Automatic Rebar Estimation Algorithms for Integrated Project Delivery

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Abstract

Integrated project delivery is advantageous in that it can reflect the constructor's expertise at the design phase. Furthermore, integrated project delivery allows project stockholders to promptly evaluate the financial performance of design decisions. However, there are many problems among existing quantity estimation processes, including human error, loss of information during data exchange and import-export, and time delays. These problems are major obstructions to the application of integrated project delivery. In particular, when it comes to rebar in structural works, errors generated during the drafting process of structural design information have a direct impact on estimation and construction. Such errors can be resolved by employing automatic quantity estimation software that uses the structural design information. In this regard, the present study proposes an automatic rebar estimation algorithm for use in integrated project delivery, the purpose of which is to further develop the software necessary for integrated project delivery. Continued development of additional algorithms for other types of resources as well as software capable of integrating these tools will lead to excellent decision-making support tools for project stockholders, including architectural designers.

1. Introduction

Technological evolution coupled with owners' ongoing demands for more effective processes for better, faster, less costly, and less adversarial construction projects continues to drive significant and rapid changes in the construction industry (The American Institute of Architects, 2007). Integrated project delivery (IPD) was proposed as a way to satisfy these demands. Importantly, the goals of integrated delivery allow designers to benefit from the early contribution of constructors expertise during the design phase, such as accurate budget estimates to inform design decisions and the pre-construction resolution of design-related issues resulting in improved project quality and financial performance (The American Institute of Architects, 2007).

However, the process of accurate quantity and budget estimation continues to be associated with a great deal of errors, as it involves significant manual work. Thus, it remains difficult to fully utilize the strengths of IPD, which are to check the financial performance of design decisions and to have those decisions reflected in the final design (Juszczyk et al., 2014). Stockholders at each phase of pre-construction, including architectural design, structural design, drafting and quantity surveying, all indicate that IPD currently has significant data exchange problems (Ssangyong Engineering & Construction Co. Ltd., 1998), with the most critical errors occurring during structural work (Lopez, 2012). Such errors in structural work not only have a large influence on the quality of buildings and their performance, but also make it difficult to accurately estimate project cost (Lopez, 2012). Especially, the person in charge of estimation is likely to make mistakes for rebar, and there can be significant differences in estimation results depending on experience and expertise (Lee et al., 2008). Further, because estimation methods require excessive manpower, they are being shifted to computer-based software (Lee et al., 2009).

In the present study, the authors analyzed the rebar estimation capability of 11 different commercial software packages that perform quantity estimation. The authors found that most of these programs provided inaccurate quantity estimates. Studies on automated rebar estimation conducted in other countries reported that software can be used for only part of the estimation process, and is unable

to eliminate human errors involving omission or duplicated calculations (Kim and Kim, 1991; Kim *et al.*, 2012; Lee *et al.*, 2012; Lee *et al.*, 2012). Likewise, there can be a loss of information during each import–export process, which can lead to erroneous results and ultimately incorrect quantities and estimations (Zhiliang *et al.*, 2011). To solve these problems, most quantity estimation processes should be automated. Furthermore, in order to avoid loss of information, estimations should be performed without changing the information or going through an import-export process within structural design software.

This study proposes an automatic rebar estimation algorithm for use in IPD, which will be useful for continued development of an integrated software package for IPD. The study was conducted as follows. First, a preliminary study was conducted to examine matters related to existing quantity estimation. Second, logical procedures for potential algorithms were presented, and each procedure was explained with examples. Third, classification of rebar was proposed for systematic estimation and prevention of errors such as omissions and duplications. Fourth, detailed mathematical algorithms for girders were explained. Fifth, a specific case was chosen to demonstrate that accurate estimation can be fulfilled using the proposed algorithms.

2. Preliminary Study

The person in charge of estimation is likely to make mistakes with rebar, and there can be significant differences in estimation results depending on experience and expertise (Lee *et al.*, 2008). The authors examined 2D based estimation, commercial software packages for estimation and existing studies in relation to IPD.

2D-based estimation has been in use for a long time, and is useful for checking whether the architectural drawing matches with the structural drawing. To this end, a cross-sectional drawing of the architecture and a detailed structural drawing are checked, and quantity is estimated considering the relationship with the processes. However, when information in drawings is found to contradict, the drawings should be modified, and depending on the architectural designers' experience and understanding, rebar estimation can be greatly impacted. Since such methods require excessive manpower, they are being shifted to computer-based software (Lee *et al.*, 2009). In this regard, the authors examined the rebar estimation capability of 11 commercial software packages that perform quantity estimation consisting of 4 programs used mainly in Korea, and another 7 used globally.

There are four types of software used in Korea for quantity estimation processes for biding, and another software is used for structural analysis and design processes for review. All Software used in Korea was found to provide approximate estimation

with respect to lapping and embedment length. If the lapping and embedment length of rebar are estimated approximately, the quantity of rebar calculated is less than the actual quantity (Kim and Park, 2006). As a result, construction firms may have to recalculate the net quantity for construction after the contract is concluded, which can increase the need for additional manpower.

Seven types of software are used globally for quantity estimation processes for biding, and only one software is used for construction processes. Evaluation of software used globally revealed 3 cases that displayed no significant difference from software used in Korea, while the remaining 4 appeared to estimate lapping and embedment with relative accuracy. These software packages perform estimations based on user input or recognizing drawings based on architectural and structural drawings. Software that requires users to input data provide only calculations and are thus time-consuming and largely unable to prevent errors arising from omissions or duplications. On the other hand, software that estimates quantity based on drawings may provide different results depending on the user's skill in using the software or other mistakes involving inaccurate part selections. Finally, the authors found it difficult to identify the source of many errors in the software evaluated.

As described above, most commercial estimation software packages are inaccurate. Especially, this is problematic in that such software is greatly impacted by the approximate estimates of lapping and embedment lengths and the user's competence or mistakes in using the software. In solving such problems, a direct data link from structural design information should be realized to avoid loss of information, and most processes of quantity estimation should be automated to prevent human errors such as omissions or duplicated calculations.

From the perspective of IPD, accurate rebar information and the quantity prepared in the design phase are necessary not only for construction contracts of structural work, but also for preparing a bar bending schedule, as well as material delivery and final account. However, for the existing quantity estimation methods or programs, accurate rebar information and quantity are generated only when a shop drawing and bar bending schedule are created, owing to the lack of information. To solve this, numerous studies were conducted, and the existing studies related to rebar work and quantity estimation can be classified into 3 main areas: 1) algorithm-based quantity estimation; 2) regression estimation; 3) BIM-based estimation. Above all, studies related to quantity estimation based on algorithms are as follows. Kim and Kim (1991) conducted a study on the development of optimization algorithms to reduce rebar loss. Their algorithms consisted of automatic rebar manufacturing equipment and an integrated system to enable more precise material

and construction management. However, the bending margin generated during rebar manufacturing was not taken into account, and the lapping and embedment length was applied with a simplified equation in which only the quantity of the approximate estimation level was determined. Kim *et al.* (2012) later developed an integrated rebar information management system to cope with the rebar management problem owing to loss of rebar. The study analyzed the existing workflow of a rebar manufacturing plant, considered the problems of system application, and proposed an improvement plan. In addition, Lee *et al.* (2012) developed an algorithm to automate the calculation of rebar volume for precast concrete while Kim *et al.* (2011) proposed an automatic optimal design algorithm for the foundation of tower cranes. The algorithms described in these studies provided significantly accurate quantity compared to other studies, yet were limited to specific cases resulting in limited utility in general structures.

Researchers have described the disadvantages of regression estimating models as: (1) having no specific or clearly defined approach to help estimators choose a cost model that best fits historical data to a given cost estimating application (Garza and Rouhana, 1995; Bode, 2000) and (2) the variables influencing the estimation must be reviewed in advance and the difficulty in using a large number of input variables (Bode, 2000; Smith and Mason, 1997). A neural network (NN) is a computer system that simulates the learning process of the human brain. NNs are widely applied in many industrial areas including construction. The applicability of NNs to construction has been extensively studied (Boussabaine, 1996; Moselhi *et al.*, 1992; Cho and Skibniewski, 1995). According to the studies mentioned above, NNs are superior to regression models for cost estimation. Case-based reasoning is an alternative to expert systems that are based on rule-based reasoning. Case-based reasoning is based on experience or memory (Chen and Burrell, 2001), whereby a case-based reasoner solves new problems by adopting solutions that were used to solve old problems (Riesbeck and Schank, 1989). Problem solving case-based reasoning is useful for a wide variety of problem solving tasks, including planning, diagnosis, and design (Kolodner, 1992). However, such studies describe the method of calculating the approximate cost, and their study scope differs from the present study, which was focused on estimation of net quantity.

Efforts regarding the development and improvement of BIM-based cost estimation include a conceptual approach to cost estimation of structural skeleton using an interactive automation algorithm (Mansour and Mohammad, 2007), a framework design for BIM-based construction cost estimating software (Ma *et al.*, 2010), a comparative study of commercially available BIM-based cost estimation software, and an investigation of the changes in work practices and workflows incurred by the adoption of the software by a construction company (Forgues *et al.*, 2012). Some case studies reporting on the results of BIM-based cost estimation are also available (Eastman, 2008; McGraw-Hill, 2008; Yu *et al.*, 2011). Most BIM tools are able to perform quantity surveying but these applications tend to lack the functions necessary to perform cost estimation, which is usually done using different software. Interactions between BIM tools and cost estimation applications are often ensured via industry foundation classes (IFC) (Monteiro and Martins, 2013). IFC has been the exchange format mostly used for BIM applications in recent years; however, it is not without flaws, as there is loss of information with each import–export process that can lead to erroneous results and ultimately incorrect quantities and estimations (Zhiliang *et al.*, 2011). For fundamental resolution of these problems, the format exchange or import–export process of data should be skipped to minimize loss of information. In other words, it is necessary to have an elaborate quantity estimation algorithm in the structural analysis and design software so as to use structural design information in its native form, as this is the primary source of data for quantity estimation to prevent errors arising from omissions or duplications in IPD philosophy.

3. Automatic Rebar Estimation Algorithms

According to Section 2, the authors found that inaccurate quantity estimates are primarily due to human errors arising from manual estimation and loss of information caused by the format exchange or import–export process of data in the construction industry. To improve this estimation problem, this study proposes an automatic rebar estimation algorithm that utilizes unaltered structural design information. The proposed algorithm is limited to rebar, which has the most complicated calculation process and is the most frequent source of estimation errors in construction (Lee *et al.*, 2008; Kim *et al.*, 2010).

3.1 Automatic Rebar Estimation Process

There are 4 main items that need to be estimated for structural works, namely, concrete, rebar, steel-frames, and forms. Concrete can be easily estimated using the volume of members, while forms can be estimated using the surface areas of members. The steel-frame can be simply estimated by calculating the length of each section. However, rebar has a higher probability of estimation error compared with the other resources, including errors in equations, omission, and duplicated calculations (Lee, 2014). The process of an automatic rebar estimation algorithm consists of 8 processes as shown in Fig.1., and the details of each process are as follows.

① Load structural design data
  - Load structural design data from a structural analysis and design software for the algorithms proposed in the study.
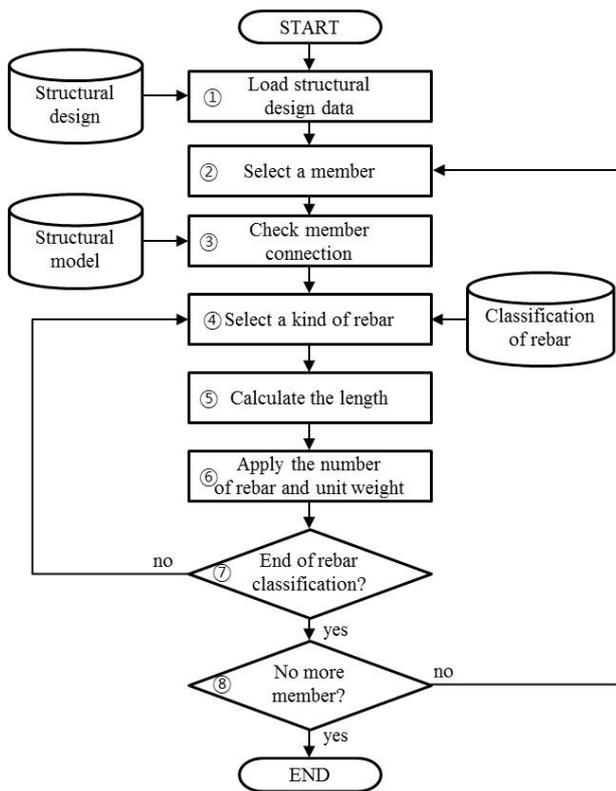
Fig.1. Automatic Rebar Estimation Process

② Select a member
- Sequentially select a member from a member list based on the structural design data.
- The proposed algorithms uses the original data of the structural design result before paper-printed drawings, DWGs, PDFs, or image files are created. Transfer among stockholders for each phase of the pre-construction process, including those involved with architectural design, structural design, drafting and quantity surveying, results in numerous data exchange problems (Ssangyong Engineering & Construction Co. Ltd., 1998). However, if the original structural design information is used as in the proposed algorithms, errors such as delay in delivery of information upon data exchange or miswriting and omission can be prevented in advance.

③ Check member connections
- Check the selected member and the connected members from the structural analysis model. At this step, the original 3D model for structural analysis is used. Each member of the structural analysis model has a unique number and the connected members can be identified by checking the associated joint information.

④ Select rebar type
- Select the rebar type from the rebar classification DB. The rebar classification DB defines the rebar type and the associated calculation equation, which varies with type. Further details are explained in Section 3.2.

⑤ Calculate length
- The length of rebar is calculated based on the mathematical equation defined in the rebar classification DB. The length of rebar is calculated using a representative equation and allotting variables per detailed conditions. The equation is applied as described in Section 3.3.

⑥ Apply rebar quantity and unit weight
- The number of rebar units and the respective weight per diameter are applied for quantity estimation. The rebar quantity can be calculated from the member list of the structural design data.

⑦ End of classification?
- Check whether all rebar calculations for the selected member type have been calculated. If there is a remaining rebar type, go back to step ④ to calculate the remaining type.

⑧ No more Members?
- Check whether there are any members left in the member list. If there is a member left, calculation for such member should be completed. If there are no more members to calculate, the algorithm is considered complete.

For example, if a girder is selected from a member list (②), the information on girders, columns and beams connected to the structural analysis model should be checked (③). Next, the information is loaded from the rebar classification DB (④) to calculate the length of the main rebar (⑤). The length of the main rebar calculated, the number of rebar units and unit weight per diameter are multiplied to estimate the quantity of the main rebar (⑥). When the quantity of the main rebar is calculated, the stirrup quantity is calculated (⑦), followed by calculation of the quantity of the next member (⑧). This algorithm has two main characteristics as described below.

First, quantity is estimated using structural design information. As mentioned in Section 2, estimators understand the architectural designer's intention using documents such as design drawings and field instructions for quantity estimation in the Korea construction industry. However, inaccurate quantity estimates may arise from insufficient design drawings, lack of understanding of field construction, calculation errors by the estimator, and delays in delivery of information (Lee, 2014). In this regard, the algorithm developed in this study performs automatic quantity estimation using a data link with structural design information. Importantly, this data link can prevent errors such as delays, miswriting, and omission in advance. In addition, if the detailed algorithm is verified, such automatic estimation may prevent errors due to a lack of understanding of field construction or estimator calculation errors.

Second, the algorithm is structured in such a way as to use a representative algorithm and then apply detailed algorithms classified by condition. The type of rebar used

Chaeyeon Lim

in structural works varies according to part, diameter, and shape. When a different algorithm is generated for each type considering the member-member connection conditions, the time required for development will increase and the efficiency of the software may decline. Thus, the present study developed a representative algorithm and adopted the use of more detailed algorithms classified by condition within the representative algorithm.

3.2 Classification of Rebar

The rebar used in structural works varies in shape depending on installation location as shown in Fig.2. For an automatic rebar estimation algorithm, the algorithm must be able to classify various types of rebar from the structural design.

As demonstrated in Fig.2., beams and girders require the largest number of different types of rebar, and thus its estimation is the most complicated. The representative rebar types used in girders can be classified as shown in Fig.3. The result of girder design includes the calculation of 3 sections, namely, external end, center, internal end, and the number of rebar units as shown in the center of Fig.3. When the design result shown in the center of Fig.3. is given, it is known that 5 types of main rebar – continuous top, top-end and bottom, discontinuous top-end and bottom-mid – are needed for the given girder. In particular, 'continuous' is distinguished from 'discontinuous' depending on the boundary condition of the member. For example,

as illustrated in Fig.3., since there are 2 upper rebar units in the center and 3 upper reinforcing bars in the internal end at the left girder as well as 3 upper reinforcing bars in the internal end at the right girder, (c) continuous rebar must be present. However, if there are 3 upper reinforcing bars at the left girder or 2 upper reinforcing bars in the internal end at the right girder, (c) continuous rebar may not be required. Using a similar method, reinforcing bars for columns, slabs, stairs, walls, and foundation can be classified and the quantity of each type of rebar can be estimated using the classification algorithm.
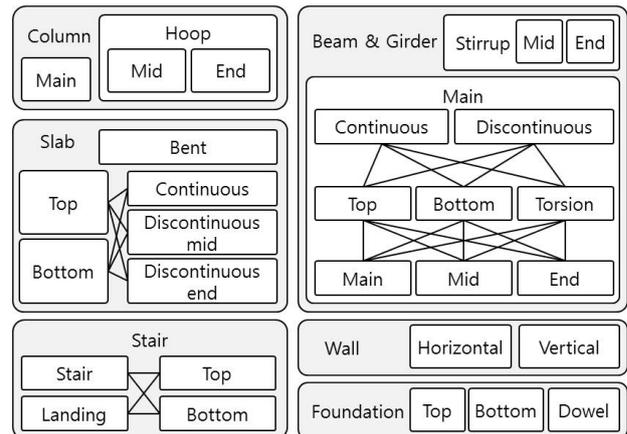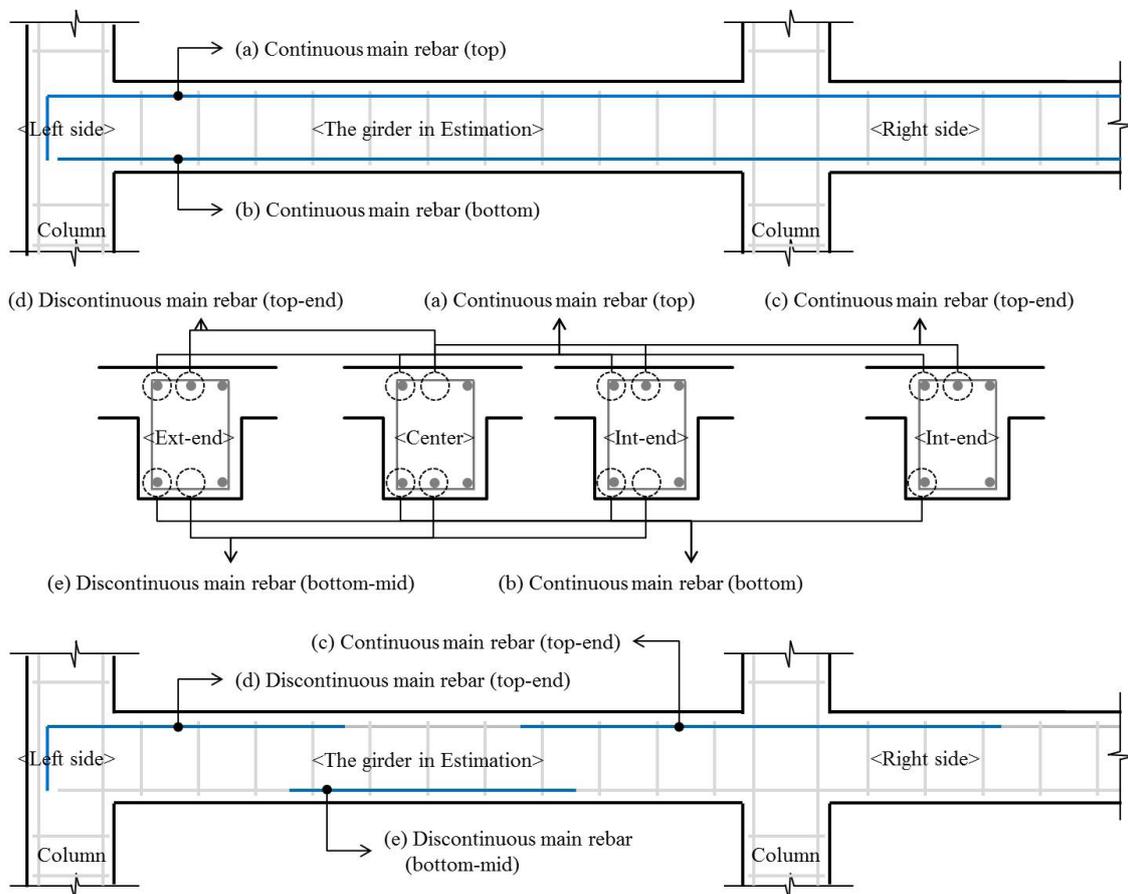

Fig.2. Classification of Rebar

Fig.3. Classification of Rebar of girder

3.3 Measurement Algorithms

For accurate estimation of rebar quantity, rebar should be classified by type to calculate the length. In the case of a girder, rebar can be largely classified into 20 types as specified in Section 3.2. On the other hand, columns can be classified into 3 rebar types. When a different mathematical algorithm is created for each type for rebar, the time required for development will increase and the efficiency of the software may drop. Thus, the authors developed a representative mathematical equation (Equation 1) that applies variables according to rebar type and boundary condition.

$$L_R = N_g \times L_g + N_{gl} \times L_{gl} + N_{gr} \times L_{gr} + 1/2 \times (N_{cl} \times W_{cl} + N_{cr} \times W_{cr})$$
$$+ 2 \times N_s \times (D_g + W_g) + N_H \times L_H + N_{S90} \times L_{S90} + N_{S135} \times L_{S135}$$
$$+ N_{TL} \times L_{TL} + N_{CL} \times L_{CL} - N_{BM} \times 2.5 d_R - N_C \times C \qquad (1)$$

Here,

L_R: length of rebar in estimation

N_g: coefficient for the ratio between mid and end part of girder depending on the construction code $[0 \leq N_g \leq 1]$

L_g: net length of girder

N_{gl}, N_{gr}: number of connected girders on left and right side [1 or 0]

L_{gl}, L_{gr}: length of rebar in girders connected on left and right side

N_{cl}, N_{cr}: number of columns connected on left and right side [0, 1]

W_{cl}, W_{cr}: width of columns connected left and right

N_s: nominal variable for stirrup; 1 is allocated only on the stirrup estimation [0, 1]

D_g: depth of girder

W_g: width of girder

N_H: number of standard hooks

L_H: length of standard hook

N_{S90}, N_{S135}: number of 90° and 135° stirrups

L_{S90}, L_{S135}: length of 90° and 135° stirrups

N_{TL}: number of tensile lappings

L_{TL}: length of tensile lappings

N_{CL}: number of compression lappings

L_{CL}: length of compression lappings

N_{BM}: number of banding margins

d_R: rebar diameter

N_C: number of coverings

C: covering thickness

The proposed mathematical equation is applied differently to continuous rebar, discontinuous rebar, and stirrups. Here, most variables in Equation 1 differ depending on the construction code in the specific country. Especially, L_H, L_{S90}, L_{S135}, L_{TL}, L_{CL} and C use values drawn from the detailed equation or the constants presented in the structural design standard or specifications, and thus are not specified in this study.

The variables used in Equation 1 can be classified into 3 categories; (1) member section: L_R, L_g, N_H, N_{S90}, N_{S135}, N_{BM}, d_R, N_C, D_g and W_g, (2) member connection information: L_{gl}, L_{gr}, N_{gr}, N_{gl}, N_{cl}, N_{cr}, W_{cl}, and W_{cr}, (3)

coefficient or numbers depending on the code: N_g, L_H, L_{S90}, L_{S135}, N_{TL}, L_{TL}, N_{CL}, L_{CL}, and C. Member section is the result of structural design, and member connection information can be determined from the structural analysis model.

For example, Equation 2 is used for estimation of the continuous main top rebar. Because continuous main top rebar is installed over the entire girder, 1 is allocated to N_g. The connected member condition according to the structural drawing is used for allocation of a suitable number or size to N_{gr}, N_{gl}, L_{gl}, Lgr, N_{cl}, N_{cr}, W_{cl}, and W_{cr}. 0 is allocated to N_s, N_H, N_{S90}, N_{S135}, N_{TL}, N_{CL}, N_{BM}, and N_C, because the other variables are not. As described above, the length of rebar is calculated with consideration of the connected girder. In other words, if the rebar that extends to or passes through the connected members is calculated at a specific member, that rebar should not be calculated at the other connected members. However, the calculated length of rebar may be longer than the market length, and thus cannot be used as is. For the accurate estimation of rebar, the calculated length of rebar from Equation 1 should be segmented by taking into account market length, lapping location, and rebar length. However, a relatively short rebar that does not necessarily require segmentation is not divided.

$$L_R = 1 \times L_g + N_{gl} \times L_{gl} + N_{gr} \times L_{gr} + 1/2 \times (N_{cl} \times W_{cl} + N_{cr} \times W_{cr})$$
$$+ 2 \times 0 \times (D_g + W_g) + 0 \times L_H + 0 \times L_{S90} + 0 \times L_{S135} + 0 \times L_{TL}$$
$$+ 0 \times L_{CL} - 0 \times 2.5 d_R - 0 \times C \qquad (2)$$

Specifically, the information is linked from the structural analysis model and the structural design result. Finally, the coefficients or code specifications are made into a database, allowing Equation 1 to be realized as an automatic algorithm. Thus, when the rebar of columns, walls, slabs and foundations is classified and the variables are defined using this method, the length of rebar can be estimated using the representative algorithm.

4. Case Application of Proposed Algorithms
4.1 Brief Description of Case Building

The case project evaluated in this study was a parking building in Gyeonggi-do, Korea, as shown in Table 1. The project was designed as a steel-reinforced concrete structure and the 1st~2nd floors composed of commercial facilities and the 3rd floor and above consisting of parking facilities. The authors intended to verify the algorithm proposed by comparing the rebar quantity estimated through the algorithm with that estimated by the contractor. As the algorithm was not yet developed into a stand-alone software package, equations and logics were inserted in Excel for quantity estimation.

4.2 Effectiveness of the Proposed Algorithms

The rebar quantity of the case project is estimated for comparison by a commercial software, which is one of the most-used software in Korea introduced in Chapter 2. The quantity estimated by the contractor cannot be

Table 1. Brief Description of Case Study

Structure type	Column-beam structure (SRC)
Location	00 City, Gyeonggi-do, Korea
Site area (m^2)	3445
Total floor area (m^2)	21,200
Volume (%)	597
Building area (m^2)	2,632
Building coverage (%)	76
Stories	8 stories with basement (B1)
use	Parking building

classified in detail in a manner similar to that of the algorithms, because the items were not classified in the contractor statement. Thus, the quantity estimated by the algorithm was the net quantity without extra quantity taken into consideration, while the other quantity considered a loss of 3%.

When the lapping and anchoring lengths of rebar are approximately estimated, the quantity of rebar is less than the actual input (Kim and Park, 2006). However, when a loss of 3% was taken into account for the quantity estimated by algorithm, the result was 1,150 tons. In other words, the quantity estimated by the algorithm was found to be about 5% less than the quantity estimated by the contractor. The authors determined that this difference was due to the method used to calculate the lapping and anchoring lengths. Specifically, the contractor calculated the lapping and anchoring length of rebar based on a general note expressed in the structural drawing. When the authors checked the lapping and anchoring length marked in the general note of structural design, the authors found that it was based on a simplified equation, implying that the lengths were overestimated. Therefore, the difference between the quantity estimated via algorithms and the quantity estimated via a contractor is a result of the quantity estimation based on extra length and overestimation. Such a difference is within 5%, so it can be said that the proposed algorithm is moderately accurate. However, when the authors applied the detailed equation proposed in the structural design standard to calculate lapping and embedment length, the resulting lengths were approximately 2/3 of those in the general note.

5. Discussion & Conclusion

IPD was proposed as a way of satisfying the owners' demand. However, existing quantity estimation methods (Lee *et al.*, 2009) and commercial software currently in use are unable to fully realize the goal of IDPs owing to inaccuracies and excessive time requirements. Furthermore, studies on automatic estimation of rebar conducted in other countries have only automated part of the estimation process and cannot eliminate human errors such as omissions and duplicated calculations (Kim and Kim, 1991). Likewise, there is a loss of information with each import–export process, which can lead to erroneous results and ultimately incorrect quantities (Zhiliang *et al.*, 2011). Especially, the person in charge of estimation is likely to make mistakes with rebar estimation, and there can be significant differences in estimation results depending on experience and expertise (Lee *et al.*, 2008). To resolve these issues, this study found that automatic quantity estimation software that uses the original structural design information is necessary. In this regard, the authors proposed an automatic rebar estimation algorithm for later use in integrated software to fulfill the goals of IPD. The results of this study are described below.

First, through a preliminary study of commercial software, the authors found that inaccurate quantity estimation is due to human errors caused by manual estimation as well as loss of information caused by format exchange and the data import-export process. Thus, it is necessary to develop automatic estimation software that uses the original structural design information.

Second, a logical procedure on automatic estimation algorithms of rebar was proposed and each step of the procedure was explained with examples. The proposed algorithm estimated quantities directly using structural design information to prevent various human errors, and the detailed algorithms classified by conditions within the representative algorithm were applied to simplify the software structure.

Third, a classification system of rebar was proposed. The classification of rebar was used for the 4th logical step of the proposed algorithm to prevent errors such as

Table 2. Quantity of Rebar Estimated by Algorithm (ton)

Floor	Column		Girder		Beam		Wall girder		Slab	Wall		Buttress		Stair	Foundation	Total
	Main	Hoop	Main	Stirrup	Main	Stirrup	Main	Stirrup		Core	Basement	Main	Stirrup			
B1	7	1	-	-	-	-	-	-	-	27	43	2	0	1	82	163
1F	13	2	2	2	6	2	0	0	14	24	-	-	-	2	59	127
2F	10	1	14	10	17	5	1	0	19	15	-	-	-	1	-	95
3F	5	1	17	12	24	8	1	0	23	16	-	-	-	1	-	108
4F	4	1	15	11	21	6	1	0	23	15	-	-	-	1	-	99
5F	3	1	14	14	27	8	1	0	22	11	-	-	-	1	-	102
6F	3	1	14	14	27	8	1	0	22	11	-	-	-	1	-	101
7F	3	1	15	14	27	8	1	0	22	10	-	-	-	1	-	101
8F	6	1	14	14	27	8	1	0	22	8	-	-	-	1	-	102
RF	-	-	20	14	46	12	0	0	16	9	-	-	-	2	-	118
Total	54	11	125	102	221	65	9	2	182	146	43	2	0	13	141	1,116

omission or duplication. the authors proposed 49 types of rebar, but this can be easily modified depending on the building, member, or rebar placement shape.

Fourth, a detailed mathematical algorithm for girders was explained. The proposed mathematical algorithm can be applied to the construction code of the respective country. Each variable used in the representative mathematical algorithm was explained based on the structural design standard of Korea.

Fifth, a specific case was selected and evaluated, and the results of this analysis showed that the proposed algorithm can accurately estimate rebar quantities. As the algorithm described in this study has not yet been developed into a software package, the equations and logics were implemented in Excel for quantity estimation. The estimate provided by the proposed algorithm was approximately 5% less than that of the contractor. However, further evaluation revealed that excessive lapping and embedment lengths were applied in the quantity estimation performed by the contractor.

The present study was conducted to provide a research basis for continued integrated software development, the purpose of which is to quickly check the financial performance of design decisions upon IPD application. The present study focused on rebar, which is the most complicated resource among the main resources of structural works, and the accuracy of the proposed algorithm was verified. Development of algorithms for additional resources and integration into software will be useful as a tool for improved decision-making support for project stockholders including architectural designers.

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