derived from the labor productivity data. Although the research were based on the real data, they merely concentrated on the simple conclusion that the labor productivity had improved or not, instead of the process interpretation. Therefore, the purpose of this research is to analyze the influence factors of the learning curve effect in high-rise project and elucidate the offset factors of the effect. Based on these factors, a model for estimating the labor productivity containing the concept of process learning is suggested.

The suggested model is based on the offset factors which are derived from the previous literature; 1) the repetition or change of each work section, 2) the workers' transit time. The learning curve from the previous theory would be modified with two steps according to the above two factors to estimate the labor productivity. Case study is conducted to verify the model's validity and it would prove the validity of the offset factors.

Through our research, traditional learning curve theory could be compensated and re-established with having more appropriateness for high-rise projects. Also, it would be helpful for work planning phase, if the manager wants to consider the learning effect of the labor. The research can be a solution of the question why the learning curve effect is not manifested enough in high-rise projects although high-rise projects have enough conditions for the learning curve effect.

Keywords: Learning Curve Effect, High-rise, Labor Productivity

Student Number: 2012-20560

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Chapter 1. Introduction

1.1 Research Background

Individual projects in construction industry include plenty of repetitive activities although they occur only once. This feature induces plenty of research to investigate the learning curve effect which means the labors' productivity gets improved from repetitive works. Especially, in case of high-rise constructions, they include more repetitive works than general projects and it means high-rise constructions have suitable condition to be manifested the learning curve effect. According to this feature, research which insists the learning curve effect should be considered when scheduling high-rise constructions receive the attention.

However, project managers in construction site would not sense the effect of improvement, unlike the previous learning curve theory. Also, Jarkas (2010) mentioned that it is difficult to find an improvement of labor productivity from learning curve effect in high-rise project. It suggests that there could be other factors interrupting the manifestation of the learning curve effect. When project manager plans the work schedule with premise that labor productivity would improve from learning curve effect, as the project progresses, the performance could be worsen due to the gap between expected and actual productivity.

Previous research tends to focusing on not the manifestation process of the effect but just the effect itself. It could derive misunderstandings that the learning curve effect always causes the productivity improvement and forms the incorrect concept about the learning curve effect in construction industry.

Therefore, in order to apply the previous learning curve theory to productivity management of high-rise constructions, modification of the theory from analyzing manifestation process should be conducted. In this research, authors introduce the analysis result about offset factors of learning curve effect in high-rise project. Based on these factors, the labor productivity estimation model would be suggested to verify the modification process.

1.2 Research Scope and Process

This research includes only the non-bearing wall construction in high-rise project which has variation of floorplan on each work section in order to look into work progress when repetitive works and newly introduced works are mixed. ‘High-rise projects’ mean the buildings with more than 40 floors according to Korean general standard. A standard unit of work repetition is the ‘floor’ and it would be used the labor productivity estimation. ‘The labor productivity per floor’ in this research means unit material per work hours (unit/h).

Also, this research contains an assumption that the learning curve effect has high validity in repetitive works of construction industry. Additionally, all materials used in construction are delivered to work space before construction is carried out.

Research processes would be as follow.

(1) Problems are discovered with literature review and influence factors of learning curve effect and labor productivity are derived from previous research.

(2) The offset factors of learning curve effect are derived from common influence factors.

(3) Labor productivity data in high-rise projects is collected and estimation of work hours is needed considering work days and number of workers of each floor. These data would be converted labor productivity of each floor and be compared with general

learning curve theory.

(4) The model for estimating labor productivity is developed using results of data analysis with complementing the weakness of prior theory.

(5) Through ‘case-study’, model would be tested its validity and model behavior would be discussed.

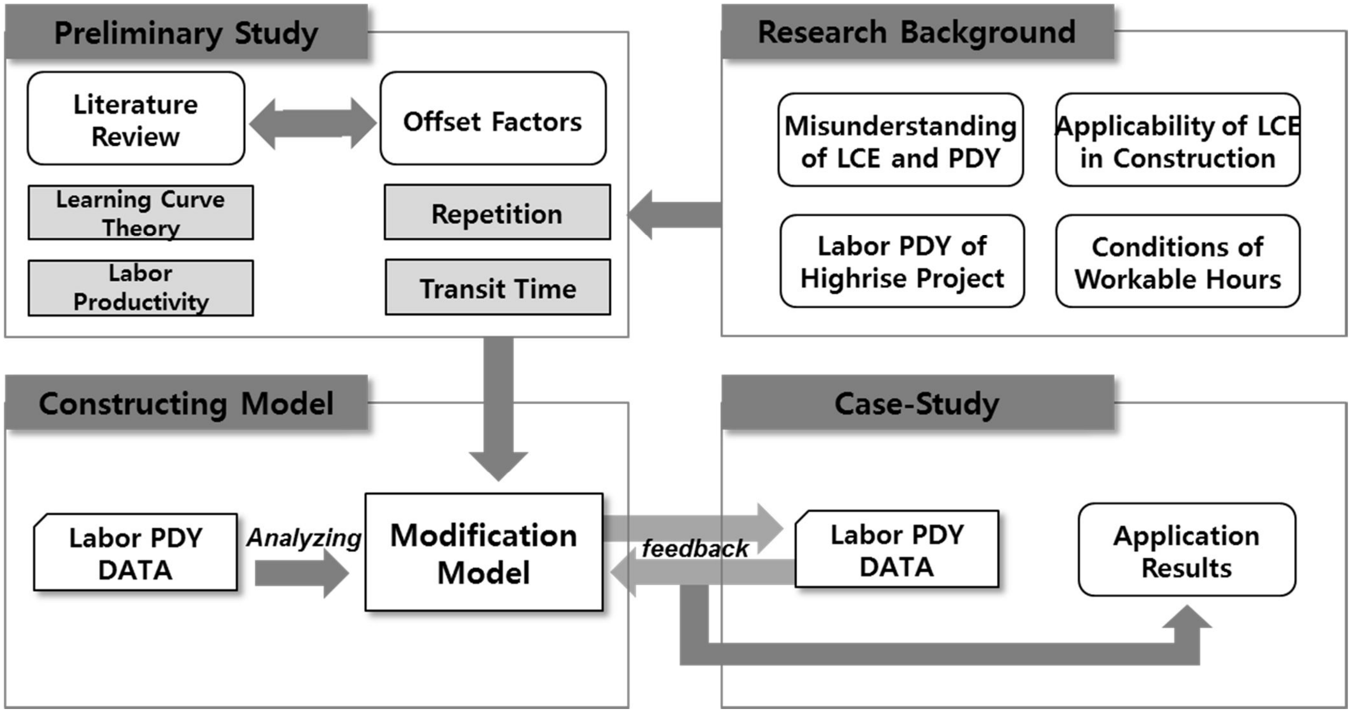


Fig 1. Research Process

Chapter 2. Preliminary Study

This chapter begins with the investigation of the learning curve effect in construction industry and also the learning curve effect itself and its history would be introduced. Also, the previous research which is relevant with this study is analyzed and the authors find that there is a certain trend about the learning curve effect. Most of the research discussed whether the learning curve effect has an actual effect or not and had insufficiency for investigating its process.

To find the offset factors of the learning curve effect, the authors studied about the characteristics of the effect and high-rise projects. The common influence factors of the two are the degree of the repetition of works and the workers' transit time. These two factors could be derived from plenty of the previous literature and would be used in chapter 3 for the assumptions of the modification model.

2.1 Learning Curve Effect in Construction

2.1.1 Learning Curve Effect

Learning curve theory states that whenever the production quantity of an new or changed product doubles, the unit or cumulative average cost (hours, man-hours, dollars, etc.) will decline by a certain percentage of the previous unit or cumulative average rate (Thomas et al., 1986). Learning Effect was first discovered by T.P. Wright in 1936 and he found that the man-hours to assemble an airplane declined by 20 percent each time the unit production volume doubled (Cunningham, 1980). Especially, it began receiving an attention during World War Ⅱ as the government contractors searched for ways that they could use to predict costs and time requirements for construction of ships and aircraft to be used to conduct the war (Yelle, 1979). After this, plenty of industries containing repetition of works, as a premise of learning curve effect made an attempt to apply to their projects (Adler and Clark, 1991; Amor and Teplitz, 1998; Cherrington et al., 1987).

Learning curve could be defined as a mathematical model considering a human characteristic that refers to 'learning from the past'. In general, five basic models are: (a) The straight-line model; (b) the Stamford "B" model; (c) the cubic power model; (d) the piecewise (or stepwise) model; and (e) the exponential model. These five models have their own assumptions and characteristics. The straight-line model has the underlying assumption that the learning rate remains constant throughout the duration of the activity. The stanford "B" model assumes that worker has 'know-how' as an acquired experience resulting from performing similar activities. When the worker has no acquired experience, this model behaves like straight-line model. The cubic model assumes that the learning rate is not a constant variable because of the phenomenon that the acquired experience and improvement of labor productivity would moderately increase as the project comes to the end. The piecewise model is a linearized approximation of the cubic model and the exponential model assumes that cost per unit that can be reduced by repetition will be reduced by one-half after a constant number of repetitions (Thomas et al., 1986).

The straight-line learning curve model is the most commonly used model for construction activities (Thomas et al., 1986) because works in construction projects are believed to have constant learning rate and high accuracy for representing real work conditions. Hence, the learning curve model in this research also adapts the straight-line model. It has exponential curve, as shown in Fig 2, and it forms a straight line when plotted on a log-log scale (Thomas et al., 1986).

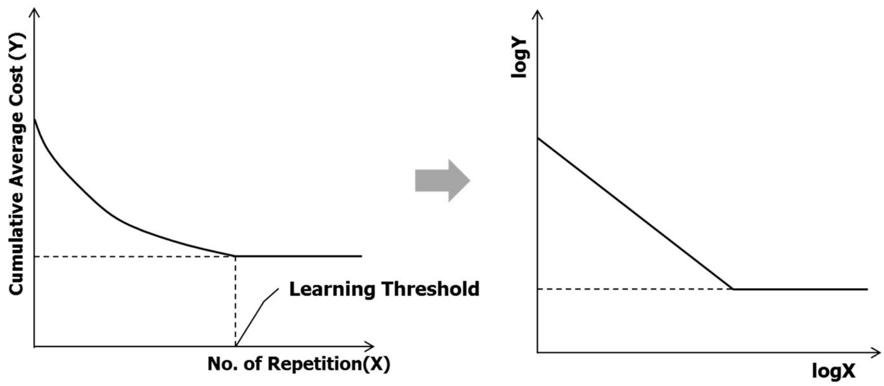


Fig 2. Learning Curve and Straight Line Model

The learning curve has its own numerical formula as described below (Yelle 1979).

$$A = KX^n \quad \text{--------} \quad (1)$$

where

A = the number of direct labor hours required to produce the X^{th} unit;

K = the number of direct labor hours required to produce the first unit;

X = the cumulative unit number;

$n = \log\varphi / \log 2$ =the learning index;

φ =the learning rate.

2.1.2 Literature Review of Learning Curve Effect and Labor Productivity in Construction Industry

From 1970s, applicability of the learning curve effect in construction industry has been researched focusing on the repetition of works (Gates and Scarpa, 1972; Thomas et al., 1986; Hinze and Olbina, 2009). Also, research of applying the learning curve effect to simulation or analyzing the labor productivity has been studied with a premise that the learning curve effect has validity in construction industry (Hijazi et al., 1992; Lutz et al., 1994; Farghal and Everett, 1997; Wong et al., 2007). However, some researcher mentioned that previous learning curve theory could not be adapted to construction industry as it is, with research that the learning curve effect actually had no 'effect' to improve the labor productivity (Thomas 2009; Jarkas 2010; Jarkas and Horner, 2011).

The above research generally focuses on the applicability of learning curve effect in construction industry and they have clear limitations that the applicability is identified from the improvement of labor productivity. For instance, Jarkas (2010) insisted that the application of learning curve effect should be reconsidered with case of re-bar fixing, because the author could not find the relevance between the learning curve effect and productivity improvement.

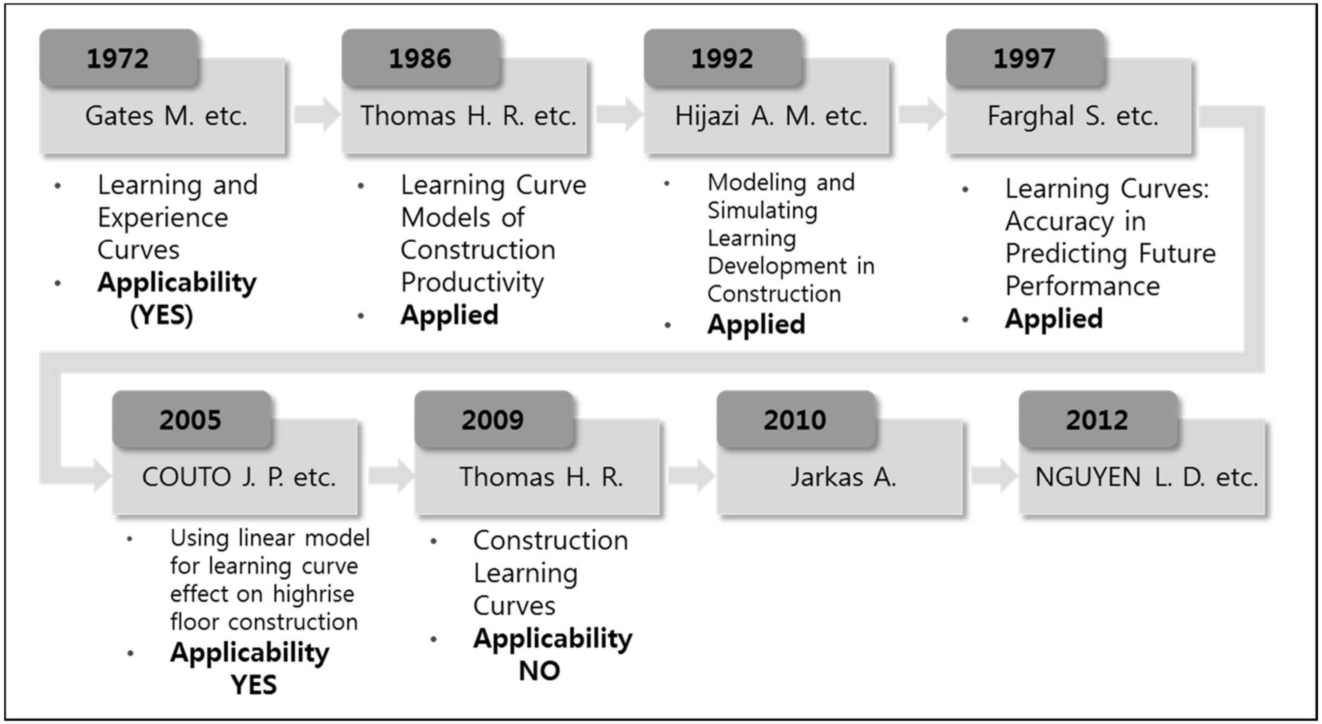


Fig 3. Analysis of the Previous Literature about Learning Curve Effect

However, the research missed out the definite classification between the learning curve effect and productivity improvement; two concepts are treated as same notion. Labors' skill improvement from work repetition is just one influence factor of labor productivity and it does not always lead to productivity improvement. In the process of manifestation, the effect of skill improvement could be diminished because of other influence factors. Hence, not only the validity of learning curve effect but also the manifestation process of the effect and improvement of labor productivity should be investigated.

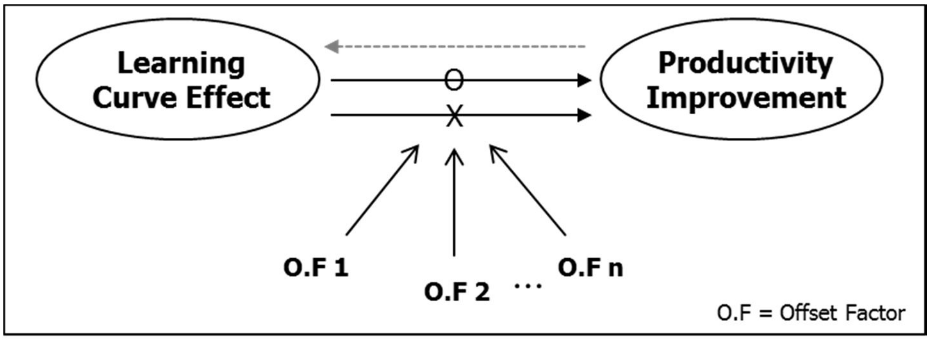


Fig 4. Relationship between Learning Curve Effect and Productivity Improvement

2.2 Offset Factors of Learning Curve Effect in High-rise

2.2.1 Learning Curve Effect in High-rise Projects

The total number of productivity influence factors in construction is enormous (Herbsman and Ellis, 1990). Kim et al. (2011) suggested that the influence factors of productivity could be classified as controllable and uncontrollable factors; controllable factors are classified as management, project and work characteristics (Liberda et al., 2004).

This research deals with learning curve effect in high-rise projects and analyzes each influence factors. In this process, the offset factors of the learning curve effect's manifestation would be found.

In case of high-rise projects, factors described at Fig 5, such as weather, space management, complexity of project and repetition of work etc. influence evenly to projects (Hegazy and Kamarah, 2008; Lee et al., 2009). Also, influence factors for manifestation of the learning curve effect consist of the difficulty of works, degree of repetition, work hours and fatigue from a repetitive works etc. (Hijazi et al., 1992); these are included the controllable factors, especially the work characteristics, from classification of Fig 5. One of the purposes of this research is analyzing the offset factors of learning curve effect; therefore, factors from work characteristics should be analyzed in detail.

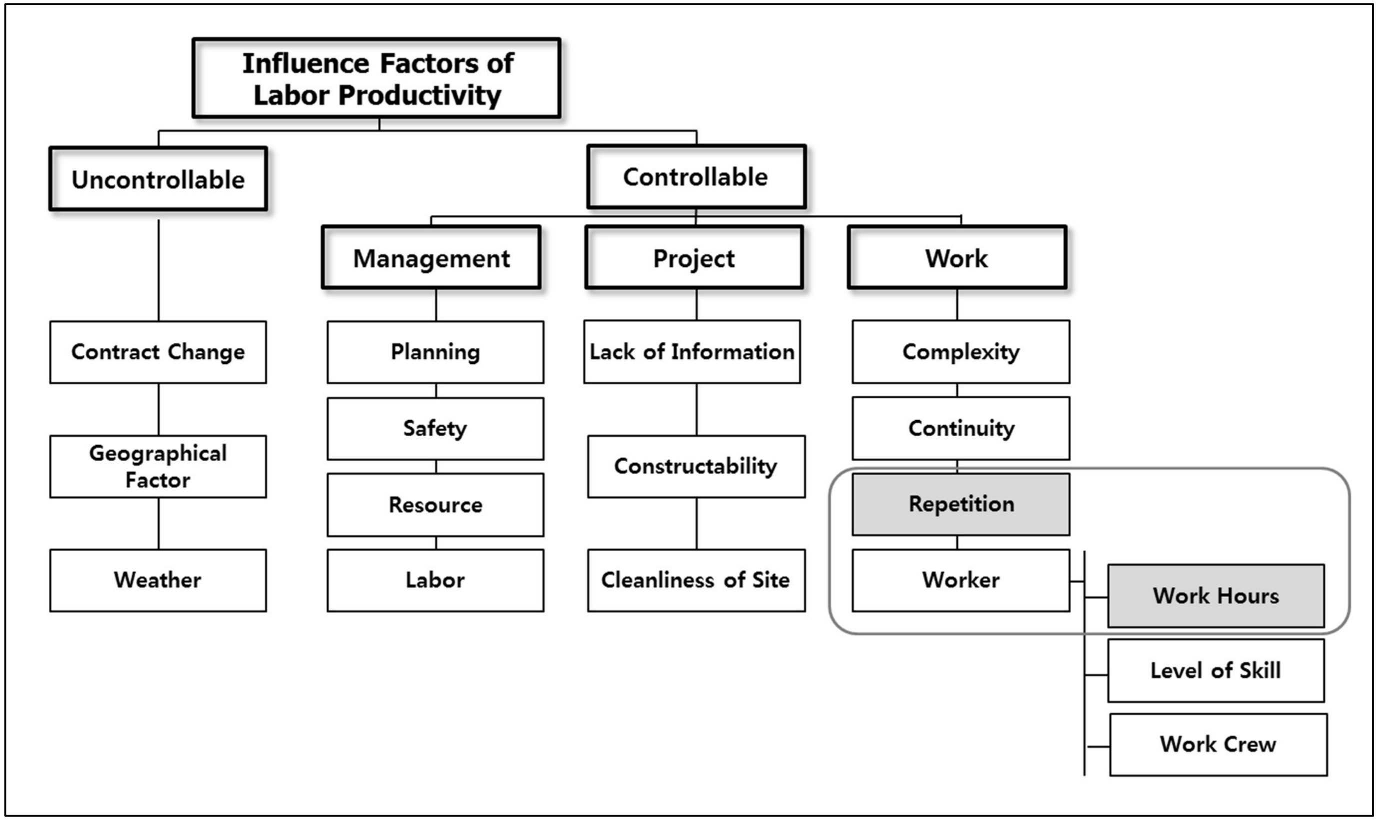


Fig 5. Influence Factors of Labor Productivity in Construction

Factors that could be reflected in productivity estimation process and have relation with work characteristics regard as potential offset factors. Especially, 'the degree of work repetition' and 'the actual work hours that workers actually invest into the work' are key factors of this research because of their importance.

'The degree of work repetition' is a basic condition of manifestation of learning curve effect and it would be maximized when the number of floors increases in high-rise projects. Nonetheless, there still exists a controversy about the authenticity of manifestation of learning curve effect in high-rise projects; hence, additional research about the degree of repetition should be performed. Also, the factors that would influence the actual work hours should be investigated because actual work hours can play an important role for the estimation of productivity improvement.

2.2.2 Degree of Work Repetition

Traditional learning curve theory has been known that it could be adapted to high-rise projects because of plenty of repetitive works. However, as shown in Fig 6, high-rise projects have variation of floorplan because of the buildings' type of use or structural planning; it means that not all works are fully repetitive.

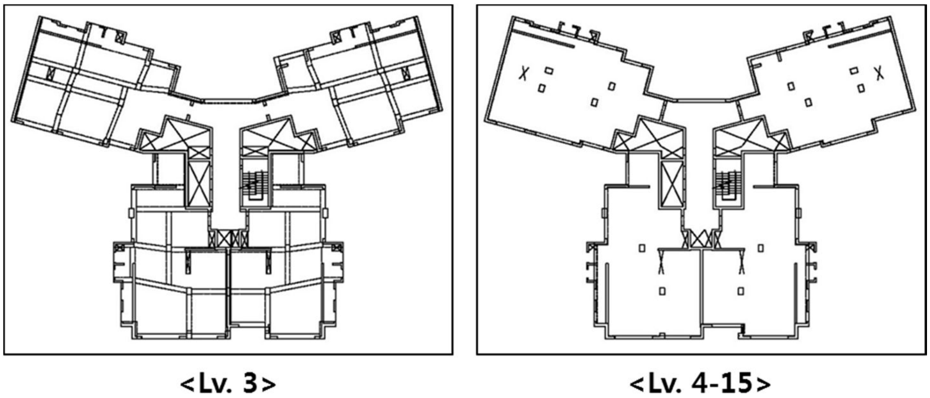


Fig 6. Example: Change of Floorplan in Identical Building

Hijazi et al. (1992) implied that learning curve effect could be offset and then re-start when the repetition of work is broken and re-started. It means that the learning curve effect should be re-estimated whenever the repetition of works is broken. Therefore, this research reflects the feature that high-rise projects have group of repetitive works and variation. It leads the learning curve effect would be re-estimated when the works have any changes or the repetition would be stopped. Fig 7 describes the influence of the learning rate’s change to work hours.

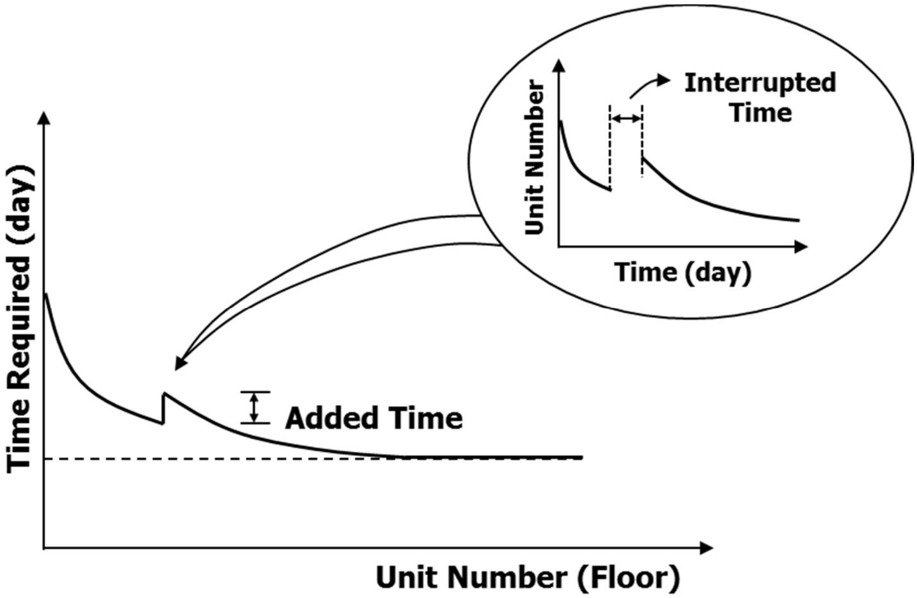


Fig 7. Possible Influences on Learning Curve Effect by Work Change
(Hijazi et al. 1992)

2.2.3 Work Hours and Workers' Transit Time

It is excessively important that requested utilities (workers, materials, equipment etc.) should be delivered in a timely manner in order to execute the high-rise projects successfully. As classified in Fig 5, worker transit time could influence to work hours which is from worker characteristics of labor productivity factors.

Especially, workers' vertical transportation is more complex than that of materials because the materials can be installed one or two days before their utilization in order to prevent the risk of interrupting work. However, in the case of workers, it is not possible to 'deliver' them during the night to their designated workspace for the following day (Park et al., 2013). The higher the floor of the building is, the longer the time takes to reach the designated workspace and it makes the actual work hour shorten. Hence, workers' vertical transit time might influence to the process of estimating the labor productivity. For instance, actual work hours could be exaggerated because the workers' transit time is included in the total work hours. Accordingly, this research determines that the workers' transit time should be taken importantly in the process of estimating the labor productivity of high-rise projects and it could be one of the offset factors of learning curve effect.

2.3 Summary

In this chapter, preliminary study is conducted to investigate how the learning curve theory matters and support the offset factors that the authors make selects.

Learning curve theory is developed in manufacturing industry first and it is adapted to construction industry because of the industry's characteristic of work repetition. There are many research that the learning curve could be applied to construction industry and they suggested the application models. However, recent research argued that construction industry would not meet the condition of learning curve theory. Accordingly, this research includes these two opinions and suggests a theory that the learning curve effect in construction industry would be offset by other factors.

In this chapter, two offset factors are guessed and they are as follows.

1) Degree of work repetition

2) Work hours and workers′ transit time

The above two factors would be applied to the labor productivity estimation model that considering the learning curve effect in following chapter.

Chapter 3. Labor Productivity Model reflecting Learning Curve Effect

In this chapter, the labor productivity model considering the two factors, the degree of work repetition and workers' transit time would be suggested. The data from the non-bearing wall construction would be analyzed and the results are reflected at the model.

The authors analyze the data and build a modification model which would be helpful for estimating the labor productivity to be more accurate. The model consists of two process; 1) reflecting the work repetition and change and 2) reflecting the workers' transit time.

In the first step, the single learning curve would be converted to curves which are different among the work sections; the sections are distinguished for whether the works are change or not. In the second step, the learning curves' exaggerated values of labor productivity would be modified to more reasonable values.

3.1 Analysis of Labor Productivity Data

3.1.1 Data Conversion and Analysis

It is challenging to find the influence of learning curve effect using the labor productivity data from work sites because it is difficult to track and investigate a worker's actual work hours, Also, special circumstances such as forming a crew make the investigation more difficult. In addition, there is a common norm that the labors' work skill would be improved as the floors of construction get higher. However, it could not reach the level of applying at the work planning phase.

Therefore, in order to investigate the influence of learning curve effect from work site data, the process which includes selecting proper data and analyzing it is needed. Table 1 describes the labor productivity data of constructing non-bearing wall construction in high-rise project of the company 'P'.

Table 1. Example: Labor Productivity Data of Constructing Non-bearing Wall in High-rise Project

Floor	Quantity(m^3)	Work Hours(h)	Standard Work Hours per day(h)	Additional Work Hours(h)	Duration (day)	No. of Workers (man)
2	963	432	8	0	18	3
…	…	…	…	…	…	…
20	963	384	8	0	16	3
21	1221	727	8	7	18	5
…	…	…	…	…	…	…
26	963	384	8	0	16	3
…	…	…	…	…	…	…
43	858	512	8	0	16	3
…	…	…	…	…	…	…
47	858	432	8	0	18	3

The above project has forty seven floors in total and all floors would be divided into five sections for work repetition. Section 1 which includes the floor 1 to the floor 20 has identical works with same amount of materials. Section 2, the floor 21 to floor 25 have different works and different amount of materials for each floor because of the work change. From floor 26 to floor 42, Section 3 again has identical works with Section 1. Section 4 (floor 43 and floor 44) and Section 5 (floor 45 to floor 47) contain new works according to change of floorplan. In summary, Section 1 and Section 3 have identical works for relatively a long period and also Section 3 is required the same amount of material with Section 1.

To analyze the above labor productivity data, a process for data conversion is needed (NGUYEN and NGUYEN, 2012).

(1) 'Total work hours' per floor is calculated by multiplying 'standard work hours' and 'duration per floor' together and adding 'additional work hours'.
(2) 'Repetitive sections of works' are identified from 'the quantity of materials' per floor which is used as a standard; the quantity of materials changes in a floor, this floor becomes an initial floor of a section.
(3) 'Total work hours' per floor is converted into 'equivalent work hours' which means the total work hours per unit material, in order to compare equivalently among the floors that have different quantity of materials.
(4) 'Cumulative average work hours' are estimated from the 'equivalent work hours'.
(5) Log values of 'work cycle number' and 'cumulative average work hours' are calculated as 'Ln X' and 'Ln Y' respectively.

Table 2. Results of the Data Conversion

Floor	Cycle No.[X]	Equivalent Work Hours(h/m^3)	Cumulative Average Work Hours(h/m^3)	Ln Y	Ln X
2	1	0.449	0.449	-0.8016	0
…	…	…	…	…	…
20	19	0.399	0.420	-0.8681	2.9444
21	20	0.590	0.428	-0.8481	2.9957
…	…	…	…	…	…
26	25	0.3999	0.445	-0.8096	3.2189
…	…	…	…	…	…
43	42	0.597	0.425	-0.8550	3.7377
…	…	…	…	…	…
47	46	0.878	0.453	-0.7917	3.8286

'Additional work hours' from phase (1) means the total additional work hours of days when 'the standard work hours' are not satisfied because of some delay, weather problem etc.. In phase (4), the learning curve is considered as the straight-line model and in order to get more accuracy, cumulative average data is used. The model using cumulative average data tends to be more accurate in predictions than the model using unit data (Thomas et al., 1986). Also, it could filter the exceptive data which could make the graph get off the trend. Table 2 shows the results from converting the raw data.

The section that work repetition is evident should be found (floor 2 to floor 20) and linear regression deduces the following equations (NGUYEN and NGUYEN, 2012).

$$LnY = \partial + n * LnX \quad \text{------------- (2)}$$

$$(LearningRate) = 2^{-n} * 100$$

where

X = cycle number;

Y = cumulative average work hours per unit material in a floor;

∂ = constant;

n = learning index.

Using the learning curve that the learning rate from formula (2) is adapted, comparison between the work hours considering the learning curve effect ($Y_{X.learn}$) and actual labor productivity from cumulative average work hours ($Y_{X.ca}$) is conducted where Y means the equivalent work hours from data conversion.

$$P_{X.actual} = \frac{1}{Y_{X.ca}} \quad \text{--------------- (3)}$$

$$Y_{X.ca} = \frac{\sum_{i=1}^{X} (t_{sti} * W_i * d_i)}{X} \quad \text{-------- (4)}$$

$$P_{X.learn} = \frac{1}{Y_{X.learn}} \quad \text{---------------- (5)}$$

$$Y_{X.learn} = Y_1 * X^n \quad \text{---------------- (6)}$$

where

$P_{X.actual}$ = the actual data of the labor productivity in the Xth floor;

$P_{X.learn}$ = the labor productivity in the Xth floor considering the learning curve effect;

$Y_{X.ca}$ = the cumulative average work hours in Xth floor;

$Y_{X.learn}$ = the work hours in X^{th} floor considering the learning curve effect;

t_{sti} = the standard work hours per day in i^{th} floor;

W_i = no. of workers in i^{th} floor;

d_i = duration of i^{th} floor;

n = the learning index.

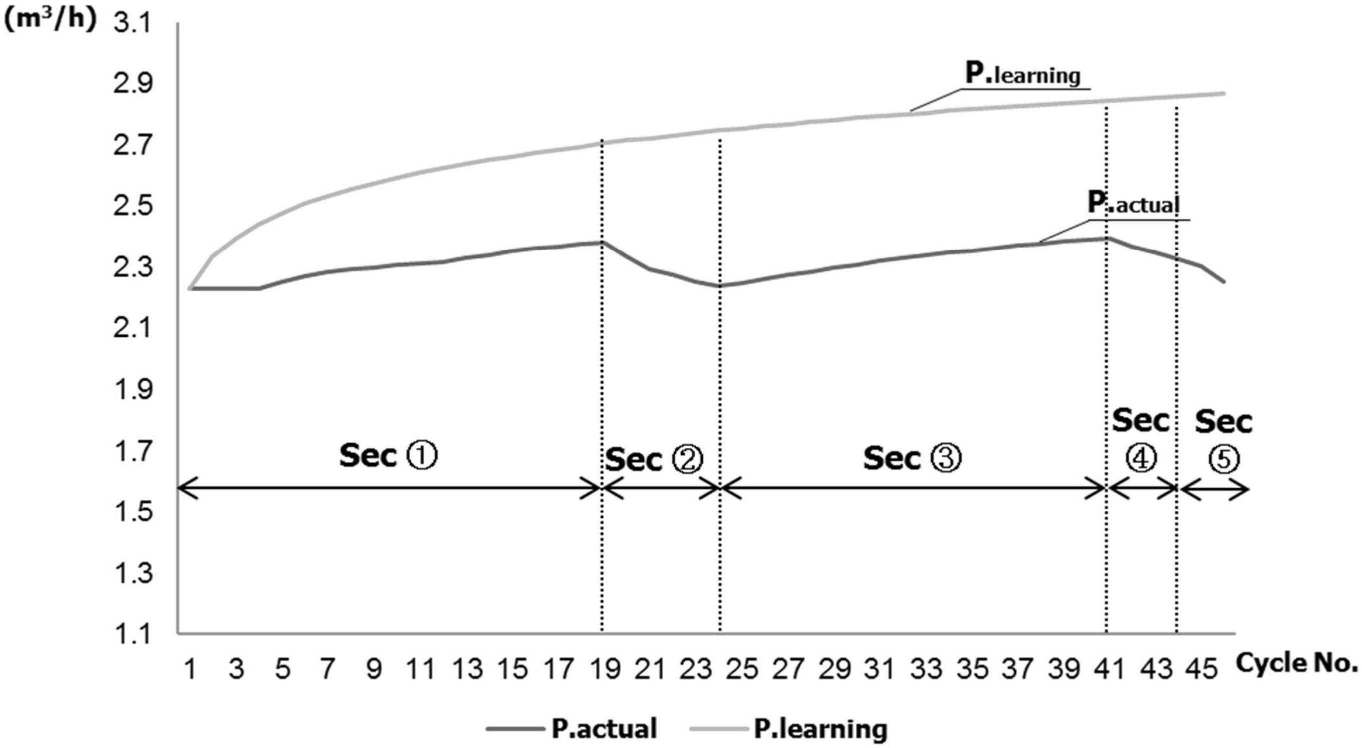


Fig 8. Example: Comparison between the Learning Curve Effect and the Actual Labor Productivity

3.1.2 Results from Data Analysis

According to Fig 8, there is a clear difference between the labor productivity considering the cumulative average work hours and that reflecting the learning curve theory. The work hours considering the learning curve effect decrease exponentially and the labor productivity increases continuously ($P_{learning}$, Fig 8). It is based on the assumption that the repetition of works is not considered and identical works are conducted at each floor. In the case of the labor productivity reflecting the cumulative average work hours (P_{actual}, Fig 8), it increases constantly except the works of cycle 20 to cycle 24. Also, the labor productivity decreases at the work of cycle 42. The floor where the labor productivity starts to decrease is same with the place where the works change. As Hijazi (1992) previously mentioned, there is a possibility to re-start the learning curve effect whenever the works change.

There is a difference in an absolute quantity of the labor productivity; the labor productivity from learning curve is always larger than that from the cumulative average work hours. It means that the theoretical labor productivity is exaggerated more than the actual one and the ideal value of productivity is offset in actual performance. Therefore, the workers' transit time should be considered when developing the labor productivity model because it might greatly affect the actual work hours.

3.2 Model Outline

Fig 9 describes the model which can estimate the labor productivity with considering the learning curve effect. The model has two step of modification process using data which would be converted as mentioned in chapter 3.1.1. The purpose of the first modification is to grant the patterns of labor productivity at each work sections. In the second modification process, to control the exaggerated values of the first process is the objective.

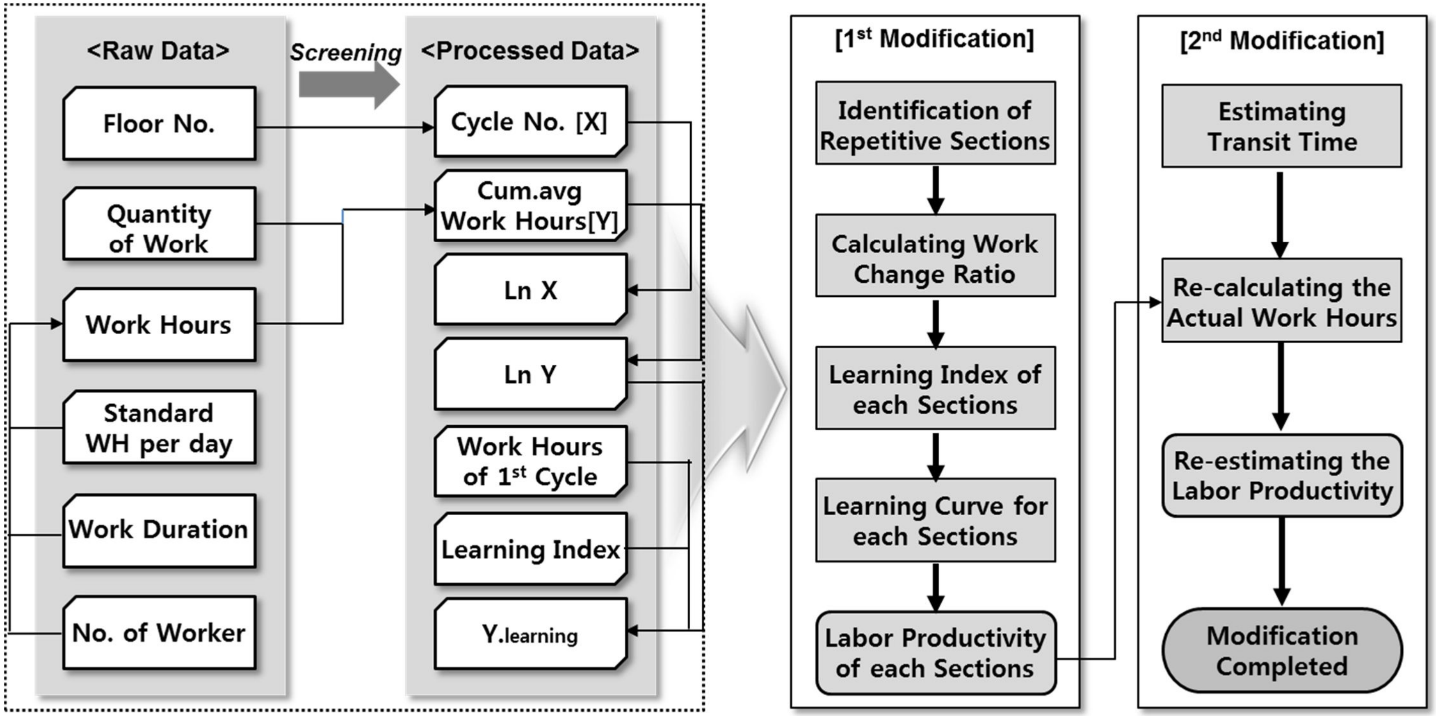


Fig 9. Model for Estimating the Labor Productivity applied the Learning Curve Effect

3.3 The 1st Modification Process

The estimation of the labor productivity using previous learning curve theory is based on the assumption that the learning rate of associated activities shows similarity. In other words, the previous theory does not consider the cases when the repetition of works is broken or the works change. However, the actual data of labor productivity could have different trend according to the repetition (when it exists or not) and its degree (Fig 8). To reflect this feature, data modification of each section would be conducted which is based on the previous learning curve theory. As a result, the circumstance that the degree of learning varies with the change of works is reflected to the model and its process is described in Fig 10.

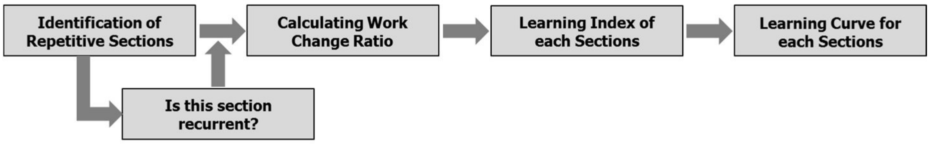


Fig 10. Process of the 1st Modification

First, the work repetition and changes are identified by quantities of materials. There are factors which could be a standard of repetition; however, when quantities of materials change the trend of labor productivity also changes and this research considered ‘quantity of materials’ as standard of work change.

In this research, more than 5 floors would be considered as a section that could reflect the learning curve effect. Also, sections which contain similar works with previous sections should be identified.

It is assumed that when works get changed, learning curve effect would re-start; therefore, each section should have its own learning curve. To reflect this, 'learning index' of each section should be calculated. Learning index is defined as an indicator which demonstrates the degree of learning and it determine the learning rate. Learning index always has minus value; the bigger its absolute value is, the smaller the learning rate is and it means the degree of learning gets bigger (Jelen and Black 1983).

When the work change occurs, 'work change ratio' between successive two sections would be calculated and reflected in the learning rate. Work change ratio describes the degree of change in the trend of work repetition. This research considers the quantity of material as a standard of work repetition; therefore, work change ratio also takes the quantity of material as a standard. Also, this research takes a case which has variation of floorplan to validate. Hence, when quantity of materials in the section changes a lot, it also means the work activity changes a lot. Work change ratio is calculated with formula (7).

$$WCR = \frac{|Q_{k+1} - Q_k|}{Q_k} \quad \text{------------} \quad (7)$$

where

Q_k = the material quantity in section k.

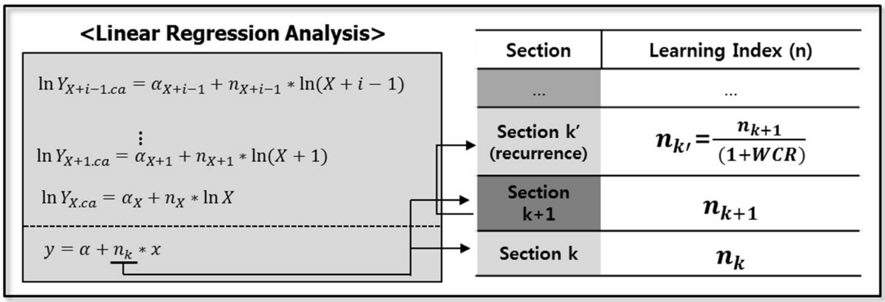


Fig 11. Re-estimating the Learning Index of each Section

When the existing works turn into other works or re-start, labor productivity is not as high as in previous works. Although workers perform identical works which have been already performed, it takes certain amount of time workers to re-adapt to prior works. Additionally, it takes much time to recover the labor efficiency when the change of works occurs frequently. However, workers would get back the previous pace faster than the first performance because of their experience. It means the learning rate of sections that contain works of change or recurrence is larger than previous sections'. Therefore, improvement of labor productivity from learning effect gets smaller than the first performance and absolute value of learning index also decreases. Thus, work change ratio should be reflected in the learning index of each section and Fig 11 describes this process.

In the first modification process, learning curve of each section would be determined and each pattern gets similar with actual labor productivity's trend.

3.4 The 2nd Modification Process

Workers' transit time increases when the construction space (floor) gets higher (Barney 2003). Workers' transit time is not spent for actual work and it means that transit time of workers should be subtracted when estimating the labor productivity per floor.

This research defines the 'Cycle Time' as the time taken when a worker boards a hoist and arrives their final destination (floor). The cycle time can be classified into three major types; flight time, door-operating time, and passenger transfer time (Park et al. 2013). The cycle time is estimated separately whether the hoist gets its contract velocity before it stops or not. It would be calculated using formula (8)~(10) (Park et al. 2013).

$$t_k = \frac{v_{ck}}{a_k} \quad (v_{ck} = a_k t_k) \text{ -- } (8)$$

$$t_{li} = \sqrt{\frac{2D_{hki}}{a_k}} \quad \left(D_{hki} = v_0 t_{li} + \frac{1}{2} a_k t_{li}^{\ 2} = \frac{1}{2} a_k t_{li}^{\ 2} \quad (v_0 = 0)\right) \text{ ------- } (9)$$

$$\text{if } D_{hki} < \frac{v_{ck}^{\ 2}}{2a_k}, \text{ then}$$

$$CycleTime_k = \sum_{i=1}^{n} (t_{li}) + (S+1)(\mathrm{tso}_k + tsc_k) + W(ti_w + to_w) \text{ ----- } (10)$$

where

D_{hki} = the ith moving distance from the current floor to the next destination floor;

v = contract velocity of a lift car;

a_k = acceleration of a lift car;

S = the number of stops in each cycle;

tso =door opening operation time of a lift car;

tsc =door closing operation time of a lift car;

W =number of workers in a lift car;

ti_w = each worker's transfer time to board;

to_w = each worker's transfer time to get off.

To apply the above formulas to the second modification model, assumptions of hoist's capacity, operation type and information about passengers are required. Table 3 describes the assumptions of hoist which is used in this modification model.

Table 3. Assumptions for Operation and Passengers of the Hoist

Classification	Assumptions
Operation	Passengers always board at the ground floor and get off at their destinations.
	Hoists can stop at every floor.
	It takes 8~10 seconds to open and close the door
Passengers	It takes 4~8 seconds to load and unload each workers.
	Each worker uses it four times a day. (once in the morning and afternoon, twice at the lunch)

Workers' transit time in this research includes only the workers who perform the work which the authors want to investigate. Thus, this research focuses only on the workers who conduct works of the non-bearing wall and considers their total flight time during a day. Their flight time should be subtracted from their 'actual work hours'.

The second modification would be performed based on the results of the first modification and the workers' transit time from the above formulas is added to the result of the first modification; because, total work hours which is spent during a floor construction includes the actual work hours and workers' transit time. Formula (11) demonstrates the labor productivity of a floor considering the second modification process.

$$P_{X.m_2} = \frac{1}{Y_{X.m_1} + t_h} \quad \text{------} \quad (11)$$

where

$P_{X.m}$ = the labor productivity in Xth floor after the 2nd modification;

$Y_{X.m_1}$ = the work hours in Xth floor after the 1st modification;

t_h = workers' transit time

3.5 Summary

In this chapter, the model that helps to estimate the labor productivity considering the learning curve effect is suggested. This model contains three steps and their details are as follow.

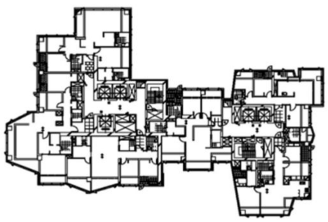
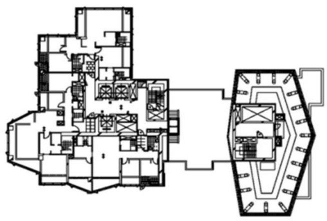
1) Labor productivity data should be analyzed from the view of learning curve effect.
2) According to suggested model, each work cycle (floor) would be classified to the sections of work repetition. The purpose of this step is that each section would get its own pattern of learning curve.
3) Workers' vertical transit time should be eliminated from the total work hours. The goal of this step is that exaggerated value of labor productivity would be shifted to more reasonable value.

As a result, actual learning curve which is considering the offset factors would be derived from raw data of labor productivity. This means that the suggested model's behavior is valid. This model would be validated in the following chapter.

Chapter 4. Case Study

To validate the authors' theory and modification model which are introduced from previous chapters, a high-rise project that satisfies the scope of this research would be applied to the model.

Table 4. Outline of Case Project

Classification	Contents
Project Name	Rebuilding the Haewoondae AID APT (H-Company)
Location	Haewoondae-Gu, Busan, Korea
Use	Residential/Commercial
Height	128.1m (45Floor)
Variation of Floorplan	 (Lv. 3-20)  (Lv. 40)

The case project includes the non-bearing wall works of 45 floors in one building. The labor productivity data from the case is described in Table 5.

Table 5. Labor Productivity Data of Constructing Non-bearing Wall in Case Project

Floor	Quantity(m^3)	Work Hours(h)	Standard Work Hours per day(h)	Additional Work Hours(h)	Duration (day)	No. of Workers (man)
2	662	480	8	0	15	4
…	…	…	…	…	…	…
20	662	416	8	0	13	4
21	860.6	952	8	0	17	7
22	721.58	768	8	0	16	6
23	662	416	8	0	13	4
…	…	…	…	…	…	…
40	662	384	8	5	12	4
41	595.8	600	8	0	15	5
…	…	…	…	…	…	…
44	595.8	520	8	0	13	5
45	463.4	600	8	0	15	5

Labor productivity data is converted as described in Table 2 and labor productivity per floor would be calculated. Fig 12 shows the graph of labor productivity which is considering the actual labor productivity per floor and the learning curve effect. The graph shows similarity with the analysis result in chapter 3. The actual labor productivity has variance within each section and it shows certain differences according to whether the learning curve effect is considered or not.

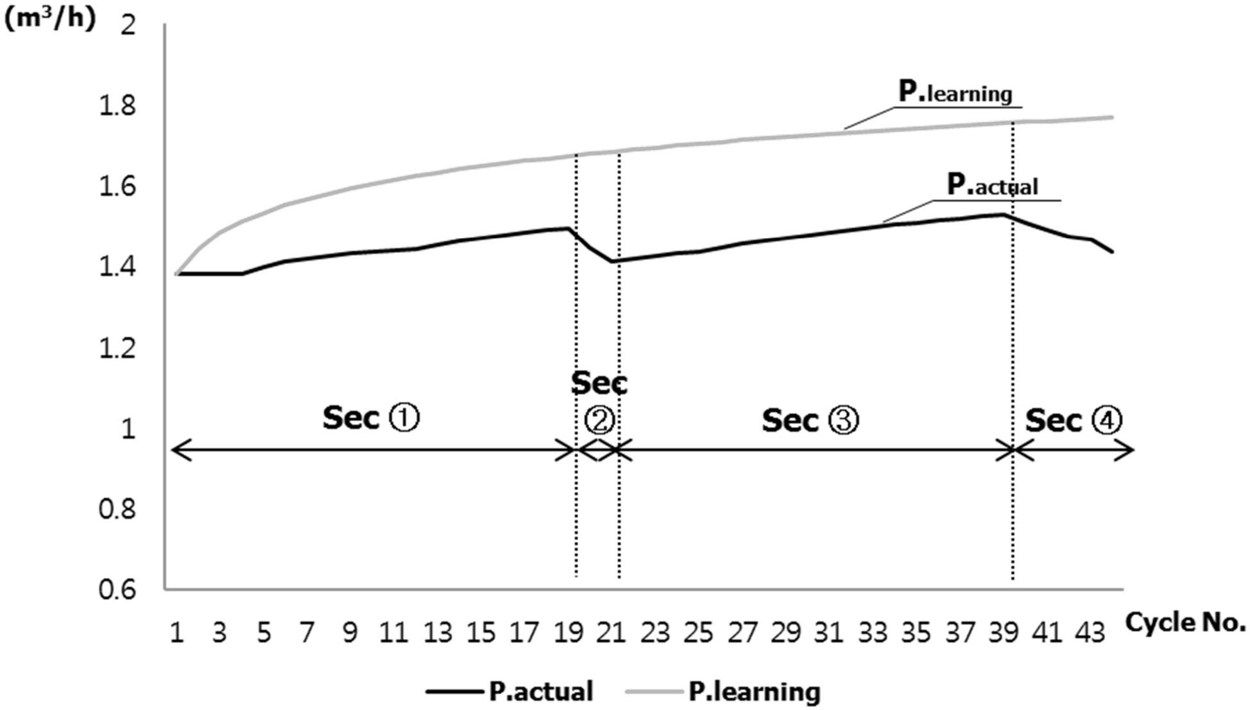


Fig 12. Comparison between the Learning Curve Effect
and Actual Labor Productivity

4.1 Modification Process of Labor Productivity

4.1.1 The 1st Modification

The first modification was performed in an order which is shown in Fig 10, based on the labor productivity considering the learning curve theory. At first, sections of work repetition were identified and the case project has 4 sections of work repetition. Section 1 consists of floor 1 to floor 10 and all floors in section 1 have same quantity of materials. Section 2 includes floor 21 and 22; these floors have different works due to the change of story height. Floor 23 to floor 40 could be referred to section 1′ because it has identical works with section 1 and these works had been stopped for a while (in section 2). The last section, section 3 consists of floor 41 to floor 44 and its works have differences because of the floors' type of use (penthouses). Floor 45 is the top floor and it has independent activities.

Table 6. Results of Estimating the Learning Index of each Section in Case Project

Section	Floor	Work Change Ratio	Learning Index
3	41~44	0.1	-0.0380
1′	23~40	0/3	-0.0446
2	21~22	-	-
1	1~20	-	-0.0657

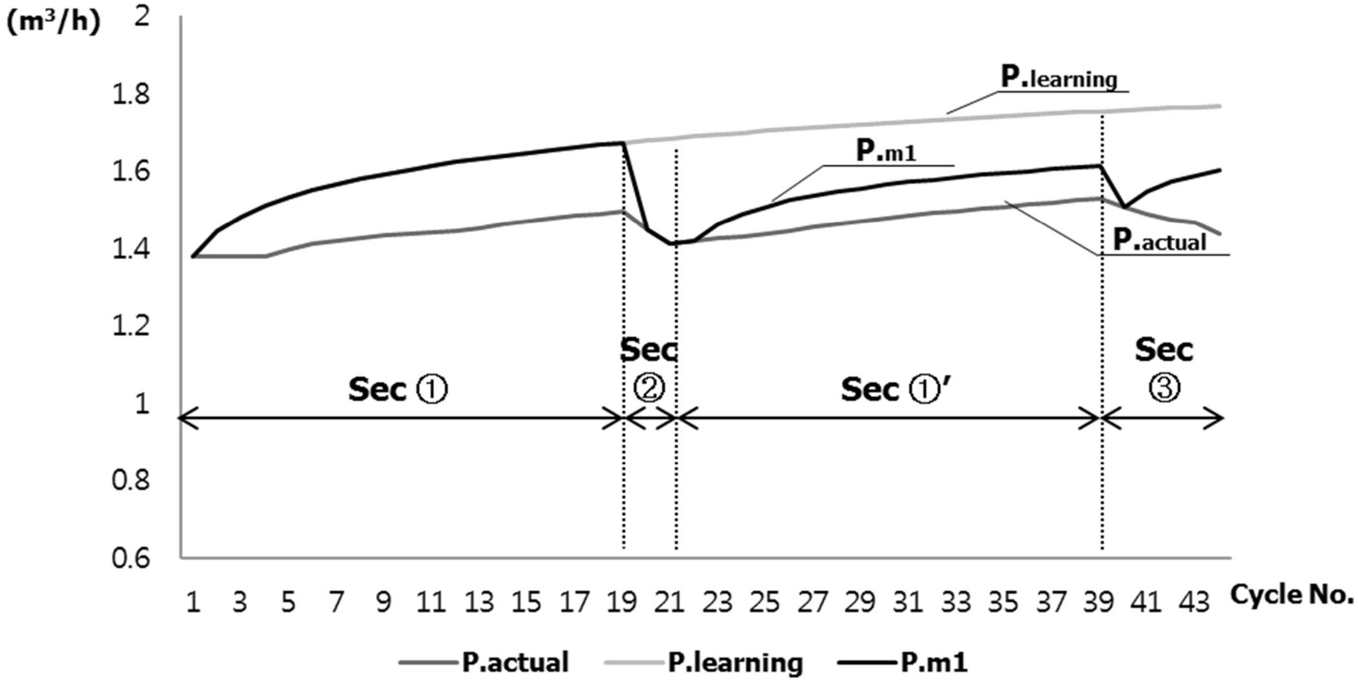


Fig 13. Results applied the 1st Modification

As a result, works of the floor 23 to floor 40 are identical with section 1 and work change ratio would be calculated from formula (7). Table 6 shows the learning index of each repetitive section. Section 2 has not enough period to manifest the learning curve effect; therefore, learning curve of this section would not be identified and just apply the cumulative average work hours.

Fig 13 shows graphs that which are the labor productivity curve (P_{m1}) of each section and the actual labor productivity curve (P_{actual}) of each floor. The labor productivity curve would be derived from the learning index of each section and the single curve ($P_{learning}$) from the learning curve theory is modified to several curves that gathered from each section and they would have individual patterns. At this stage, there was certain difference between two curves; however, the characteristics of each section's labor productivity were considered and it means that purpose of the first modification was achieved.

4.1.2 The 2nd Modification

In this step, workers' transit time would be estimated and subtract from the work hours. To perform this modification, The 'Cycle Time' of hoist is estimated from formula (8), (9) and (10) (Park et al. 2013). The assumptions of hoist's operation and passengers are described in Table 3 and the basic information of hoist is as follow.

Table 7. Hoist Information of the Case Project

Classification	Contents
Type	Twin
Model	ALIMAK 650
Capacity	2200kg
Cage Size (W*L*H)	1.5m * 4.6m * 2.3m
Contract Speed	65m/min

Fig 14. Workers' Transit Time of Case Project

As shown in Fig 14, the higher the construction floor is, the larger the time taking workers to transit. Also, floor 21 and floor 40 have works' change due to the change of story height (from 3.0m to 4.0m) and it leads the drastic increases of workers' transit time from the increases of transporting distance and workers.

The above results are considered in formula (11) and the second modification was performed to calculate more accurate labor productivity (P_{m2}). Based on the result of the first modification which is the labor productivity curve with patterns of each section, the exaggerated value of work hours was modified and the results got more close to the actual data. Especially, section 1′ had robust similarity with the actual labor productivity data and it implies that the purpose of the second modification was achieved. Fig 15 shows the graph of the modified labor productivity with the actual one.

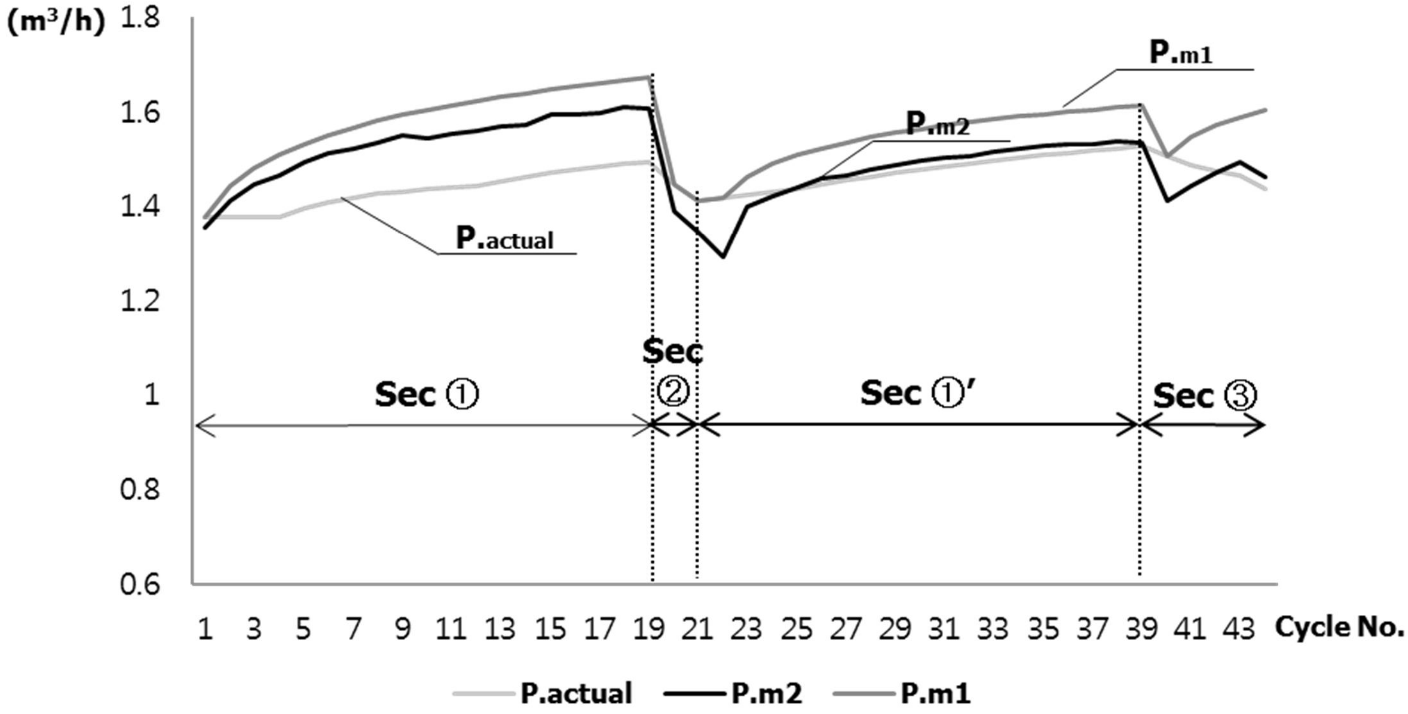


Fig 15. Results applied the 2nd Modification

4.2 Application Results

The purpose of the modification of the labor productivity is to estimate the labor productivity which is considering the characteristics of high-rise projects and works, based on the learning curve theory.

In the first modification process, the patterns of learning were considered with separating the sections which are contains the change and repetition. As a result of case study, the modification results got quite similar with the actual data and the detailed analysis is as follow.

In section 1, the differences between the second modified results and actual data were the largest; therefore, the applicability is the lowest in this section. It always happens in the first section and is the typical limitation of this modification model which is from the two characteristics of the first section.

First, the effect of workers' transit time which is the second offset factor would be relatively low in the first section. Also, it is expected that a certain amount of time would be taken workers to adapt the work environment and acquire the information of the project. This model does not fully reflect this feature and it makes the every first section be inaccurate.

Another limitation is that the initial values of the first section always be smaller than the actual data in the second modification process; because the initial value of the first section is not converted due to the learning curve theory. It leads that the initial values of each section are always smaller than the actual data. Also, there was a difficulty to modify the section 3, the last section, because the period of this section was not long enough to have a pattern. Thus, the high-rise projects which consist of relatively short sections (like the section 3 in the case project) are difficult to apply this model.

4.3 Summary

In this chapter, the model that is suggested in prior chapter is validated with a case project. The project contains works which are suitable for the scope of this research. Through three steps of this model, the raw data of labor productivity is modified to actual learning curve. In this process, some limitations are found and they make the result of modification be inaccurate compared to actual data.

Nevertheless, each purpose of each step is achieved and the authors find that the model is fully valid and coincident with the suggested theory.

Chapter 5. Conclusion

5.1 Result and Discussion

This research analyzed the offset factors of the learning curve effect in high-rise projects and suggested the modification model of labor productivity. Also, the relation between the learning curve effect and the labor productivity was clearly identified and the process of manifestation of the learning effect was investigated. In detail, the authors found the two offset factors of learning curve effect.

1) Repetition and change of works

2) Workers' transit time

To validate these two factors' appropriateness, the modification model for estimating the labor productivity was constructed.

The model contains the two steps according to the two offset factors; in the first step, the learning curve would get the each pattern according to the work sections' characteristics. In the second step, the exaggerated value of labor productivity would be modified to more reasonable value compared to the actual data. With the model's behavior, it was found that the above two factors make the learning curve effect be offset and they should be considered in the phase of estimating labor productivity.

Also, the authors could find that the repetition or change of works and workers' transit time would offset the learning curve effect in high-rise projects. More details are as follow.

(1) Change of works could affect the degree of learning. When the degree of learning changed, the learning index of the sections was also changed. The change of learning index between the two sections was considered using the work change ratio. As a result of this step, each section had their own patterns and it fit with the actual data.

(2) The workers' transit time is not used to actual work and it should be subtracted from the work hours for accuracy. As a result of this step, the exaggerated value of labor productivity was controlled and the trend became closer to the actual trend. Therefore, the authors believed that the purpose of the modification was achieved and the two offset factors are defined properly.

5.2 Contribution

The contribution of this research could be summarized as follows.

(1) Using the suggested model in this research, the applicability of the learning curve effect in construction of high-rise projects and offset factors could be validated.

(2) The relation between the learning curve effect and improvement of labor productivity is clearly defined in this research and it could suggest the solution of the question that why the learning curve effect is not so effective in high-rise projects.

(3) It is possible to estimate accurate labor productivity and it is helpful to plan the work schedule considering the learning curve effect.

(4) When the model is used in the early times of the project, crew formation or labor management could be more accurate than the previous learning theory.

5.3 Further Study

This research limits the scope to high-rise projects which have a variation of floorplan and it should be validated when the general case is applied to this model. In addition, this model selects ‘the material quantity’ as a standard of the degree of learning and the further study is needed to apply this model to general work(not only the non-bearing wall work). At the same time, there is a possibility of other offset factors except the two factors and the applicability of this model would be increased when the additional study is conducted.

Appendices

Appendix A. Labor Productivity Data of Case Project

Appendix B. Terms used in Formulas

Appendix A　Labor Productivity Data of Case Project

Floor	Quantity(m^3)	Work Hours(h)	Standard Work Hours per day(h)	Additional Work Hours(h)	Duration (day)	No. of Workers (man)
2	662	480	8	0	15	4
3	662	480	8	0	15	4
4	662	480	8	0	15	4
5	662	480	8	0	15	4
6	662	448	8	0	14	4
7	662	448	8	0	14	4
8	662	448	8	0	14	4
9	662	448	8	0	14	4
10	662	449	8	1	14	4
11	662	448	8	0	14	4
12	662	448	8	0	14	4
13	662	448	8	0	14	4
14	662	416	8	0	13	4
15	662	416	8	0	13	4
16	662	418	8	2	13	4
17	662	416	8	0	13	4
18	662	416	8	0	13	4
19	662	416	8	0	13	4
20	662	416	8	0	13	4
21	860.6	952	8	0	17	7
22	721.58	768	8	0	16	6
23	662	416	8	0	13	4
24	662	416	8	0	13	4
25	662	416	8	0	13	4
26	662	416	8	0	13	4
27	662	384	8	0	12	4
28	662	384	8	0	12	4
29	662	384	8	0	12	4
30	662	384	8	0	12	4
31	662	384	8	0	12	4
32	662	384	8	0	12	4
33	662	384	8	0	12	4
34	662	384	8	0	12	4

35	662	384	8	1	12	4
36	662	384	8	2	12	4
37	662	384	8	0	12	4
38	662	384	8	0	12	4
39	662	384	8	0	12	4
40	662	384	8	5	12	4
41	595.8	600	8	0	15	5
42	595.8	600	8	0	15	5
43	595.8	560	8	0	14	5
44	595.8	520	8	0	13	5
45	463.4	600	8	0	15	5

Appendix B Terms used in Formulas

Term	Definition	Related Formula
A	Number of direct labor hours required to produce the X^{th} unit	Formula (1)
K	Number of direct labor hours required to produce the first unit	Formula (1)
X	Cumulative unit number (cycle number)	Formula (1) Formula (2) Formula (4) Formula (6)
n	Learning index	Formula (1) Formula (2) Formula (6)
φ	Learning rate	Formula (1)
Y	Cumulative average work hours per unit material in a floor	Formula (2)
$P_{X.actual}$	Actual data of the labor productivity in the X^{th} floor	Formula (3)
$P_{X.learn}$	Labor productivity in the X^{th} floor considering the learning curve effect	Formula (5)
$Y_{X.ca}$	Cumulative average work hours in X^{th} floor	Formula (3) Formula (4)
$Y_{X.learn}$	Work hours in X^{th} floor considering the learning curve effect	Formula (5)
t_{sti}	Standard work hours per day in i^{th} floor	Formula (4)
W_i	Number of workers in i^{th} floor	Formula (4)
d_i	Duration of i^{th} floor	Formula (4)
WCR	Work change ratio	Formula (7)
Q_k	Material quantity in section k	Formula (7)
D_{hki}	i^{th} moving distance from the current floor to the next destination floor	Formula (9)
v	Contract velocity of a lift car	Formula (8)
a_k	Acceleration of a lift car	Formula (8) Formula (9)
S	Number of stops in each cycle	Formula (10)
tso	Door opening operation time of a lift car	Formula (10)
tsc	Door closing operation time of a lift car	Formula (10)
W	Number of workers in a lift car	Formula (10)
ti_w	Each worker's transfer time to board	Formula (10)
to_w	Each worker's transfer time to get off	Formula (10)
$P_{X.m}$	Labor productivity in Xth floor after the 2^{nd} modification	Formula (11)

$Y_{X.m_1}$	Work hours in X^{th} floor after the 1^{st} modification	Formula (11)
t_h	Workers' transit time	Formula (11)

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국 문 초 록

건설 프로젝트 내의 작업의 반복성에 주목하여 건설산업에의 학습곡선효과 적용에 관한 연구가 꾸준히 이루어졌다. 그러나 충분한 반복 작업을 가지는 초고층 프로젝트에서 학습곡선효과가 실제로 발생하는가에 대한 논란은 지속되고 있다. 이에 관해 기존의 연구들은 실제 건설 현장의 작업 생산성 데이터 분석을 통해 효과의 유무를 검증하였으나 작업 생산성의 향상 여부에만 초점을 맞추고 있을 뿐, 효과가 발생하는 과정에 관한 연구는 이루어지지 않았다. 이에 본 연구는 초고층 프로젝트에서 학습곡선효과가 발현되는 과정에 영향을 미치는 요인들을 분석하여 그 효과를 상쇄시키는 요인들을 찾고, 이를 반영한 작업 생산성 산정 모델을 제시하고자 한다.

제시된 모델은 1) 작업 구간 별 반복 및 변화, 2) 작업자의 수직이동시간을 학습곡선효과의 상쇄요인으로 고려하고 이를 반영한다. 기존의 이론에서 도출된 학습곡선으로부터 두 단계의 보정을 추가함으로써 작업 생산성을 산정하도록 한다. 사례분석을 통해 제시된 모델의 유효성을 확인함으로써 반영된 상쇄요인들의 타당성을 확인한다. 이를 통해 기존의 이론을 보완하고 건설산업에서의 학습곡선효과 이론을 재정립하는 데 기여할 수 있으며 이를 바탕으로 프로젝트 초기에 학습효과를 고려한 작업 계

획을 수립하는 데 도움을 줄 수 있다. 또한 초고층 프로젝트에서의 학습효과 발현이 기대에 미치지 못하는 현상에 대한 해답을 줄 수 있을 것으로 기대된다.

주요어: 학습곡선효과, 초고층 프로젝트, 작업 생산성

학 번: 2012-20560