Multi-Criteria Decision Analysis Applied to Subcontractors Selection in Construction Projects

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Abstract. In construction projects worldwide, Main Contractors (MC) have to choose Sub-Contractor (SC) with varying degrees of previous experience. This adds an extra layer of uncertainty to the project that may impact costs and time directly or indirectly. Adequately assessing and selecting amongst alternative SCs is a well-known risk management strategy to mitigate threats and realize opportunities. But this is often done empirically. This paper discusses a mean to identify and weight SC and MC characteristics in each project's context in a way that enables a systematic and optimized decision-making process when selecting SCs in construction projects. Multi-criteria decision analysis (MCDA) and M-MACBETH software is applied to an empirical case study from a construction company in Malaysia. A cabling project of a double electrified railway in Malaysia provides the context for the decision-making problem, criteria, audit data and information. A sensitivity and robustness analysis is included in the paper.

1. Introduction

As the environment is uncertain, complex, dynamic, competitive, and finite, a decision-maker needs to balance the choices (logical balancing) of the factors (economic, environmental, technical, competitive) that affect an ideal decision. Decision analysis lets us start to allocate the consequences of the whole procedure of decision making to the outcome. Various features of the problems lead to consensus, called the value of information (Howard, 1979).

Sub-Contractor is generally known as the company hired by the MC to do the specific task in the project. In construction projects (Yates, 2014), several parts of the project need to execute by their experts. For example, when the main contractor takes a highway or road project, various sub-projects need to be done to complete the project, like utility networks, earthmoving activities, retaining wall constructions, pavement, and other detailed sub-items.

In the modern world, making the right decision would be a challenge for all enterprises. When a project is awarded to a company to be constructed, there is a certain need to outsource some part of the project by breaking down the project activities and give them to subcontractors. The main contractors seek the best SCs in their field, not only professional in executing the work at a good price but also finishing the project on time with a sufficient amount of staff and equipment. However, there would be a specific need for a subcontractor to perform a job. Sometimes a subcontractor with a smaller size would be more manageable for main MCs than the dominant ones. Pre-qualification documents would be a great tool to collect their general information, followed by a specific questionnaire to acquire specific information.

2. State of the Art Title of first section (11pt bold, exactly 14pt spacing, 3pt after)

There would be time to deciding by MCDA (Bana E Costa, Carnero and Oliveira, 2012). In this stage, all the collected data need to be clustered and weighted based on their importance for the DMs ideas and biased. We are biased in this stage because always being good in all aspects would not lead to selecting a specific SC (Zavadskas, Turskis and Tamošaitiene, 2010). For example, there would be a perfect SC, but the MC knows that they have many ongoing projects at the moment of participating, and they remove that selection and goes for the second option. Generally, that is to say, there is no direct instruction because of this and that we have to select specific options while there are very hidden criteria that will come to light in the further steps. Making the last decision based on the weighted criteria in the different levels of a Decision Tree (DT) is the main goal of this study. This paper will discuss how that MC will make their decision and facilitate this process through MCDA by analysing a case study/ a real example.

Generally, “Decision analysis is an operations research technique for analysing complex decisions with multiple objectives and uncertainty.” The probability axioms, utility theory, and the systems analysis philosophy used in decision analysis. Bayesian was decision analysis characteristic until believing that probability is an individual evaluation of our acceptance in the product of an occasion based on our information, biases, and heuristics. People make decisions with uncertain data and the preference of value and time with the risk and uncertainty (Zavadskas, Turskis and Tamošaitienė, 2010; Almeida *et al.*, 2015; Aven, 2016). The decision dimension is the type, number, and decision level of the alternatives. Usually, decision complexity increases as the decision level increases. Also, the complexity increases as the number of decisions and the potential for new alternative designs increases (Parnell, 2009).

In this process, we have contacted the Construction Manager at a well-known Corporation, one of the DM. The company requires a subcontractor for the cabling work, and they need to evaluate the criteria. They have collected information from the different subcontractors who can work for them. Moreover, they make a simple spreadsheet and a direct scoring system without weighting the variables. These would make a biased decision model while all the criteria have been considered the same because people mostly are biased and limited in their decision (Phillips, 1984).

Choosing Criteria is another Processes by holding various meetings on the decision board. The construction manager and other technical staff have decided which criteria would be the most important for the project as a whole. While receiving all the Pre-Qualification Documents, the specific questionnaire of the targeted amount of job which needs to be done has been sent to SCs, and they provided the information needed for the decision board. In the later steps, the decision model needs to create the main branches of the decision need. The second step should ask the decision board to do the weighting procedure by the swing technique or qualitative pairwise comparison judgments of difference in attractiveness in the tenders and bid evaluation (Bana e Costa *et al.*, 2008). More simple cross weighting weighs each criterion compared to the other criteria and weighing each criteria options of criteria qualitative or quantitative options vertically. Using on-the-spot modelling and application of information technology and combining social processes with technical modelling help create a socio-technical approach to problem-solving that benefits from expert facilitators and unbiased decision analysis of the group (Phillips, 2006). These all tend to “a decision support system for creating aligned commitment within an organisation” (Phillips, 2005).

By this, the DMs would be surer that which criteria would affect the decision they would make. However, this approach cannot be a comprehensive approach to decision making, while all the weighting system in the main branches of the decision tree would not work separately. They all are related to each other due to having a total weight of one unit, and the score given to the SC cannot have criteria under other criteria. The last breakdown branches are the criteria by themselves. The latest Criteria would compare the associated weight together, and the sum of all the weights would be one.

3. Multi-criteria decision-making

In this research, the MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) MCDA methodology was used. MACBETH is an interactive approach that requires only qualitative judgments about differences to help decision-maker(s) quantify the relative attractiveness of the options. It employs an initial, interactive questioning procedure that compares two options by asking to what degree do you prefer the first option to the second option.

4. The Criteria and the options

Defining the project’s criteria is to make each component individually effective and play an important role in decision analysis. Follow by these criteria need to be clustered. By clustering criteria, the group can distinguish them and build a tree of clustered criteria called Decision Tree (DT).

Based on the DMs point of view, various contractual and performative criteria need to evaluate. The DMs decided the first group will be the number and types of equipment (machinery) such as excavator, backhoe, low-loader, Lorry, and HDD (Horizontal Directional Drilling) Machine. Another criterion is the percentage of the hired machinery and equipment from outside by each SC. In this item, the ownership of each piece of machinery will guarantee the duration of the machinery presence on the working site. And the percentage of

the plant. The last one in the first group is the productivity rate of the plant or machinery in which these criteria are compared based on the submitted document by each SC. The second group is the organisational capability, including an organisational chart, key personnel qualifications and CVs, mobilisation schedule, and letter of undertaking. The last group is the list of suppliers and SCs, include the cable, electrical pole and lighting poles, ducts, and the availability of HDD subcontractors.

The model started by creating criteria that are the key aspects of the project requirement based on the decision-maker notion based on the risk assessment analysis (Karimiazari *et al.*, 2011) and the graph (Freitas *et al.*, 2018). After finalising the clustering of these criteria, the facilitator will start to complete the model by using the subjective weighting by applying the swing technique and start using the M-MACBETH (Bana E Costa, Carnero and Oliveira, 2012), the pairwise comparison. By giving the judgement from very weak, weak, moderate, strong, very strong, or extreme, and then make consistent ranking from neutral to good (Bana e Costa *et al.*, 2008).

The options are the list of selected companies and participated in the bidding and modelled in the M-MACBETH as an option defined.

5. Clustering

The concept of clustering is an important element of the decision process. Reviewing multiple concepts provides a means of deciding on choosing a subcontractor to construct the railway. There are three main clusters, as they are mentioned above. Judgmentally dependent elementary concerns or value dimensions leads us to cluster to reduce the operational risk within the project selection procedure (Bana E Costa and Beinatt, 2005).

Plant and machinery: The activities involved in construction projects where the magnitude of the work are on a large scale, Speedy Work and Timely Completion of Work with Quality Control are vital. Plant and machinery are important topics in subcontractor analysis. As stated in the project description, railway construction and electrical cabling are some of the specialised branches in the field of construction related to the power of companies in ownership of heavy machinery and plant and supplying the cable elements.

Organisation structure: The organisational structure affects organisational action and provides the foundation on which standard operating procedures and routines rest. It determines which individuals get to participate in which decision-making processes.

Subcontractors and supplier list: Suppliers have a hugely important role in time delivery. This project supplier of the elements relates to the caballing railway and other subcontractors for each company to cover the HDD drill machine playing a significant role for DM.

6. Decision Tree

Decision trees can help organisations structure and automate (complex) information. Decision trees are decision models that answer a specific question based on a question structure and certain conditions. These models are presented schematically in a tree structure and made available to the user through a digital and interactive tool (Phillips, 2005).

As a rule, a decision tree starts with a root node, after which it branches into various possible outcomes. These outcomes then lead to additional nodes until one reaches the right outcome. Therefore, the purpose of using a decision tree is to present the required information to the user in the most efficient way, using a logical question structure, providing relevant information, and avoiding irrelevant questions and unnecessary detours. In any construction project, before starting to select a subcontractor, the most important part is to identify the project needs and the client's priorities to create an appropriate decision tree in terms of item making by weighing the issue with the client's purpose. In this project, the main goal is to select a subcontractor for replacing the current single rail line with a double track and laying electrical cabling along a 197 kilometre stretch of track between Johor Bahru and Gemas town in Negri Sembilan in Malaysia(Hutchinson and Zhang, 2020).

7. Weighting Criteria

Criteria need to be weighed based on their importance for the contractor by the swing weighting and the trade-off method. These methods are used to reduce the biased direct scoring effects. “Swing weighting procedure” used in SMART can compare criteria with the others. This procedure is used in MACBETH (Bana E Costa, Carnero and Oliveira, 2012). To not allow the group decision-making processes propagated by the anchoring and group over-confidence rooted in group polarisation and initial estimates (Montibeller and von Winterfeldt, 2015), we played the role of facilitator decision analyst make debiasing. We need to ask a question like in what intensity do you prefer EX over BH, and the answer would be very weak, and so on. This procedure will continue till all the tables filled with the judgment.

In Figure 1 (Criteria pairwise comparison matrix scores, collected from DMs) and Figure 2 (Decision tree with their associated weight resulted from comparison matrix), there are three different weighting scores based on the MACBETH basic and anchored calculated from the swing scoring and weighting. These are followed by the visual illustration that shows some of the criteria are scores very less and do not cover the expectation from that criteria, so the DMs decide to adjust anchors to a preferable place that they expect to have. After applying the judgment in the value tree, we can obtain the weight breakdown and the path through the whole tree to 100 percent, which is the whole project.

Figure 1. Pairwise comparison Matrix (up), Weighting diagram (down)

Figure 2. Value tree with implemented weights (Left) Different weighting technique by Macbeth (Right)

8. Judgments

Describing each criterion by performance scale defined by a value scale through qualitative judgments of differences in attractiveness between two options performance levels. MACBETH qualitative categories facilitate comparison of pairs ranking difference in attractiveness by the value (or codes): very weak, weak, moderate, strong, very strong, or extreme (Bana E Costa, Carnero and Oliveira, 2012). As the “option+ two references”: the upper (good) and lower (neutral) (The references scores limitation), which are considered from 0 to 100 respectively. The current scale and the option’s score are obtained accordingly shown in Figure 3.

Excavator

	SISJ	upper	RESB	lower	MTSB	PSB	HTSB	CLEESB	WESB	Current scale
SISJ	no	strg-extr	strg-extr	strg-extr	extreme	extreme	extreme	extreme	extreme	115.00
upper		no	strong	positive	v. strong	v. strong	v. strong	v. strong	v. strong	100.00
RESB			no	strong	strong	strong	strong	strong	strong	49.98
lower				no	strong	strong	strong	strong	strong	0.00
MTSB					no	no	no	no	weak	-15.00
PSB					no	no	no	no	weak	-15.00
HTSB					no	no	no	no	weak	-15.00
CLEESB					no	no	no	no	weak	-15.00
WESB									no	-22.50

Consistent judgements

Figure 3. Excavator Judgement matrix in M-MACBETH

The final score classifier, which is called a thermometer, represents the difference of scoring on each option while using the swing technique and the mathematical foundation of M-MACBETH (Bana E Costa, Carnero and Oliveira, 2012) is. It is also an ideal tool to indicates the differences pairwise and all as a package to have a comprehensive view. It is adjustable, and the facilitator can move the hangers up and down to reflect the DMs ideas.

9. Result and Discussion

After collecting companies’ (Subcontractors) rankings or paired comparisons (Linstone and Turoff, 2011) on each criterion, we derived a table of ranking as a generalised form shown in Figure 4(Bana E Costa, Carnero

and Oliveira, 2012). Based on the neutral and good ranking, the result would be obtained in Figure 4, which shows each option's score based on the ranking and the judgment table. As we here defined the upper level and the lower level as the good 100 score and neutral 0 scores, respectively, based on the DMs opinions. It is obvious based on the presented result that there are different overall scores for each option, indicating the benefit of choosing each company over the others. HTSB, SISJ, PSB are the probable winners, respectively, with a slight difference in their scores indicates that these three would be the most probable option to be the bidding winner. As a facilitator, we need to inform the DMs that these options are almost near. It is better to look into which indicates the power of each option in different criteria.

Table of rankings

EX	BH	LL	Lorry	HDD	H/O %	PLMC-age	PLMC-rate	Info-Level	KPQ	Mob Sch	UL	Cable	EPLP	Ducts	HDD-sub
SISJ	upper	SISJ	PSB	PSB	SISJ	rec	Sub	Suf	PSB	Com	UL	Suf	Suf	Suf	Suf
upper	RESB	upper	HTSB	CLEESB	PSB	HTSB	RESB	RESB	HTSB	RESB	RESB	RESB	RESB	RESB	RESB
RESB	MTSB	RESB	upper	upper	HTSB	CLEESB	MTSB	MTSB	Strong	PSB	MTSB	MTSB	MTSB	MTSB	MTSB
lower	PSB	HTSB	RESB	RESB	upper	SISJ	PSB	HTSB	SISJ	SISJ	PSB	PSB	PSB	PSB	PSB
MTSB	SISJ	lower	MTSB	MTSB	CLEESB	old	SISJ	WESB	CLEESB	HTSB	SISJ	SISJ	SISJ	SISJ	SISJ
PSB	HTSB	MTSB	SISJ	SISJ	CLEESB	RESB	HTSB	Nsuf	Weak	WESB	HTSB	HTSB	HTSB	HTSB	HTSB
HTSB	CLEESB	PSB	CLEESB	HTSB	RESB	MTSB	CLEESB	PSB	WESB	CLEESB	WESB	CLEESB	CLEESB	CLEESB	CLEESB
CLEESB	lower	CLEESB	lower	lower	lower	PSB	NSub	SISJ	MTSB	Brief	CLEESB	Nsuf	Nsuf	Nsuf	Nsuf
WESB	WESB	WESB	WESB	WESB	WESB	WESB	WESB	CLEESB	RESB	MTSB	N-UL	WESB	WESB	WESB	WESB

Table of scores

Options	Overall	EX	BH	LL	Lorry	HDD	H/O %	PLMC-age	PLMC-rate	Info-Level	KPQ	Mob Sch	UL	Cable	EPLP	Ducts	HDD-sub
[all upper]	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
HTSB	88.58	-15.00	70.00	90.00	140.00	0.00	120.00	100.00	100.00	100.00	150.00	100.00	100.00	100.00	100.00	100.00	100.00
SISJ	85.02	115.00	70.00	120.00	50.00	80.00	135.00	70.00	100.00	0.00	50.00	100.00	100.00	100.00	100.00	100.00	100.00
PSB	84.00	-15.00	70.00	-10.00	200.00	141.00	120.00	0.00	100.00	0.00	150.00	100.00	100.00	100.00	100.00	100.00	100.00
CLEESB	66.80	-15.00	70.00	-10.00	50.00	141.00	95.00	100.00	100.00	-10.00	50.00	100.00	100.00	100.00	100.00	100.00	100.00
RESB	65.06	49.98	70.00	50.00	50.00	80.00	10.00	0.00	100.00	100.00	-60.00	100.00	100.00	100.00	100.00	100.00	100.00
MTSB	52.54	-15.00	70.00	-10.00	50.00	80.00	90.00	0.00	100.00	100.00	-60.00	-10.00	100.00	100.00	100.00	100.00	100.00
[all lower]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
WESB	-0.04	-22.50	-33.33	-40.00	-50.00	-20.00	-5.00	0.00	0.00	100.00	-60.00	100.00	100.00	-10.00	-10.00	-10.00	-10.00
Weights :		0.1017	0.0928	0.0390	0.0614	0.0434	0.0345	0.0479	0.0703	0.0569	0.0928	0.0434	0.0883	0.1017	0.0659	0.0300	0.0300

Figure 4. Table of ranking (up) and score (down) in M-MACBETH

Having the near overall scores leads us to go through the sensitivity and robustness analysis to better look into their detail and uncertainty in both options and criteria.

10. Sensitivity analysis

It compares the criteria when having variations on the overall score of the option score from 0 to 100%. There is a possibility to check a slight change in parameters and how this change affects other weights reflecting the overall result (M-macbeth, 2017). There are all HTSB, SISJ, PSB three probable winners, and by selecting show interval, it is also clear that if the score of EX increases from 10.17 to 12.6 HTSB, SISJ will take the same score at 85.8. Additionally, this change will be further for SISJ by increasing the effective criterion percentage from 0 to 100% to score over 110.

In Figure 5, is the sensitivity analysis shows when we apply weighting variation for each criterion, there is variation in the options scores. Furthermore, it can be seen that by increasing the score in the LL criterion, the highest score will start to increase gradually, and SISJ will get more scores, and in 14.1% of weight in LL, the SISJ will take the lead on this item. Also, it can be seen in the Lorry. When decreasing from 6.14% to 2.3%, the PSB would be the least in this criterion. However, this is not the case for criteria (BH, H/O%, PL&MC, Mob Sch, UL, Cable EP&LP, Ducts, and HDD-Sub) the same rate of change in the increasing direction.

Figure 5. All criteria sensitivity analysis

So the critical Item for DMs would be the item with crossing shape behaviour, which indicates that by increasing or decreasing the criterion, the score of options moves in an inverse direction (EX, LL, Lorry, HDD, PL&MC-age, info-Level, and KPO). Consequently, it is again dependent on DMs to decide which criteria should get the highest score by adjusting the scores.

11. Robustness analysis

When there are uncertainties in both criteria and options, analysing the robustness will require more confidence for an applicable model with a low level of failure. Initially, to look at the robustness analysis in the M-Macbeth, without adding any uncertainty, by turning on all the options. These include ordinal (only rank attractiveness), MACBETH (semantic judgment), and cardinal (DMs validated specific score) for all of the criteria and global information, which will give an insight into what would be the uncertainty. All the cases have partial and absolute dominance over each other when no uncertainty has been applied. As we

discussed in the sensitivity analysis, there is a need to compare the specific top three options (HTSB, SISJ, PSB), which are so near to each other shown in Figure 4.

After adding 1% of uncertainty in the global information; the cardinal indicator, 2 question mark appears in the robustness matrix, which indicates with just 1% deviation in the criteria amount there are scores changing and dominant change as well, so in this case, the HTSB cannot get the highest score. The same is happening for the second and third options, which are SISJ and PSB, respectively. However, it can be seen that there would be no dominant change between the first and the third (HTSB and PSB).

Let us add more uncertainty in the global information cardinal, and in 2%, nothing new happened while in 3%, the First and third also face dominant uncertainty. There is no need to go further while we reach the maximum uncertainty in our top three options, and further analysis in the differences profiles section is needed.

	[all upper]	SISJ	HTSB	PSB	RESB	CLEESB	MTSB	[all lower]	WESB
[all upper]	=	+	+	+	▲	+	▲	▲	▲
SISJ		=	?	?	+	+	+	▲	+
HTSB		?	=	?	+	+	+	+	▲
PSB		?	?	=	+	+	+	+	+
RESB					=	?	+	+	▲
CLEESB					?	=	+	+	+
MTSB							=	+	+
[all lower]								=	?
WESB								?	=

Global information		
ordinal	MACBETH	cardinal
☒	☒	☒ ±3% ↕

Figure 4. Robustness analysis with 3% global uncertainty

By going further in robustness analysis in can be seen EX by 6%, LL by 16%, Lorry by 9%, HDD by 12 %, PL&MC-age by 22%, and KPQ by 6 % uncertainty can cause uncertainty in the model and need to be considered as key elements in the DMs decision criteria.

12. Differences profiles

Here is the point to check the pairwise comparison between companies, which indicates each company's power in each criterion compared to a different company. By having the pairwise comparison of each option (HTSB, SISJ, PSB), we should have three unweighted and three weighted profiles. In Figure 5 (a) comparing PSB to SISJ, it can be seen that PSB gets a higher score while there are four criteria (EX, LL, H/O%, and PLMC-age) weaker in them rather than SISJ. The Same Happened between PSB and HTSB on the criteria (LL, PLMC-age, and info-Level) as well as SISJ and HTSB in Criteria (Lorry, PLMC-age, info-Level, and KPQ). DMs, later on, decide with more confidence by having these profiles analysis in their hand; Even they can change their opinion on the subjective weighting criteria.

There is an option to make the items in the order in M-MACBETH. After using that and discussing it with DMs, we decide not to use that because of the importance of the orders based on the pairwise weighting matrix. These could help them to focus on a specific criterion rather than a general ordered overview.

Figure 5. Differences profiles

13. Conclusion

In this paper, a cabling subcontractor selection for the a company in Malaysia has been considered as an empirical case-study to show the importance of having a well-established and systematic MCDA-based subcontractor selection process in construction companies (Topcu, 2004; Taylan *et al.*, 2014). The proposed approach encourages a thorough analysis of the problem and proper definition of criteria and options, followed by subjective weighting by pairwise questioning. It was possible to collected all the required information and use the M-MACBETH software successfully.

Results show that there would be three options with a near score at the top of the score table so that some other parameters could change the decision result, and this would be upon the DMs decision to select which one. At this stage, the sensitivity analysis and robustness analysis performed, which indicate the EX, LL, Lorry, HDD, PL&MC-age, info-Level, and KPQ, need to consider as critical criteria. Next, in robustness analysis which shows by having 1% and 3% of uncertainty in criteria subjective weighting (pairwise), there would be dominant shifting in our options. Also, EX by 6%, LL by 16%, Lorry by 9%, HDD by 12 %, PL&MC-age by 22%, and KPQ by 6 % uncertainty can change the model confidence by making the dominant first option uncertain.

Next, by profile assessment of the top three options, it can be obtained there are specific criteria which companies have differences in both unweighted and weighted profiles. However, the final decision based on these indicators could be upon the DMs point of view and their specific need or even based on some unknown or hidden criteria that we can call the company or personal concerns. These procedures can redo as much as the main company's DMs reach consensus in one option.

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