Proceedings of the 2017 Winter Simulation Conference
W. K. V. Chan, A. D'Ambrogio, G. Zacharewicz, N. Mustafee, G. Wainer, and E. Page, eds.

SYNTHESIZING ENGINEERING DESIGN, MATERIAL TAKEOFF AND SIMULATION-BASED ESTIMATING ON A BRIDGE DECK REINFORCEMENT CASE

Ming Lu
Chaoyu Zheng
Chaojue Yi
Monjurul Hasan

Department of Civil & Environmental Engineering
University of Alberta
7-203 DICE, 9211 - 116 Street NW
Edmonton, Alberta, T6G 1H9, CANADA

ABSTRACT

To enhance the accuracy in estimating material and crew costs for steel reinforcement installation, numerous estimating tools have been developed. “Precise estimating” in general considers both lapping details and other required supporting structures while deriving the crew cost by accounting for reinforcing operations. In contrast, “rough estimating” ignores rebar lapping details in quantity takeoff and relies on industry benchmark productivity data for crew cost estimation. The distinction between “precise estimating” and “rough estimating” still lacks quantitative evidence and remains vague to both academic researchers and professional estimators. This research presents systematic comparison between the two estimating strategies with a case study of a bridge deck. A discrete event simulation tool is used to aid in estimating the crew cost in reinforcement handling and installation. The estimating results indicate that compared with the “precise estimating” approach, the “rough estimating” approach underestimates the material and crew costs by 13% and 38%, respectively.

1 INTRODUCTION

Procurement, handling, and installation of reinforcing steel accounts for a significant portion of the total construction cost of building and infrastructure projects. However, in practice, the quantity takeoff process for reinforcing steel is generally tedious and time consuming, due to (1) the variety of rebar types in the structural elements; (2) the variability in rebar arrangement in realization of engineering design; (3) rebar connections patterns (e.g. weld, bolt, threaded coupler and etc.) and positions; and (4) various types of reinforcing accessories. Given limited bidding time, estimators often hasten the submission of the bid while (1) ignoring the lapping details in takeoff, plus other reinforcing accessories which are indispensable for reinforcing steel installation, (2) referring to industry benchmark data as the estimating basis, which represents average crew productivity and cost. The underestimated quantity take-off and the roughly derived crew productivity tend to result in an inaccurate estimate and missed opportunities in winning the bid and delivering the work with higher cost performance. In reality, a more accurate while still cost effective approach to estimating reinforcement costs is much more desired.

Simulation modelling of complicated, dynamic, and interactive processes in construction is essentially a computer-supported implementation of a systems approach. Here, a system is fundamentally an integrated combination of the components and activities designed to follow a common purpose; a system exists to achieve a better understanding of the problem and hence help to create a ‘tool’ to resolve the problem (Riley and Towill 2001). Simulation modelling builds a logical model of a system for

978-1-5386-3428-8/17/$31.00

experimenting with the system on a computer (Prisker 1986). Valid simulation models provide practical tools to assist construction managers in (1) facilitating productivity level estimation for complicated processes, (2) improving repetitive process scheduling, and (3) planning adequate resource assignment that minimizes time and cost (Gonzales-Quevedo et al. 1993). Discrete event simulation tools can play a major role in detailed cost estimating and work planningA special purpose simulation environment called SIMPHONY was introduced to facilitate construction crew estimating and operations planning for achieving cost efficiency and productivity in building simulation models (Hajjar and AbouRizk 1999). Meanwhile, the simplified discrete-event simulation approach (SDESA) was proposed with the goal of streamlining simulation modeling into a process of designing an enhanced version of activity-on-node (AON+) diagram model. Specifically, the simulation modeling process of SDESA is to create a network diagram model which is relatively stable in representing the dynamic resource allocation and resource transit between various locations in a construction system. To some extent, the whole process of simulation modeling resembles preparing the AON network model for the critical path method (CPM) (Lu 2003; Lu et al. 2008). As the sophistication and accessibility of simulation tools continue to grow, simulation based experiments for planning construction operations can be readily conducted on computers. Over the past decades, tremendous inroads have been made in regards to workflow modelling, simulation methods and practical applications, aimed to simplify simulation and promote implementation in the practice of construction engineering and management.

Nonetheless, the application of simulation modeling has been widely restricted to the work planning with particular emphasis on resource allocation and utilization and time events scheduling. There is a lack of modelling frameworks and practical applications in the literature which link simulation modeling with engineering design, temporary facility design, and material quantity takeoff in an integrative, seamless approach. In other words, simulation has only provided the means to develop the workflows and crews while taking the work definition itself as given input. In fact, structuring, scoping and designing a particular work package require engineering knowledge, practical know-how, and system modeling skills. Work package definition itself can be a more demanding process than simulation modeling itself. The two processes constitute two seamlessly integrative and indispensable components in the implementation of a complete, successful construction engineering simulation in the real world.

The Integrated Project Delivery (IPD) concept is essentially a holistic approach to planning and executing construction, in which all project participants work in highly collaborative relationships through all phases of design, fabrication, and construction in order to achieve efficiency and effectiveness (Tatum 2012). In this paper, the IPD concept is loosely borrowed to enhance cost estimating by integrating the perspectives of cost estimator, structural design engineer, and field foremen/superintendent. It is anticipated that guided by an IPD-based systematic approach to work planning and cost estimating, the estimator can come up with an improved cost estimate with finer granularity and higher accuracy. Specifically, the proposed IPD based approach consists of (1) detailed reinforcing engineering design to generate material quantity take-off and corresponding material cost, and (2) simulation-based workface planning for representing field workflows and estimating crew costs in reinforcement installation.

The remainder of the paper presents a case study on how to apply an integrated project delivery approach to rebar detailing design and work planning on a bridge deck in support of estimating material cost and crew installation cost. The estimating results between the simulation based “precise estimating” approach and the RS Means (RS Means 2016) based “rough estimating” approach are contrasted. “Rough estimating” ignores lapping details in quantity take-off and cost estimate; while “precise estimating” entails detailed lapping design before quantity takeoff and relies on simulation to decide the crew installation effort in the field. In conclusion, this paper gives a reliable quantitative answer to the question: to what extent does the RS Means based "rough estimating" approach underestimate against the simulation based "precise estimating" approach? The methodology is applied to the bridge deck case; it also serves as a more generic framework conducive to guide the estimating of structural elements of similar type in the future.

2 THE "CREEK DECK" CASE

The size of the "creek deck" (typical design for highway bridges crossing creeks in Alberta) is 57.5m in length and 11m in width. According to the design drawings, rebars are placed in two layers and two perpendicular directions, namely: top and bottom layers, and short and long directions. In the long direction, both top and bottom bars are configured with 15M bars (16mm diameter, 1.570 kg/m) with no bends, and spaced 300mm apart; at both sides of the long direction, there are extra top bars (15M, 5.8m long) placed 150mm apart on each side of the deck. In the short direction, 20M rebars (19.5 mm diameter, 2.30kg/m) are spaced 300mm at both top and bottom layers, extra top bars are 20M rebars of 4m length, with end tilt hooks, placed 300mm apart at both sides. The concrete cover is 75mm. Based on RS Means (2016), the average bare labour rate of reinforcing labour used in the estimate is $53.00/hour. The unit cost of steel rebar is $1423.80/ton. Rebar stock will be processed in a rebar bending yard next to the site and then delivered to site as cut-to-length rebar segments. Note only the bare cost (i.e. the summation of all labor and material costs that are directly incurred in production activities) is considered in this case in order to clearly contrast the estimating results. The rebar types and arrangement details are shown in Figure 1.

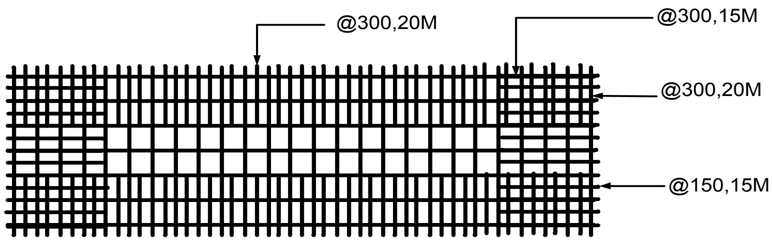


Figure 1 (a) Top layer.

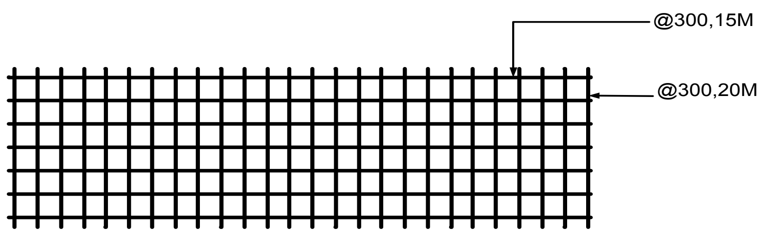


Figure 1 (b) Bottom layer.

Figure 1: Bridge deck design drawings.

3 "ROUGH ESTIMATING" SCENARIO

In this scenario, rebar lappings are neglected in the quantity take-off process. The take-off result according to the engineering design is summarized in Table 1:

Table 1: Quantity take off for "No lapping" scenario.

Position	Type	Diameter	Unit weight	Length	Weight
Long direction	15M	16 mm	1.570 kg/m	5217 m	8190.69 kg
Short direction	20M	19.5mm	2.355 kg/m	3630 m	8548.65 kg
	15M	16 mm	1.570 kg/m	2094 m	3287.58 kg
Total weight					20026.92 kg

Based on the takeoff quantity (total weight) and unit cost, the material cost can be calculated. The benchmarking data from RS Means (2016) is referenced for crew production rate and cost. The material cost and crew cost are calculated and summarized in Table 2:

Table 2: Total cost summary for "Rough estimating" scenario.

Line number	Quantity	Material Bare Unit	Crew Bare Unit	Description
032111600400	20.03 ton	$1,423.80 /ton	$644.87 /ton	Reinforcing steel in place, Elevated slabs, #10M to #25M
Bare total = Material Bare Total + Crew bare total =				$41,435.46

Note: the crew consisting of four rodmen as per RS Means and the crew bare unit cost is to factor in the bare labor rate ($53/lab-hr.), the crew size, and daily output (2.63 ton/day) Crew bare unit = $53/lab-hr. × 4 × 8 hr. over 2.63 ton /day = $644.87 /ton

4 "PRECISE ESTIMATING" SCENARIO

The first step of installing reinforcement is to cut the stock bars procured from the market into required rebar segments; before concrete pouring the rebar segments are then placed and lapped by reinforcing laborers according to engineering design. Lapped splices are commonly used for joining two pieces of reinforcing rebar segments. Usually the positioning of lap splices is staggered along the rebar arrangement in one particular direction, for two main reasons: (1) to reduce reinforcement congestion in locations where a relatively heavy amount of reinforcement are placed, such as in a lower story column of a multi-story building, and (2) to reduce a concentration of bond stresses at the bar ends of the lap splices (CRSI 2013). Figure 2 shows a typical staggered lap splice arrangement.

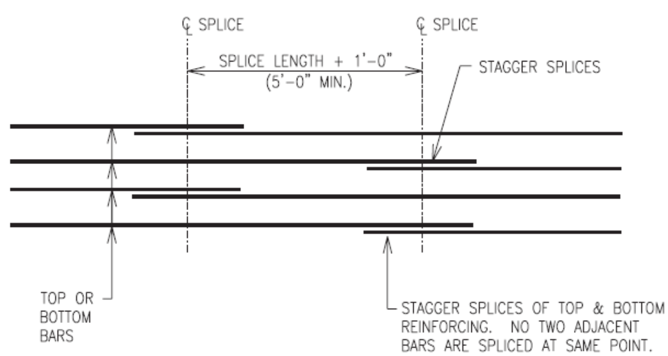


Figure 2: An example of typical staggered lap splice details (source: CRSI 2013).

In practice, the deck thickness is not identical along the short direction, as the thickness gradually reduces from the central point towards the sidewalk with a slope ratio of 1:0.02. Thus, an "L" shaped rebar (rebar No.1 in Table 3) is positioned at the central zone. Note the "L" shaped rebar in the centre piece is 6000 mm in length with a deflection angle of 178 degrees (Figure 3); this asymmetrical length arrangement is designed to facilitate the handling and installation in the field. Based on the interpretation of the design drawings, the rebar configurations in the structure can be summarized in Table 3 below.

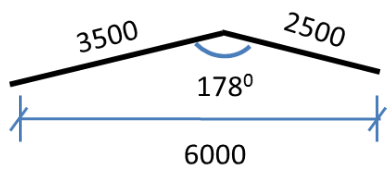


Figure 3: "L" shaped rebar drawing.

Based on the above specific design, for vertically arranged (short direction) rebar, top bars consist of three parts: the mid bar (rebar No.1 in Table 3) is 6m long, and the two bars with ends hooked are 2.97m and 3.97m long respectively (rebar No.2 and No. 3 in Table 3); the detailed drawing is shown in Figure 4. Extra top bars are 4 m long (rebar No.4 in Table 3) put in the short direction. Bottom bars are straight with the length of 10.85m (rebar No.5 in Table 3).

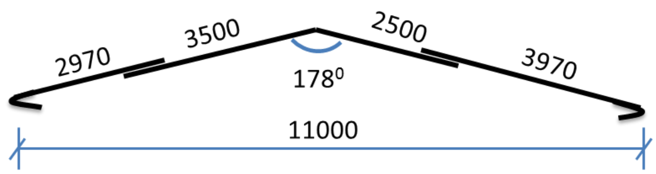
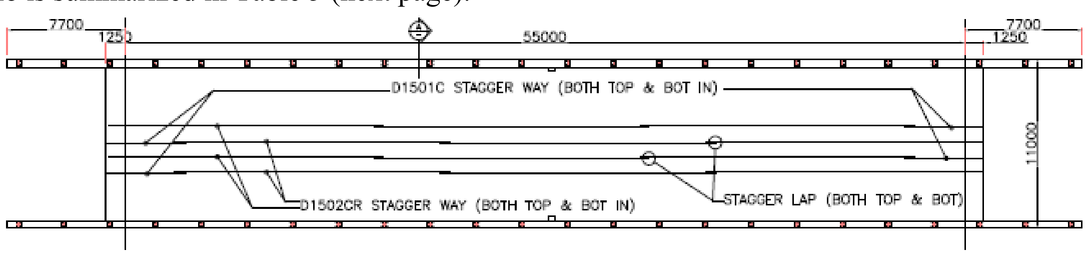
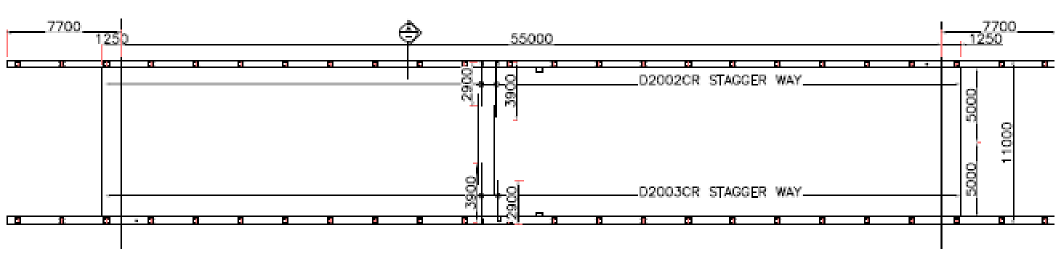


Figure 4. Top bars detail drawing.

As for the horizontal rebar arrangement (long direction), both top and bottom bars consist of three 18m bars (rebar No. 7 in Table 3) with a 5.15m bar (rebar No. 6 in Table 3) at one end. At both sides of the long direction, there are extra top bars (rebar No. 8 in Table 3) which are 5.8m in length.
Note that maximum available bar size in market is 18m in length and the lapping length is 600 mm in the long direction and 800mm in the short direction; concrete cover is 75 mm. The bar lap joints should be staggered so that two consecutive bars in the same layer are not be spliced at the same position. The staggered lap design can be realized by alternating the positions of rebars with different lengths; staggered lap designs for both directions are shown in Figure 5 below. Detailed quantity takeoff is processed based on design details and summarized in Table 4 (next page). The material cost for "precise estimating" scenario is summarized in Table 5 (next page).



Long direction



Short direction

Figure 5: Staggered lap splices of bridge design drawing.

Table 3: Rebar information.

Rebar No.#	Position		Shape and Length(mm)
	Direction	**Top or bottom**	
1	Short	Top	6000
2	Short	Top	2970
3	Short	Top	3970
4	Short	Top	4000
5	Short	Bottom	10850
6	Long	Top and Bottom	5150
7	Long	Top and Bottom	18000
8	Long	Top	5800

Table 4: Summarized quantity takeoff.

Location	Length (mm)	Nos. per line	Nos of Lines	Total Nos of Bar	Total Length (m)	Total Weight (kg)
Long direction	5150	2	38	76	391.4	614.50
	18000	6	38	228	4104	6,443.28
	5800	2	74	148	858.4	1,347.69
Short direction	6000	1	193	193	1158	2,727.09
	2970	1	193	193	573.21	1,349.91
	3970	1	193	193	766.21	1,804.42
	4000	2	192	384	1536	3,617.28
	10850	1	193	193	2094.05	3,287.66
Total						21,191.3

Table 5: Material cost summary.

Material	Description	Bare Unit cost	Quantity	Bare total cost
Rebar	Slab rebar plain steel	$1423.80/ton	21.19 ton	$30,170.32
Bar tie	Bag tie for reinforcing steel	$ 6.78/hundred	221.76 C	$1503.53
Bar chair	High chairs for reinforcing steel (plain steel)	$122.04/hundred	4.9 C	$598.00
Total				$32,271.85

5 CONSTRUCTION PROCESS

The installation operation of reinforcing steel is decomposed into two work packages (WP):

(I) Work Package 1: Carrying bars to the bridge site; in this particular case study, two labourers work as a team on WP1. The speed to carry bars to the construction site is distributed on the range [30, 40, 50] m/min (here, 30 is the minimum, 50 is the maximum and 40 is the target value most likely to occur in the field); the time for looking for the exact rebar is in the range [1.2, 1.5, 2.5] min. The two labourers can carry 30 kg on each trip; the distance from the rebar bending shop to the site is 25 meters.

(II) Work package 2: Placing the bars on blocks, chairs and spacing them (two reinforcement placing labourers collaborate to place bars at [7, 9, 12] kg/min) and tying the bars at intersections (each labour can make [5, 7, 8] ties/min). A total of four reinforcing labours are employed on-site for this job. The detailed operation process can be illustrated in Figure 6.

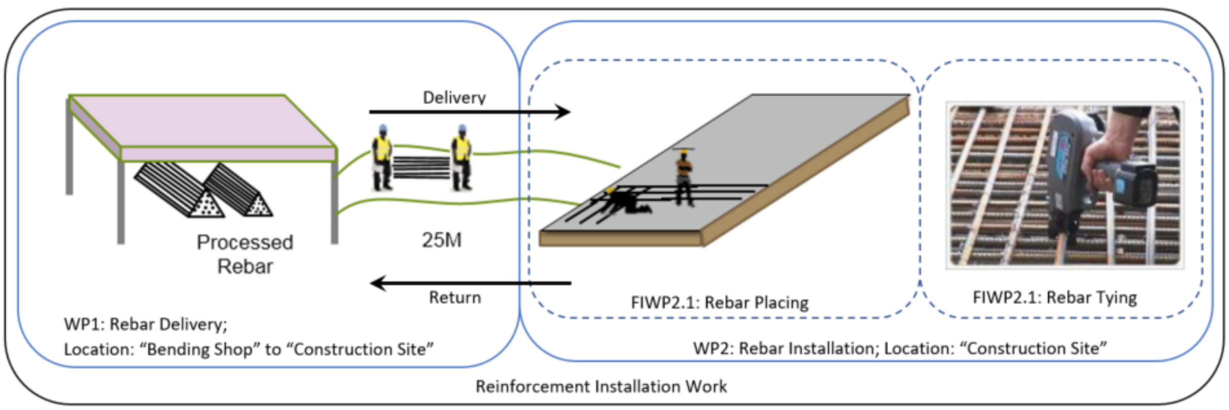


Figure 6: Detail reinforcement installation work process.

5.1 "AON Plus" Model

The "AON Plus" model of the above construction process is presented in Figure 4. SDESA simulation modelling tool is used to construct the computerized simulation model (Lu 2003; Chan and Lu, 2008). The "AON Plus" model comprises of two operation flows corresponding with the two work packages. In the first one, two delivery labourers (non-disposable resource) grab already-processed rebar segments and deliver them to the bridge deck construction site, then return. This operation starts at the off-site bending shop and ends at the construction site. In the next one, two installation labourers (non-disposable resource) place the delivered rebar segments and tie them up. This operation takes place at the deck construction site.

Reinforcement installation labourers can start work as soon as the first cycle of delivering rebar segments is complete. In the "AON Plus" model, the "rebar delivery" work package starts with activity "Looking for appropriate rebar." When the two delivery labourers grab 30kg rebar segments, activity "Deliver" in the model is activated to represent rebar delivery activity from the offsite bending shop to the construction site. The time for the two rebar delivery labourers to travel back to offsite bending/fabrication shop is defined in *Resource Transit Information System* (RTIS) table of the "AON plus" model. A disposable resource "Rebar Ready To Install" is generated once 30 kg rebar segments are delivered (end of "Deliver" activity of Rebar delivery work package) to the construction site. At the beginning of the second work package, "Rebar Ready To Install" is required as a resource before initiating the installation process, meaning the second work package can only be started when one cycle of rebar delivery is done at the construction site, ready for immediate installation. Two activities, namely "Rebar Placing" and "Rebar Tying" are carried out consecutively. Once 707 (21191.3kg/30kg) cycles of rebar delivery and installation are completed, the simulation terminates, and the total operation duration is obtained. The simulation model is shown in Figure 7.

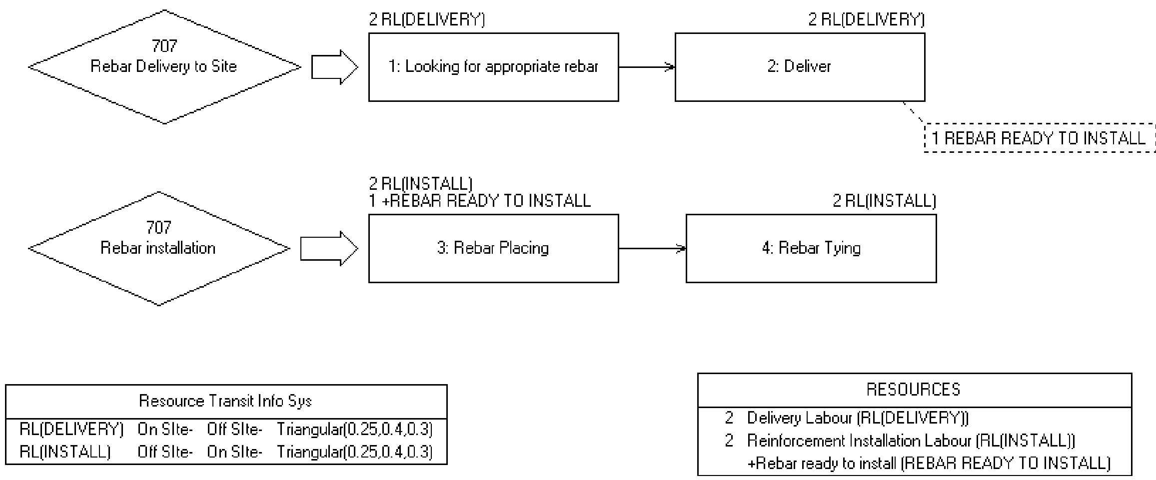


Figure 7: SDESA modelling for reinforcing operation.

5.2 Simulation Results

By running the model for 1000 times, the average duration of the field operations was obtained, as 98.59 hours in total. With the total working hours, the production rate was derived as 21191 kg/98.59 hr = 214.94 kg/hr. Then the crew cost was calculated as ($ 53/hr × 4) / 214.94 kg/hr × 21191 kg =$ 20,901.14. With the material and the crew costs determined, the total reinforcement installation cost is derived as given in Table 6:

Table 6: Total cost summary for "Precise estimating" scenario.

Category	**Material cost**	**Crew cost**	**Total bare cost**
Bare unit cost	$1,522.90 /ton	$986.37 /ton	$2,509.34/ton
Bare cost	$32,271.85	$ 20,901.14	$53,172.99

6 COMPARISON BETWEEN THE TWO APPROACHES

A comparison of the bare cost resulting from these two estimating approaches is given in Figure 8, revealing the following facts: (1) for the material cost, the estimate by the "rough estimating" approach is $28,518.71, while the estimate by the "precise estimating" approach is $32,271.85. "Rough estimating" would result in a 13% underestimate in material cost compared with "precise estimating." As a guideline, this underestimate can be compensated by assigning a factor valued at 1.1-1.2 for typical structural elements which are similar to the bridge deck. It is noteworthy the factor value can be higher given more complicated structural designs; and (2) for the crew cost, the estimate resulting from "precise estimating" is almost doubled against that resulting from the "rough estimating" (based on RS Means). The significant discrepancy between the two estimating approaches justifies the use of "precise estimating" approach for critical design elements. Alternatively, a factor valued at 1.5-1.7 is recommended to apply in adjusting the RS Means based estimate for typical structural elements which are similar to the bridge deck.

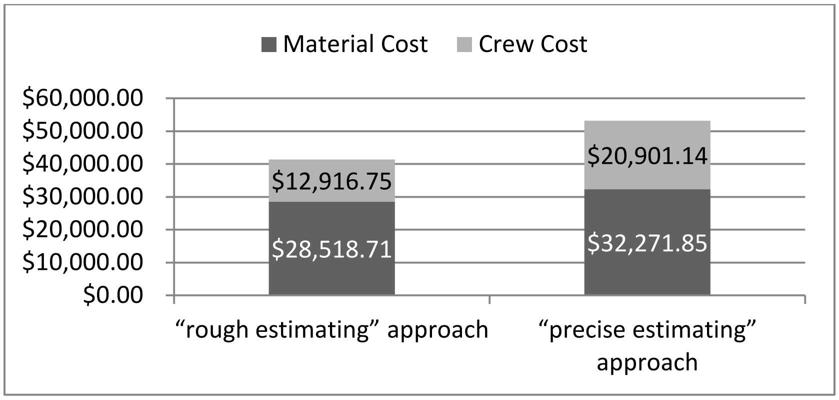


Figure 8: Comparison of “rough estimating” approach vs. “precise estimating” approach.

7 CONCLUSIONS

This research presents a systematic comparison between the two estimating strategies with a case study of a bridge deck. It has been shown that the "rough estimating" approach results in estimates which are considerably lower than those from "precise estimating"; in this particular case study, lower by 13% in material cost and 38% in crew cost, respectively. The results indicate a factor valued between 1.1-1.2 should be applied to adjust the reinforcing material cost estimate based on "rough estimating" method. However, the factor value may vary between different reinforcement design, construction methods, and other engineering design requirements (e.g. exceptional seismic resistance) and constructability constraints specific to a site. Besides, for the crew cost, the estimate derived by "precise estimating" (based on detailed operations simulation) is almost doubled against that resulting from "rough estimating" (based on RS Means.) The significant discrepancy between the two estimating approaches justifies the use of "precise estimating" approach for critical design elements. Alternatively, a factor valued at 1.5-1.7 is recommended to apply in adjusting the RS Means based estimate for typical structural elements which are similar to the bridge deck. However, in practice simulation resource may not be readily available or estimators have only limited time, preventing the application of the “precise estimating” approach. This research can be immediately applied to guide the adjustment of estimates resulting from the “rough estimating” approach based on the use of RS Means. It must be pointed out, using one small case study consisting of specific work packages is not statistically convincing, so future research can focus on more case studies in order to further validate the results obtained from the current case and generate more data to correlate the two estimating methods. The methodology being proposed and applied to the bridge deck case serves as a framework conducive to guide estimating structural elements of similar type in the future.

8 ACKNOWLEDGMENTS

Authors are grateful to Malika Ali, Senior Structural Engineer, CH2M HILL, Inc., for sharing invaluable insight in bridge design and providing the engineering designs of the bridge deck case.

9 REFERENCES

Concrete Reinforcing Steel Institute (CRSI). 2013. “Staggered Lap Splices.” *CRSI Technical Note ETN-C-3-13*, Schaumburg, Illinois.

Chan, W.H., and M. Lu. 2008. “Materials handling system simulation in precast viaduct construction: modeling, analysis, and implementation.” *Journal of Construction Engineering and Management*, 134(4):300-310.

Gonzales-Quevedo, A. A., S. M. AbouRizk., D. T. Iseley., and D. W. Halpin. 1993. "Comparison of Two Simulation Methodologies in Construction." *Journal of Construction Engineering and Management,* ASCE, 119 (3): 573-589

Hajjar, D., and S.M. AbouRizk. 1999. "Simphony: an environment for building special purpose construction simulation tools." *In Proceedings of the 31st conference on Winter simulation*, edited by P. A. Farrington, H. B. Nembhard, D. T. Sturrock, and G. W. Evans, 998-1006. ACM New York, NY, USA.

Kim, S.K., W.K. Hong., and J.K. Joo. 2004. "Algorithms for reducing the waste rate of reinforcement bars." *Journal of Asian Architecture and Building Engineering*, 3(1):17-23.

Kim, S.A., S. Chin., S.W. Yoon., T.H. Shin., Y.H. Kim., and C. Choi. 2009. "Automated building information modeling system for building interior to improve productivity of BIM-based quantity take-off." *In Proceedings of the 26th International Symposium on Automation and Robotics in Construction*, Austin, TX, USA, 2009.

Lu, M., 2003. "Simplified discrete-event simulation approach for construction simulation." *Journal of Construction Engineering and Management*, 129(5):537-546.

Lu, M., H.C. Lam., and F. Dai. 2008. "Resource-constrained critical path analysis based on discrete event simulation and particle swarm optimization." *Automation in Construction*, 17:670-681.

Monteiro, A., and J. P. Martins. 2013. "A survey on modeling guidelines for quantity takeoff-oriented BIM-based design." *Automation in Construction*, 35:238-253.

Porwal, A., and K.N. Hewage. 2011. "Building information modeling–based analysis to minimize waste rate of structural reinforcement." *Journal of Construction Engineering and Management*, 138(8):943-954.

Pristsker, A. 1986. *Introduction to Simulation and SLAM II.* New York: John Wiley and Sons.

Riley, M. J., and D. R. Towill. 2001. "Business systems engineering− can it work in construction?." New Civil Engineering International, Institute of Civil Engineers, March 2001, 44-49.

RS Means Company, 2016. *Building construction cost data*. RS Means Company. 1099 Hingham St, Ste 201 Rockland, MA 02370.

Tatum, C.B. 2012. "Integrated construction engineering activities to satisfy challenging project objectives." *Construction Research Congress ASCE 2012: Construction Challenges in a Flat World*, 139-148.

AUTHOR BIOGRAPHIES

MING LU is Professor in Hole School of Construction at the University of Alberta (CANADA). His research interests include surveying-computing-construction integration and automation, methodologies and applications of construction operations simulation, enhancements to construction project scheduling, construction logistics optimization, applied photogrammetry for construction engineering. His email address is mlu6@ualberta.ca

CHAOYU ZHENG is a PhD student in Hole School of Construction at the University of Alberta (CANADA). Her research interests include the integration of simulation and analytics, combinatory optimization, operation simulation and advanced informatics in cost estimation. Her e-mail address is czheng1@ualberta.ca.

CHAOJUE YI is a PhD student in Hole School of Construction at the University of Alberta (CANADA). His research interests include earthmoving operation and simulation, operational optimization, design optimization, deep foundation engineering and management. His e-mail address is chaojue@ualberta.ca.

MONJURUL HASAN is an MSc student in the Department of Civil and Environmental Engineering at the University of Alberta (CANADA). He has received his BSc in Civil Engineering from Bangladesh University of Engineering and Technology. His e-mail address is mdmonjur@ualberta.ca.