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Modelling of Project Buffer in Critical Chain Scheduling

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Abstract: The aim of this research is to increase the accuracy in planning of the project duration by developing a mathematical model for project buffer to create a critical chain that will end with project duration near to the actual one required for building construction projects in Bahrain. Gathered actual data and questionnaire survey data were used to evaluate the previous models for project buffers as well as new developed ones; one was selected as the best model to be used for two story villas in Bahrain. The selected one was developed further to obtain a new model that will be more effective, and realistic to enhance the planning stage of such projects in Bahrain. The results showed that a merged model of critical chain density and resource density is the best model that has produced final project duration with a variance of 23.065 days from the actual project duration of 89.94 days obtained from the documented data of two story villas. A model was developed based on the above by creating a relationship between actual and planned durations of the selected best model, this model was then validated. Although the focus of this research is on projects of two story villas in Bahrain, having defined the specifications of these projects, the developed model can be used for projects with similar specifications.

Keywords: Project Management, Critical Chain, Project Buffer, Planned Project Duration

1. Introduction

Construction projects play a great role in the economy of any country; also it is a great source of income for investors and stakeholders. Time is related to cost in any project, it is one of most important aspects to be planned and scheduled. The accuracy of project duration was the concern of planners and estimators throughout the project management history, many tools and methods were used to get this accuracy, at first the traditional methods such as critical path and program evaluation and review techniques were used. Then a relatively new method, which is critical chain, was introduced to overcome the pitfalls found in the traditional methods and to increase the accuracy of the planned project duration. This will decrease cost and time overruns on one hand, and will increase the profit of the project on the other hand.

The safety margin was introduced in Golderat novel by the concept of theory of constraints (TOC) [3], this gave the project management a new limitation tool to increase the accuracy of the project durations, as critical path method did not had this concept, and it was dependent on the estimation that is based on the experience of the estimator, which lead to a final project duration with less accuracy and high safety. Golderat replaced the safety margins that people tend to introduce in project scheduling, by introducing three buffers, namely: project buffer that is the total safety margin added to the project duration; safety (feed) buffers added to non-critical activities in order to avoid being critical during project execution; and finally resource buffers added to resources to avoid lack of resource during project duration.

Many researches were implanted in this filed such as Hegazy [6] who improved resource allocation heuristics by using activity priorities based on the application of theory of constraints. Rand [17] explored the relationship between the ideas developed in Goldratt novel and the critical path method/PERT approach. Herroelen and Leus [8] applied computational experiments on a benchmark problem set, in order to test the impact of the working principles and fundamental assumptions of critical chain. In another research Herroeelen and Leus [7] concluded that the critical chain method is not applicable to be implemented due to oversimplification, Kuchta [13] made a formal description of critical chain, and Lechler [14] analysed the critical chain approach in managing projects. Tian and Demeulemeester

[18] analysed the roadrunner and railway scheduling with regard to the impact of applying resource flow networks on a number of project duration related parameters. Also, Tian and Demeulemeester [19] in a different research identified the parameter combinations that result in a minimal project length by applying the concept of critical chain. Feng [2] created project portfolios based on the similarity principle, and explained the multi-resource allocation priority based on quantitative analysis. Penga and Huang [16] formulated the resource constraints and the uncertainty of the duration in a critical chain schedule. Yaghoubzadeha, and Roghanianb [20] noted that the critical chain is relatively a new emerged method in the construction field and it is needed due to the wide range of complexity of projects'. Hutanu [9] reported that the main and most important objective of high technology projects is to reach the milestones of the project. They compared IT projects having classical life cycle and a conceptual model, which was developed by using critical chain method.

Also [12] presented a comparative analysis of the traditional scheduling using critical path and the application of the critical chain project management for construction of marinas in north-western Poland. There results had possible application by building contractors or investors.

"It is important to have a measurable input", [21] who developed a framework for measuring construction project speed. They did that by identifying a range of key performance indicators (KPIs), which helped to measure the acceleration of a construction project by setting a benchmark. From that they constructed a performance measure, and then they tailored it to actual case of a project of constructing a road. They concluded that delays in speed and time can be managed in construction projects.

Since the accuracy of estimation is one of the important aims of the project management it is essential to specify the most efficient method to calculate the safety margin. Kuchta [13] in his effort to give a formal description of the critical chain presented the project buffer as the 50% level of confidence. Similarly, Hutanu [9] used half time or the fifty percent level of confidence in building the critical chain. This rule was also used by Izmailov [10] and [11] in their project management research. All these researchers used the following two models: the first model is using 50% rule, where the project buffer (B) is given by half the time interval of the critical path in the chain:

$$B = [\sum_{\forall k \text{ of crtical path}} (ae_k * 50\%)] \tag{1}$$

Where B is the project buffer, K is the number of activities, ae is the actual duration.

The second model is using root-square method, where B is given by the square root of half the time interval of the critical path in the chain, and se is the planned duration:

$$B = \{ [\sum_{\forall k \text{ of crtical path}} (se_k - ae_k)]^2 \}^{0.5} \tag{2}$$

Another two models presented by Vanhouxke [15] are designated as third and fourth models. The third model is based on the density procedure. The network density is taken into account by using the squared root of the variances of the path having the buffer, and scaling it by a factor related to the network density. Thus, the buffer is defined by this model as:

$$B = K_1 \text{ x } \sigma_{path} \tag{3}$$

Where K_1 is the scaling factor of the density of the sub network; and σ_{path} is the squared root of the variances of the critical path feeding the buffer. This model is based on the extent of network density in terms of precedence relations between the activities and their number. The network density is calculated for the critical path by dividing the number of all preceding activities by the total number of activities in the sub network, this value of density is presented as the coefficient of network complexity (CNC).

The fourth model is based on the tightness of the resource, which measures the degree of resources used along the duration of all activities on the chain leading to the buffer. It compares the available total resource of each activity during a time horizon with all resources' content used by these activities, which are leading into the buffer. This model defines the buffer as:

$$B = K_2 \text{ x } \sigma_{path} \tag{4}$$

Where K_2 is the scaling factor based on the tightness of the resource, and σ_{path} is the critical path standard deviation.

In addition to these models there are other methods reported as noted by Ghaffari and Emsley [5], namely, high confidence Root Square Error Method (RSEM), Error Approach, Improved RSEM, RSEM Based on Lognormal Distribution, and Dependence Assumption between Activities, and some other approaches using simulations done by computer and Fuzzy Logic. These methods have not been used in Critical Chain Project Method (CCPM) implementation cases and software products, and not widely mentioned in other academic investigations. Only 50% rule (Base method), RSEM (based on normal and lognormal distributions) and Base plus Root Square Error Method (BPRSEM) are widely used in CCPM applications.

2. Existing Models Analysis and Model Development

It is important to select the best model for construction projects with certain specifications in order to create the best critical chain that have planned durations near to the actual durations. The selection will be from the four models specified in section 1 and described by Equations (1)-(4), and three models developed within the context of this work. The best model will be selected based on actual and questionnaire data for two story villa projects in Bahrain.

The selected model is used to develop actual duration models for major activities of two story villas using regression analysis. The actual duration models can be used to establish the project buffer for given planned durations.

2.1. Extension to the Surveyed Models

The four models defined by Equations (1) - (4) are used to develop the following three buffer models, which are basically obtained by merging the reviewed models.

Model 5:

$$B= K_1 K_2 \sigma_{path} \quad (5)$$

Model 6:

$$B= 0.5(K_1+K_2) \sigma_{path} \quad (6)$$

Model 7:

$$B= 0.5 \{[\sum_{\forall k \text{ of crtical path}}(ae_k * 50\%)] + ([\sum_{\forall k \text{ of crtical path}}(se_k - ae_k)]^2)^{0.5}\} \quad (7)$$

The seven models (reviewed plus developed ones) are evaluated by applying them to construction projects in Bahrain.

2.2. Collection of Data

2.2.1. Surveyed Data

Due to lack of documented information on two story villas in Bahrain a questionnaire was used to collect relevant data. The questionnaire was distributed in printed and electronic form through e-mail and by hand to professional engineers in private sector in Bahrain. The questionnaire was sent to a total of 60 engineers, of whom 50 responded, i.e. a response rate of 83%. Most of the engineers were from grade C companies, which were defined by Ministry of Works for a project value below $800,000. Few engineers were form grade B, which was for a project value between $ 800,000 and $2,700,000. The respondents specified a duration for eleven activities and for each activity they specified two durations actual and planned durations, resulting into twenty-two durations in which eleven for actual and eleven for planned. Thus, a range for planned and actual durations for each activity was developed as per the survey as shown in Table 1. The data is required to build the critical chain of a two story villa project with defined specifications. All data values for skewness and kurtosis fall between -2 and +2, thus, the assumption that the data are normally distributed is acceptable [4].

In order to check the validity of the ranges of both the actual and planned activities' durations specified by the survey, the actual ranges were used for random generation of 300 problems to create 300 critical chains. For each critical chain seven final project durations were obtained by using the seven models stated earlier. These project durations were checked with actual documented data collected in order to define the valid range and to select the best model.

Table 1. *The Range of Activity Durations as per Survey for Two Story Villa.*

Activity description	Activity code	Planned Range (Days)	Actual Range (Days)
Excavation and backfilling	A-1	7-11	6-10
Foundation	A-2	14-20	11-19
Columns of ground floor	A-3	8-12	6-11
Block works of ground floor	A-4	7-11	4-10
Beams of first floor	A-5	14-20	11-19
Columns of first floor	A-6	8-11	6-10
Block works of first floor	A-7	12-17	9-16
Beams of roof	A-8	12-17	9-16
Columns of stair roof	A-9	6-8	3-7
Block works of stair roof	A-10	3-4	1-3
Beams of stair roof	A-11	4-8	4-7

2.2.2. Actual Data

The actual project's data should contain: planned schedules of the project, actual site reports that specify the date of finalizing each activity, the number of labours that were present on site according to the daily reports; the area of construction; and the number of floors. The actual data collection was done for two story villas from a private company documented files. Beside reluctance of most companies to release their projects data, it was difficult to get all required information such as labour used and duration of each activity from documented projects. Only a total number of thirty-six contracted projects out of sixty-eight had accessible actual data but most of it was not complete for analysis. Also some activities had no durations, and in some projects there were missing activities.

Due to the difficulties of finding the full information for the actual and planned durations for the activities of these projects, as well as the area of each project, only the final project completion date was obtained for each of the 36 projects. These projects should have similar specifications with the questionnaire specifications for comparison purpose. Thirty-six of the 68 project data sets that had full useful data consisting of the following:

1. Starting date stated in the contract
2. Finishing date stated in completion certificate
3. Starting date stated in the inspection report
4. Foundation finishing date stated in the inspection report
5. First floor finishing date stated in the inspection report
6. Roof finishing date stated in the inspection report

Data was organized based on the above categorization and final projects durations were calculated, minding that these projects differed in the construction area and the number of labours. The main difference was in the construction area, while the number of labours did not differ very much and it was similar to the questionnaire specifications. To make the area of the documented data similar to the questionnaire specifications, which was 310 m^2, each activity duration was obtained by multiplying the activity area commonly used in two story villas (150 m^2 per floor) by the documented activity duration and dividing the result by the activity's documented area. The columns of ground floor had very few documented durations so they were not included. The adjusted durations were obtained using the following equations:

Foundation + ground duration (FD) = (150) (DD)/ (DA) (8)

First floor duration (FFD) = ((150) (DD)/ (DA) (9)

Roof duration (RFD) = ((10150) (DD)/ (DA) (10)

Project duration= FD+FFD+RFD (11)

Where DD is the documented duration, and DA is the documented area.

In case there was a second floor, project duration would be for foundation, first floor, second floor, and roof as follows:

Second floor duration (SFD) = (150) (DD)/ (DA) (12)

Project duration= FD+FFD+SFD+RFD (13)

The averages of the 36 project's data were calculated, and the distributions of the data were established by SPSS software as shown in Table 2. As Table 2 shows that the data for all activities was considered normal as their skewness and kurtosis fell between -2 and +2 except for the second floor activity. For that reason the average total project duration drawn from foundation, first floor, and roof was used in this research, which was 89.94 days.

Table 2. *Results of Describitve Analysis of Actual Data.*

Activity	Number	Min (Days)	Max (Days)	Mean (Days)	Std. Deviation (Days)	Skewness		Kurtosis	
						Stat	Std. Error	Stat	Std. Error
FD	25	1.01	64.14	29.83	17.63	1.43	0.464	1.42	0.902
FFD	25	5.42	110.30	42.55	25.18	1.04	0.464	1.06	0.902
SFD	7	16.05	198.37	73.969	64.67	1.91	0.794	3.64	1.587
RFD	22	0.01	51.44	17.58	15.68	1.03	0.491	-0.018	0.953

2.3. Best Model Selection

After establishing the total average project duration for two story villa as specified in actual collected data of thirty-six projects of two story villas in Bahrain, random problems were generated in order to identify the best model that will give total average project duration near to this value which was 89.964 days. A first trial was done by creating 200 problems; each problem requires actual and planned durations for each activity to create a critical chain. The actual and planned durations were produced randomly using Excel random-number generator (RNG) and the survey-based ranges specified in Table 1 for each activity. From the first trial run, only models 1, 2, and 7 had a project duration equals to or more than 89.94 days. The results of this run are shown in Table 3.

Table 3. *Results of the Seven Models for the First Trial.*

Model	Number of projects with final duration ≥ 89.94 days	Project duration nearest to 89.94 (days)	Mean (days)	Variance (days)	Standard deviation (days)
Model 1	64	90.5	95.09	39.79	6.31
Model 2	20	89.96	93.92	24.17	4.92
Model 3	0	-	-	-	-
Model 4	0	-	-	-	-
Model 5	0	-	-	-	-
Model 6	0	-	-	-	-
Model 7	47	89.96	93.56	24.61	4.96

A second trial was carried out and another 200 problems were created by using different ranges for three of the eleven activities, namely A-1, A-2 and A-11 shown in Table 4 as per the average actual duration ranges found in the actual documented data. As a result, a number of critical chains created in this trial reached and exceeded 89.94 days duration of full project. Based on this trial, the results obtained by the seven models are shown in Table 5. Table 5 shows that model 1 and model 7 scored the highest number of problems that gave project durations which reached or exceeded 89.9 days. All models except model 1 gave the nearest duration to this value, model 6 gave the nearest mean and the lowest variance and standard deviation from the average documented final project duration (89.94 days). Based on these results model 6 (Equation (6)) was considered as the best model for project buffer to be used for creating critical chains for the two story villas in Bahrain.

Table 4. *Actual Ranges for Documented Activities.*

Activity code	Planned range (Days)	Actual range (Days)
A-1	11-20	6-19
A-2	15-30	11-29
A-3	8-12	6-11
A-4	7-11	4-10
A-5	14-20	11-19
A-6	8-11	6-10
A-7	12-17	9-16
A-8	12-17	9-16
A-9	6-8	3-7
A-10	3-4	1-3
A-11	6-8	5-7

Table 5. *Results of the Seven Models for the Second Trial.*

Model	Number of projects with final duration days ≥ 89.94	Project duration nearest to 89.94 (days)	Mean (days)	Variance (days)	Standard deviation (days)
Model 1	200	99.00	116.02	769.63	27.74
Model 2	113	89.96	97.60	96.58	9.82
Model 3	65	89.96	94.54	32.35	5.68
Model 4	38	89.96	93.82	24.055	4.90
Model 5	100	89.96	95.47	46.11	6.79
Model 6	35	89.96	93.74	23.02	4.80
Model 7	197	89.96	104.373	281.16	16.77

2.4. Model Development

To develop the intended model, the following steps were applied:

1. Using the best model selected for project buffer, the planned and actual duration's sets for each activity were obtained. These durations produced the nearest project duration to the actual documented data.

2. For each activity, a relationship between planned and actual data was developed.

Regression analysis was used to develop the relationships between the planned and actual data, using for each activity the 35 data points of the planned and actual durations that had resulted into project duration greater or equal to 89.94 days with model 6 (Table 5). Different relationships were generated after that from these data using exponential, linear, logarithmic, and power trend regressions. The final models in Table 6 are based on the best R squared value, which are linear for all activities. For activity A1 as an example, the different regressions between actual and planned durations and the corresponding R squared values are shown in Figures (1) - (4).

Table 6. *Actual Duration Model for Each Activity Depending on Planned Duration (Linear Regression).*

Activity	Developed model	R^2
A-1	Actual duration = (0.8748 x planned duration) - 2.1581	0.37
A-2	Actual duration = (0.638 x planned duration) +5.1815	0.28
A-3	Actual duration = (0.568 x planned duration) +2.0617	0.50
A-4	Actual duration = (0.5529 x planned duration) +2.147	0.39
A-5	Actual duration = (0.6451 x planned duration) +3.0551	0.30
A-6	Actual duration = (0.603 x planned duration) + 1.5366	0.30
A-7	Actual duration = (0.5986 x planned duration) + 2.9402	0.45
A-8	Actual duration = (0.6325 x planned duration) + 2.6415	0.36
A-9	Actual duration = (0.7188 x planned duration) + 0.4375	0.42
A-10	Actual duration = (0.3435 x planned duration) + 3.6613	0.20
A-11	Actual duration= (0.7432 x planned duration) + 0.4135	0.51

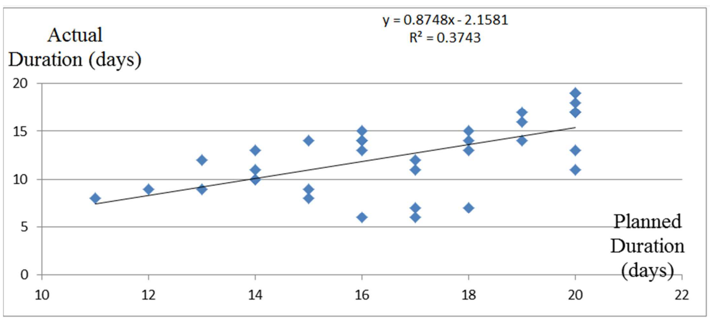

Figure 1. *Linear Relationship for Activity A-1 of Planned and Actual Durations of the Best Selected Model.*

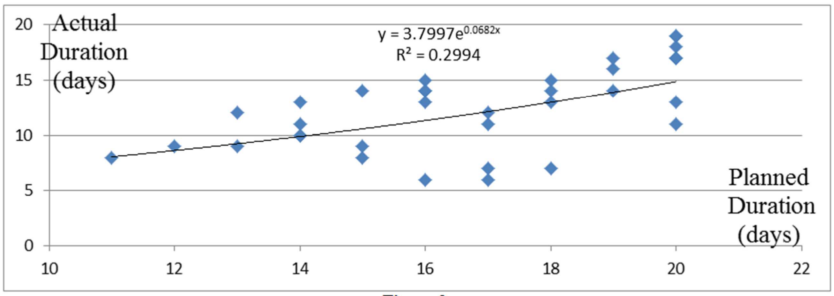

Figure 2. *Exponential Relationship for Activity A-1 of Planned and Actual Durations of the Best Selected Model.*

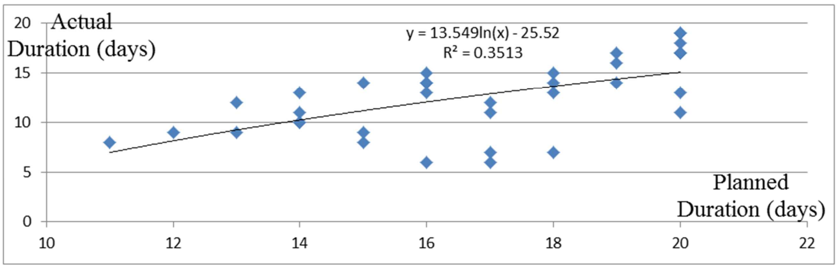

Figure 3. *Logarithmic Relationship for Activity A-1 of Planned and Actual Durations of the Best Selected Model.*

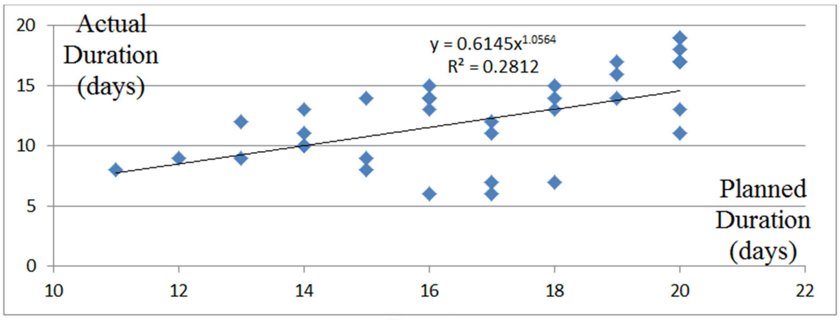

Figure 4. *Power Relationship for Activity A-1 of Planned and Actual Durations of the Best Selected Model.*

After developing relations between actual and planned durations for each activity the project buffer was calculated using Equation (6) the selected best project buffer model. Application of Equation (6) necessitated calculation of σ_{path}, K_1, and K_2 as explained in the following paragraph.

First the expected actual durations were presented as function of planned durations using the equations in Table 6, after that Equation (6) was applied to establish variance for each activity as shown in Table 7. The variance of activity Ai designated VAi was given by Vanhouxke (2012) as:

$$\text{VAi} = ((\text{planned duration of activity - actual duration of activity})/2)^2 \qquad (14)$$

For example, variance of activity A1 is (VA1):

$$\text{VA1} = \{[\text{A1 planned duration} - ((0.8748 \text{ x A1 planned duration}) - 2.1581)]/2\}\text{\textasciicircum}2 = [\ 0.0626\text{*A1 planned duration} + 1.079]\text{\textasciicircum}2$$

After that the project standard deviation was calculated as the square root of the sum of the activities' variances of the longest path as follows:

$$\sigma_{path} = (\textstyle\sum_{\forall\ \text{Ai crtical}} \text{VAi})\text{\textasciicircum}0.5 \qquad (15)$$

While K_1 was a standard for the whole project, as it was assumed that the activities were the same for all generated critical chains, for that K_1= 1+ (7/8).

K_2 was varying as it depended on the actual durations and their associated labour requirements, so it was calculated at the end of the chain, as follows:

$$K_2 = [\text{ Max (activity labours} * \text{activity modeld actual duration)}]/[\textstyle\sum_{\forall\ \text{Ai}} \text{labours of (Ai)} * \text{duration of (Ai)}] \qquad (16)$$

For activity A1, it had 2 labours, and the modelled actual duration obtained by (0.8748* A1 planned duration - 2.1581), by multiplying these values the resource density for this activity was obtained. Resource densities of other activities were obtained in a similar way.

Finally, the project buffer was given by Equation (6).

Table 7. *Variance Models for Each Activity as per the Best Project Buffer Model Selected.*

Activity	Developed variance model
A-1	VA1 =[0.0626 x planned duration + 1.07905]^2
A-2	VA2=[0.181 x planned duration - 2.59075]^2
A-3	VA3=[0.216 x planned duration - 1.03085]^2
A-4	VA4=[.22355 x planned duration - 1.0685]^2
A-5	VA5= [0.17745 x planned duration - 1.52755] ^2
A-6	VA6=[0.1985 x planned duration - 0.7683]^2
A-7	VA7=[0.2007 x planned duration -1.4701]^2
A-8	VA8=[0.18375 x planned duration -1.32075]^2
A-9	VA9=[0.1406 x planned duration - 0.21875]^2
A-10	VA10=[0.32825 x planned duration -1.83065]^2
A-11	VA11=[0.1284 x planned duration - 0.20675]^2

2.5. Validation of the Developed Model

For the validation of each activity actual duration model, 200 random problems were generated to produce activity actual and planned durations. The activity planned durations were used to calculate activity durations using the associated models developed in Table 6. For each activity, the mean of the modelled actual durations for all problems and the mean of random actual durations are shown in Table 8. From Table 8 it could be seen that the standard deviations of the modelled actual duration from the random actual duration are high for activities A1, and A2, while they are relatively small for the other activities.

Table 8. *Model Validation Results.*

Activity	Random actual duration mean (days)	Modeled actual duration mean (days)	Variance (days)	Standard deviation (days)
A-1	10.215	11.65499	13.25	3.64
A-2	16.62	19.80765	23.62	4.86
A-3	7.43	7.69342	1.33	1.15
A-4	8.56	8.859206	3.93	1.98
A-5	13.57	13.93149	2.67	1.63
A-6	7.15	7.280175	1.082	1.040
A-7	11.32	11.54807	2.37	1.54
A-8	11.4	11.907625	3.32	1.82
A-9	5.58	5.508634	0.35	0.59
A-10	6.52	6.383538	0.36	0.60
A-11	5.455	5.612184	0.37	0.60

The 95% confidence interval of the difference between the means of two populations is calculated by taking a sample from these two populations and taking their means and standard deviations as per the following equation [1]:

$$(x1\text{-}x2)\text{-}(Z_{(\alpha/2)}.(\sqrt{(\sigma 1/n1)+(\sigma 2/n2)}) < \mu 1\text{-}\mu 2 < (x1\text{-}x2)+(Z_{(\alpha/2)}.\sqrt{(\sigma 1/n1)+(\sigma 2/n2)}) \quad (17)$$

Where x1 and σ1 were the mean and standard deviation of sample 1, x2 and σ2 were the mean and standard deviation of sample 2, µ1 and µ2 were the means of the first and second populations, respectively. α was the significance level. For 95% confidence interval α was 1.96 from the normal distribution table.

The total mean of the 200 random results generated was considered as the population mean, thus, µ1-µ2 was calculated as the difference between the random actual durations mean and the modelled actual durations mean, respectively. Two samples, each of 150 random results, were generated, sample 1 from the 200 random actual durations, and sample 2 from the 200 modelled actual durations. The means and standard deviations of sample 1 and 2 were x1, σ1, and x2, σ2, respectively. Using Equation (17) the results of Table 9 were generated:

Table 9. *95% Confidence Interval for Mean Differences Between Random and Modelled Actual Durations.*

Activity Code	µ1-µ2 (days)	σ1 (days)	σ2 (days)	x1-x2 (days)	Confidence interval (days)
A-1	-1.44	3.51	2.50	-1.38	-1.77< µ1-µ2< -0.98
A-2	-3.19	4.34	2.85	-2.92	-3.34< µ1-µ2<-2.92
A-3	-0.26	1.31	0.77	-0.28	-0.51< µ1-µ2<-0.04
A-4	-0.30	2.51	1.80	-0.35	-0.68< µ1-µ2<-0.02
A-5	-0.36	2.04	1.32	-0.44	-0.74< µ1-µ2<-0.15
A-6	-0.13	1.17	0.68	-0.13	-0.35< µ1-µ2<-0.09
A-7	-0.23	1.67	0.97	-0.12	-0.38< µ1-µ2<-0.13
A-8	-0.51	1.99	1.08	-0.54	-0.82< µ1-µ2<-0.26
A-9	0.07	0.74	0.60	0.05	-0.13< µ1-µ2<0.24
A-10	0.14	0.74	0.28	0.12	-0.04< µ1-µ2<0.28
A-11	-0.16	0.66	0.61	-0.16	-0.34< µ1-µ2<0.02

From Table 9, it could be concluded that the developed models achieved 95% confidence interval for all activities, i.e. the difference between modelled and expected actual activity durations was insignificant at 95% confidence interval. In other words, the means of the modelled and randomly generated actual durations of each activity were insignificant. This was an adequate validation of the developed models for the activities of two story villas' projects.

2.6. Analysis and Discussion of Model Results

Based on the thirty-six documented data used to establish a project final duration that is needed to be met by the critical chain, model 6 (Equation 6) of the project buffer was selected based on the standard deviation and mean results. Activity models were developed from the thirty-five points obtained by Equation (6) of the project buffer for the random problems generated (Table 5). These models show at 95% confidence interval that the difference between the mean of the activity modelled duration (the activity planned duration subtracted from it the activity modelled buffer) and the mean of the activity random actual duration was insignificant. The project buffer was calculated as the sum of the activity buffers of the longest path in the critical chain, and this was based on the critical chain built as per Equation (6).

The validation of the models was carried out by generating 200 random problems to produce 200 planned as well as actual durations for each activity. Final project duration was calculated based on the planned and modelled project activity durations; this project duration was compared with the project actual final duration based on the randomly generated actual durations of the activities. The comparison was done using Equation (11) and a sample of 150 of the generated 200 problems. Parameters µ1 and µ2 of Equation (17) were the means of the actual and modelled final project durations of 200 random problems. σ1 and σ2 were the standard deviations of the actual and modelled final project durations based on activity durations of two samples of 150 problems each from the randomly generated 200 problems, while x1 and x2 were the means of these samples. Table 10 shows that the modelled project duration satisfies the 95% confidence interval, and this proved the validation of the modelled project buffer.

Table 10. *95% Confidence Interval for Project Buffer Validation.*

μ_1-μ_2 (days)	σ_1 (days)	σ_2 (days)	x_1-x_2 (days)	Confidence interval (days)
-13.46	5.36	4.83	-13.87	$-14.38<\mu1-\mu2< -13.36$

The following is a flow chart that shows the steps of model construction.

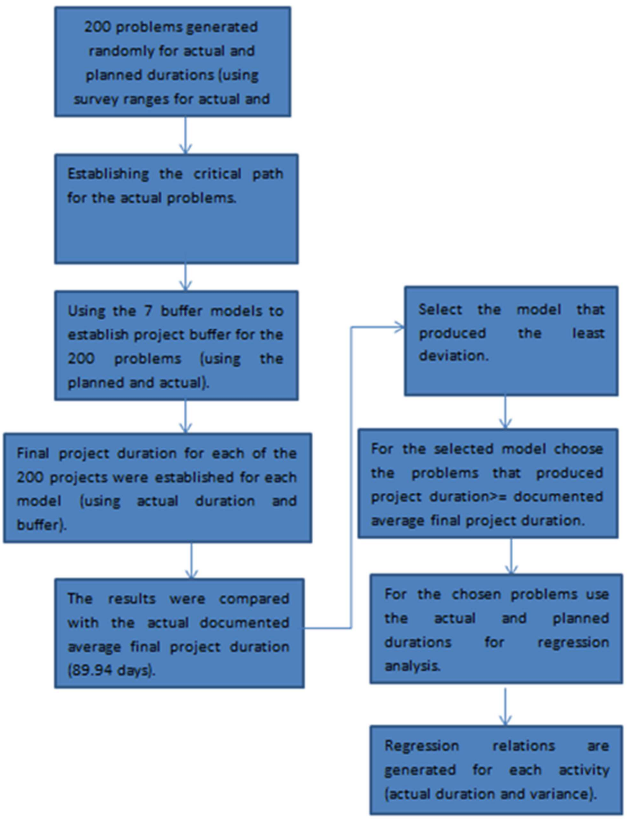

Figure 5. *Flow chart of model construction.*

3. Conclusions

This research presented a modelling approach of the project buffer in critical chain scheduling. The research surveyed four models used in calculating the project buffer for the critical chain. Furthermore, three additional models were developed for the same objective. The seven models were compared using actual and random instances, and the best was identified. Regression models were developed for the actual durations as functions of planned durations of the eleven major activities for two story villa projects in Bahrain. These models were used to establish the activity buffers based on the best model selected from the seven buffer models mentioned above. Then the project buffer was obtained for the critical chain.

The modelled project buffer could be used while creating the project schedule using the critical chain. The project manager should assign the planned durations of the activities, and the project final duration (expected actual) would be calculated by subtracting the modelled project buffer from the planned project duration. The project buffer would be used as a stand by duration at the end of the project.

A model was developed for the project buffer of the critical chain that could be used for two story villa projects in Bahrain. The model was validated and evaluated using available and simulated data for the major activities of such projects. As a result of the application of the model it was expected that the modelled planned duration of the project would approach the actual project duration, and the difference between these durations was insignificant at 95% confidence interval.

Construction is a rising industry in Bahrain and having a model for the project buffer that will reduce time and save money and will give project managers additional power to enrich this industry.

Further research: Critical chain has three buffers, this research modelled only the project buffer, and a further research is needed to model the safety and resource buffers. Also this research covered the model for only two story villas a further research is needed for other types of projects.

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