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BENEFIT/COST MODEL FOR EVALUATING PREVENTION THROUGH DEISGN (PTD) SOLUTIONS

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Abstract: Research has shown a significant association of construction fatalities with design decisions, and Prevention through Design (PtD) has been hailed as an effective tool for the prevention of injuries on construction sites by addressing hazards during the design phase. The European Union (EU) identified this link and in 1989 enacted legislation requiring member countries to start practicing PtD. Attempts to enact similar legislation in the United States have failed, and efforts to encourage designers to practice PtD in the general construction industry have not been very successful. Previous research has shown that in order to generate traction for PtD, it is essential to target owners since they are seen as the industry group with the most influence for PtD. More importantly, the method with which that interest for PtD can be generated is by proving the business case. An evaluation and comparison of benefits and costs can be instrumental to encourage owners to demand PtD practice from their designers. This paper describes the use of a multi-criteria analysis decision tool to evaluate between PtD solutions and traditional construction using two test cases. The line items used in the decision making tool were developed using the Delphi method, and the test cases were evaluated using input from industry professionals.

1 INTRODUCTION

The US construction industry continues to claim about 1000 lives a year in the US. The latest figures released for 2017, indicate that the US construction industry had 971 fatalities with an incidence rate of 9.5 per 100,000 full-time equivalent workers (BLS 2019). The Prevention through Design (PtD) concept holds some promise and has potential to eliminate some of the fatalities since it aims to remove hazards from construction sites by considering construction site hazards during the design phase. Prior research by Behm (2005) has shown that there is a connection between design decisions and construction site fatalities, where 42% of investigated fatalities were linked to design. The ability to influence safety was theorized by Szymberski (1997) to be the greatest early in the life of a project, i.e. during the conceptual and design phases. As an extrapolation to that theory, it can be suggested that the cost of incorporating safety is the smallest in the earlier phases of a project as well (Biddle 2013, Malcolm 2008). Thus it is important to compare alternatives and determine if PtD decisions are, in reality, more cost effective compared to traditional construction solutions. This paper aims to describe a method for comparing between design alternatives, and help in the decision for choosing PtD over other solutions, based on a business case approach using Mutli-Criteria Analysis (MCA).

2 BACKGROUND

Previous research has identified that there are perceived economic obstacles for incorporating PtD in the design phase (Tymvios et al. 2016a), with 61.5% of architects and engineers surveyed in a US national survey stating that there are economic obstacles for PtD implementation in the US construction industry. That percentage for owners and contractors was 43% and 50.3%, respectively. A Delphi Panel that was convened to determine the direction for implementing PtD in the US (Tymvios et al. 2016b), established that the "Business Case Method" needed to be implemented to achieve that goal, and the group that needed to be targeted is the "Construction Facility Owners."

The term "Business Case" has many definitions. According to Biddle (2013), a business case thinking and mindset should be answering the question "What is it in for the company?" A Business case for PtD should therefore be answering that question by providing evidence that implementing a PtD solution is more beneficial than not implementing it or implementing traditional practices that might not be considered as PtD. There is definitely a need for investigation of the relationship between PtD and construction project business measures, as suggested by Gambatese (2013), where he recommends that representative case study models be prepared and presented to US construction industry stakeholders in order to encourage PtD practice in the US.

3 METHODOLOGY

3.1 BUSINESS CASE LINE ITEMS

In a previous investigation (Tymvios et al. 2016b) using the Delphi method, industry professionals assisted in the creation of a list of line items that can be used to determine pros and cons between PtD solutions or options. The Delphi panelists were initially asked to identify benefits and costs (monetary and non-monetary) that implementing PtD solutions would impose to Facility Owners, Architects, Engineers, and Contractors. The line item costs and benefits were grouped into broad categories that included: Design, Personnel, Construction, Management, Post-construction, Market, Contracts, and Insurance/Liability. The panelists were also asked to respond regarding whether these costs and benefits would be incurred on just one project or on multiple projects, but the 14 panelists participating did not achieve consensus on all the line items regarding their impact on a single or multiple projects. These line items can be very subjective and depend on a project's characteristics; it is difficult to distinguish them in such a binary method (Tymvios et al. 2016b). These line items can be observed in Figures 4 and 5 that show the case studies investigated. Many of the line items were intangible by nature and speculative, and a direct comparison between them was difficult. For that reason an MCA method was necessary in order to compare the effects of each line item on a project, and to assist in evaluating alternatives.

Since the panel members identified the line items as either positive or negative, the line items were turned into neutral statements as in the example that follows:

> Line item identified by Delphi panel: *"Potential for increased amount of RFI requests"*
>
> Neutral line item used in the model: *"Number of RFI requests (Increase/Decrease)"*

In addition, the identified line items included future speculations that are difficult to estimate such as "Potential for litigation," and items such as "Morale of construction crews" and "Quality of recruited workforce" are abstract terms with no tangible dimension attached to them. For this reason, it is necessary to modify the criteria to have a universal dimension.

3.2 MCDM METHOD

To compare between alternatives, multi-criteria decision-making (MCDM) methodologies were evaluated for the best one to use. There are multiple types of methods that can be broadly divided into discrete methods and continuous methods. Continuous methods require mathematical programming with multiple objective functions, while discrete methods use a set of decision alternatives that has been predetermined (Triantaphyllou 2000). Because of the complexity of the continuous methods, a model for the decision analysis between PtD alternatives using discrete MCDM method was chosen, which is more practical in nature. For this model, the Weighted Sum Method (WSM) was chosen, the most widely used MCDM for MCA.

As defined by Triantaphyllou (2000), all MCDM methods can be compressed into a matrix format as shown in Figure 1. As observed, the set of “A” values from 1 to m refers to the decision alternatives to be evaluated; the set of “C” criteria from 1 to n refers to the decision criteria used to evaluate the various alternatives. In these case, the decision criteria are the line items identified by the Delphi Panel. Each criterion is associated with a weight of importance that is shown in Figure 1 with “w” ranging also from 1 to n; the number of criteria. In MCDM methods, it is assumed that the “weight of importance” values are already determined by the person performing the evaluation (Triantaphyllou 2000; Triantaphyllou et al. 2005). The a_{ij} values in the matrix refer to the impact the criteria would have on an alternative.

CRITERIA

	$\mathbf{C1}$	$\mathbf{C2}$	…	$\mathbf{C_n}$
Alt.	$\mathbf{w_1}$	$\mathbf{w_2}$	…	$\mathbf{w_n}$
$\mathbf{A_1}$	$\mathbf{a_{11}}$	$\mathbf{a_{12}}$	…	$\mathbf{a_{1n}}$
$\mathbf{A_2}$	$\mathbf{a_{21}}$	$\mathbf{a_{22}}$	…	$\mathbf{a_{2n}}$
⋮	⋮	⋮	⋱	⋮
$\mathbf{A_m}$	$\mathbf{a_{m1}}$	$\mathbf{a_{m2}}$	…	$\mathbf{a_{mn}}$

Figure 1: Typical MCDM matrix for MCDM methods

The WSM can only be applied to single-dimensional comparisons. These are comparisons where alternatives are compared with only one variable. In order to avoid this limitation it is suggested that the dimensions be replaced by equivalent ranking values. The performance of each alternative is measurable and it is the same unit for all alternatives and all criteria. The alternative with the highest value is the one to choose. The overall score for the solutions was calculated using Equation 1 (Triantaphyllou 2000).

$$[1]\ A_i = \sum_{j=1}^{n} a_{ij} w_j$$

The use of this method is simple, but it becomes more complicated when it is applied to multi-dimensional evaluations. With the introduction of a ranking system for the dimensions, instead of the actual units, the problem can be avoided (Garber et al. 2002). In this model, and as shown in Equation 1, for each “Business Case” line item, two values needed to be determined; “Impact” and “Importance” factors.

3.3 IMPACT AND IMPORTANCE FACTORS

Impact factors allow individuals who evaluate various options to assign a numerical value of the “impact” each line item for a PtD alternative would have on the project when compared to a traditional non-PtD solution. The range of the Impact Factor values was defined with a seven point scale, ranging from -3 to 3. An Impact Factor value of 3 suggests that the line item for the PtD solution is extremely favorable when compared to the line item of the traditional solution. An Impact Factor value of -3 suggests that the line item for the PtD solution is extremely unfavorable when compared to the line item of the traditional solution. Finally a “0” value suggests that the line item for the PtD solution has the same impact when compared to the traditional solution.

This scale facilitates the comparison targeted in the model. Because each PtD solution to be implemented on a project is compared to traditional measures, a negative Impact Factor suggests that the PtD solution affects the project negatively when compared with traditional means and methods of construction. A positive Impact Factor suggests that the PtD solution affects the project in a positive way. The Impact Factor values are equivalent to the a_{ij} values in the dimension matrix in Figure 1. The impact factors for each item are subjective and the end users of the model would have to use their best judgment and experience for determining these values. The use of the impact factor facilitates converting all of the various criteria dimensions into one dimension.

The equivalent to the weight of importance “w” shown in Figure 1 is the “Importance Factor”. The range of the Importance Factor values was defined with a five point scale ranging from 0 to 5, where a value of 0 has no importance and 5 has great importance for the owner.

Of the criteria considered in the model, only the criterion associated to costs has a comparable monetary impact that can be easily measured. For that reason, the Impact Factor in the model was determined by comparing costs between alternatives as shown in Table 1.

Table 1: Impact Factor Values for Design and Construction Costs

Percentage in savings from more expensive option	Impact Factor
Greater than 200% in savings	5
Savings between 150% and 200%	4
Savings between 100% and 150%	3
Savings between 50% and 100%	2
Savings between 0% and 50%	1
No savings	0

The steps used in the model are summarized in Figure 2, and the model was completed using a spreadsheet that is shown in Table 2. The solutions are first identified, and an estimate for the design and construction costs is developed. For each of the solutions and for each line item the Impact Factors are rated, followed by the Influence Factors. The total score is calculated automatically and the solution with the highest score is the one to choose, i.e., is evaluated as having the greatest benefit to cost ratio.

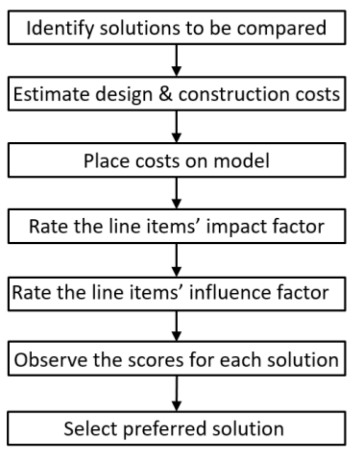

Figure 2: Steps for Completing the “Business Case” Model

4 CASE STUDIES

To test the functionality of the model, two case studies were identified and conducted. The first case study involved a real project in a Detroit plant where a PtD solution was implemented, and the other involved a building construction project in Portland, Oregon, where the PtD solution was not implemented.

4.1 CASE STUDY 1 – PRE-ASSEMBLED CABLE TRAYS

The first case study involved the benefit/cost analysis of cable tray assemblies at the Detroit Edison Monroe Power Plant (PP) Flue Gas Desulfurization (FGD) Units 1 and 2. The assemblies were part of work for the retrofit of the aging PP that involved the replacement of the FGD system to provide increased reliability and sulfur removal efficiency. The cable trays were necessary to support the system, and carry all the ductwork necessary for its operation. Babcock & Wilcox power generation and URS Corp. provided the engineering, procurement, and construction of the FGD system, and URS provided the engineering, procurement and construction of the absorber buildings (URS Corp. 2011; B&W 2019). URS designed and constructed the cable trays in the case study and the design personnel considered alternatives to the traditional (stick built) on site cable trays. The personnel came up with the solution of preassembled cable trays that were built offsite, transported to the site, and then lifted into place. URS Corp. developed a detailed estimate for the stick built solution, and tracked the engineering and construction costs for the preassembled solution (URS Corp. 2012).

Shown in Table 3 is a summary of the comparison of the direct costs of the two solutions, which was provided by URS Corp. The workforce that was required for the preassembly included electricians and ironworkers. The engineering cost involved the design and layout of the trays, and no additional design cost was included for the stick built solution since the designs were replicated from other similar buildings in the facility. The material costs were approximately the same, with the preassembled trays needing some additional material for fastening the trays to the overhead beams. Designers working for URS were contacted and asked to fill out the spreadsheet from the viewpoint of the owner. Their responses are shown in Figure 4. All Impact Factors for option B are zero in this case because option B is the traditional solution.

Table 3: Cost comparison for alternatives (Case Study 1)

Cost category	**Preassembly**	**Stick built**	**Difference**
Craft hours	1300	7910	6610
Craft related costs	$79,812	$477,391	$397,579
Material and assembly costs	$142,408	$132,389	($10,019)
Engineering hours	743 (to develop design of trays)	0 (original design based on typical details)	($743)
Engineering costs	$92,292	0	($92,291)
Total costs	**$314,511**	**$609,780**	**$295,269**

The monetary costs were vital to the project and given an Importance Factor of 5. Within the personnel list of line items, only two items were scored in terms of impact: owner personnel training and hiring of additional personnel. Their importance was relatively low and they were given an Importance Factor of 1. None of the line items within the “owner time commitments” received any impact value. Both construction and design time received a value of 5 for importance, but they differed in the impact value. Design time received a value of -2, while construction time received a value of 3. The design Impact Factor was negative due to the increased time for design, while the construction time value was positive because of the reduced construction time.

The items under the category project issues received a variety of impact and importance values. The most notable item was the Importance Factor value for worker productivity (5). The designers rated that item with a high value since construction time for the project was critical. The PtD solution received an impact value of 2, suggesting that there were gains associated with the solution and the productivity of the crews. All the line items under the safety category received a positive value for impact, suggesting that there were gains in safety with the PtD solution. The importance factors for the safety line items were between 4 and 5, values that imply safety concerns were important on the project. All the items under litigation/insurance received a positive value for impact, except the item “owner furnished insurance” which was given a value of 0. The importance factor given for all of these items ranged from 1 to 3. The items under the “Post Construction” category received impact values ranging from 0 to 2 while their importance factors were between 1 and 3. The items under the marketability category received 0 for impact except “number of bidding contractors” which received a -1. The marketability category importance factors were between 1 and 3. The overall score for Option A, the PtD solution, was calculated using the method discussed earlier and received a score of 78. The traditional solution received no points. This score suggests that the PtD solution was the best choice between the two. If the score for Option A was negative, then the PtD would not have been favorable. In cases where the scores for the two options are equal, then both solutions are ideal. In such cases the user would need to decide based on other factors that are not listed on the model.

This is a Benefit/Cost analysis for the Owner to decide whether to proceed with a PtD solution			
Option A: Cable Trays - Preassembly - PtD Solution A Option B: Cable Trays - Stick Build - Traditional Solution			
	Option A PtD solution A Impact Factor	**Option B** Traditional Solution Impact Factor	**Importance** **Factor**
Design& Construction Costs			
Design Costs	$ 92,291.00	$ -	5
Construction Costs	$ 222,220.00	$ 609,780.00	
	$ 314,511.00	$ 609,780.00	
	% Difference	% Difference	
	-94%	94%	
Personnel			
Need for Owner Personnel Training	1	0	1
Need of hiring additional personnel	1	0	1
Quality of recruited workforce	0	0	1
Staff Retention	0	0	1
Owner Time Commitments			
Owner commitment for meetings & coord. (Increase/Decrease)	0	0	2
Owner commitment for site visits (Increase/Decrease)	0	0	2
Owner time for drawing/specs reviews (Increase/Decrease)	0	0	3
Construction/Design Time			
Design Time (Increase/Decrease)	-2	0	5
Construction Time (Increase/Decrease)	3	0	5
Project Issues			
Number of RFI requests (Increase/Decrease)	2	0	3
Complexity of Bidding contract (Increase/Decrease)	-1	0	3
Complexity of awarding contract (Increase/Decrease)	-1	0	2
Complex. of manag. Constr. contract (Increase/Decrease)	2	0	3
Maturity of contractors & workers	0	0	1
Worksite productivity	2	0	5
Relationships between Designers and Contractors	1	0	1
Worksite Organization	1	0	1
Safety			
Overall Construction Safety	3	0	5
Number of workers on site	1	0	4
Costs/Savings from safety concerns	1	0	4
Litigation/Insurance			
Potential for litigation	1	0	1
Potential for workers' compensation	2	0	3
Owner furnished insurance costs	0	0	1
Owner inherent liability via designers (Increase/Decrease)	1	0	2
Blurs of lines between "Design" and "Build"	1	0	1
Post Construction			
Sustainability of final capital assets (Improved/Worsened)	1	0	3
Overall potential of project quality (Better/Worse)	2	0	3
Life cycle of capital assets (Increase/Decrease)	0	0	1
Maintenance/operation costs	1	0	3
Ease of facility operations with safety in mind	0	0	3
Marketability			
Morale for construction crews	0	0	1
Owner image to the general public	0	0	3
Number of bidding contractors (Increase/Decrease)	-1	0	3

	Option A	**Option B**
Total =	**78**	**0**

Figure 4: Benefit/Cost analysis (Case Study 1)

4.2 CASE STUDY 2 – INCREASED PARAPET HEIGHT

The second case study involved the benefit/cost analysis of constructing two types of parapets at the edge of a roof under construction. The two parapets had a height of 30.5 cm (12in) and 99 cm (39in) respectively. In this case the 39in parapet is the PtD solution, while the 12in parapet is the traditional solution. A height of 39 in is the minimum OSHA requirement for any work to be performed without the use of a temporary protection barrier. The roof had an area of 929 m2 (10,000 ft2). Information for this case study was collected from an article by Rajendran et al. (2013) and through personal communications with Dr. Rajendran who worked as a safety supervisor for the contractor on the project.

The construction project was located in the Portland Metro area and was a physical plant building, part of a medical facility that housed an emergency power room, a normal power room, a chiller room, a boiler room, and a control room (Rajendran et al. 2013). The 12in parapet was designed for the building, while the possibility for the 39in parapet was only considered by the authors.

Information about the two options was gathered from the subcontractors involved in the project through Requests for Information (RFI). The three subcontractors were the walls and ceilings contractor, the roofing contractor, and the exterior skin contractor. Because a shorter parapet requires the installation of permanent roof anchors on the roof, information for the cost of these anchors was collected from the firm that produces the anchors and the contractor that installs them (Rajendran et al. 2013).

Construction personnel were interviewed to determine time and effort requirements for the installation of the temporary fall protection equipment. The material cost for these fall protection measures was obtained through vendors that rent them. The labor cost for the workers necessary to install the equipment was obtained from the specific contractors involved. The authors also accounted for delivery costs, hoisting, and any necessary training needed for the protective measures on site (Rajendran et al. 2013).

The authors also asked the facility's designer whether there would be additional cost for the design of a taller parapet. The designers indicated that there would be no difference in design costs between the two parapet heights (Rajendran et al. 2013). Figure 5 shows the completed spreadsheet for the case study as completed by Dr. Rajendran. He was asked to complete the spreadsheet from the viewpoint of the owner, and because of the close working relationship that he had with the owner organization, he was able to do so.

Under the category safety, the "overall construction safety" and "cost/savings from safety concerns" items each received an Impact Factor of 3 and an Importance Factor of 1. Continuing with the post-construction category, "maintenance/operations costs" and "ease of facility operations with safety in mind" received Impact Factor of 2 and Importance Factors of 1. Lastly under marketability, the "morale" line item received an Impact Factor of 3 and an Importance Factor of 1.

The overall score for the PtD solution was 42, while the score for the traditional solution was 25. Even though the traditional solution received a lower score, it was less expensive than the PtD solution. At the time of construction the owner only considered monetary cost in the decision for the parapet height, and as a result the shorter parapet was constructed. In addition the taller parapet was not considered during design.

This is a Benefit/Cost analysis for the Owner to decide whether to proceed with a PtD solution			
Option A: PtD solution 39in Parapet Option B: Traditional solution 12in Parapet			
	Option A PtD solution A Impact Factor	**Option B** Traditional Solution Impact Factor	**Importance** **Factor**
Design& Construction Costs			
Design Costs	$ -	$ -	5
Construction Costs	$ 44,028.00	$ 5,025.00	
	$ 44,028.00	$ 5,025.00	
	% Difference	% Difference	
	776%	-776%	
Personnel			
Need for Owner Personnel Training	3	0	5
Need of hiring additional personnel	3	0	4
Quality of recruited workforce	0	0	4
Staff Retention	0	0	3
Owner Time Commitments			
Owner commitment for meetings & coord. (Increase/Decrease)	0	0	1
Owner commitment for site visits (Increase/Decrease)	0	0	1
Owner time for drawing/specs reviews (Increase/Decrease)	0	0	1
Construction/Design Time			
Design Time (Increase/Decrease)	0	0	1
Construction Time (Increase/Decrease)	-3	0	1
Project Issues			
Number of RFI requests (Increase/Decrease)	0	0	1
Complexity of Bidding contract (Increase/Decrease)	0	0	1
Complexity of awarding contract (Increase/Decrease)	0	0	1
Complex. of manag. Constr. contract (Increase/Decrease)	0	0	1
Maturity of contractors & workers	0	0	1
Worksite productivity	3	0	1
Relationships between Designers and Contractors	0	0	1
Worksite Organization	2	0	1
Safety			
Overall Construction Safety	3	0	1
Number of workers on site	0	0	1
Costs/Savings from safety concerns	3	0	1
Litigation/Insurance			
Potential for litigation	0	0	1
Potential for workers' compensation	0	0	1
Owner furnished insurance costs	0	0	1
Owner inherent liability via designers (Increase/Decrease)	0	0	1
Blurs of lines between "Design" and "Build"	0	0	1
Post Construction			
Sustainability of final capital assets (Improved/Worsened)	0	0	1
Overall potential of project quality (Better/Worse)	0	0	1
Life cycle of capital assets (Increase/Decrease)	0	0	1
Maintenance/operation costs	2	0	1
Ease of facility operations with safety in mind	2	0	1
Marketability			
Morale for construction crews	3	0	1
Owner image to the general public	0	0	1
Number of bidding contractors (Increase/Decrease)	0	0	1

	Option A	**Option B**
Total =	**42**	**25**

Figure 5: Benefit/Cost analysis (Case Study 2)

5 CONCLUSIONS AND LIMITATIONS

The benefit/cost model that was developed favored both PtD solutions that were evaluated. In the first case study, URS engineers designed and supervised construction of the cable trays with construction safety in mind. URS has a PtD program and promotes construction worker safety during design (Zagres et al. 2008). As a result the PtD solution was evaluated after it had been designed and constructed. The second PtD solution was the result of an independent study of construction methods at a Portland area construction site, where the author was supervising construction safety for the contractor. The PtD solution was not constructed because it was not designed in the building in the first place (Rajendran et al. 2013).

Only two solutions have been evaluated with the decision spreadsheet as part of this research. The model requires validation for it to be used confidently in a professional setting. It is suggested that more PtD projects be added to the evaluation in order to ensure that the model is adequate and correct in assessing the various solutions to be implemented in a construction project. In addition there is a possibility that some bias was contained in the case studies discussed in the manuscript, since they were evaluated by personnel that are champions in the field of PtD.

These additional evaluations would help determine if the line items adequately address the concerns for PtD costs and carefully assess the benefits. It is expected that many of the line items would have similar impact values for various projects and with subsequent evaluations these would be identified and grouped together, thus reducing the amount of input required by the users of the model.

It is also possible that more benefit and cost items can be added to the model. The Delphi panel that identified the items listed might have overlooked items that could be identified only after subsequent use, implementation and evaluation of the model by multiple individuals.

For the validation of the model the authors suggests that a sensitivity analysis be conducted, once more projects are evaluated with the model.

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