

A Decision Model for Technology Selection in Renovation Project Planning

Shu-Chien Hsu¹ and Qingbin Cui²

¹ Graduate Research Assistant, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD, 20742, Ph. (301) 405-7768; E-mail: markhsu@umd.edu

² Assistant Professor, Department of Civil and Environmental Engineering, University of Maryland, College Park, MD, 20742, Ph. (301) 405-8104; Fax: (301) 405-2585; E-mail: cui@umd.edu

Abstract

As infrastructure ages, a significant portion of US capital expenditure is incurred for the renovation and retrofit of existing facilities. Renovation projects are complex, high risk, and involve extensive coordination and planning, primarily due to uncertain site conditions and continuing operation requirements of existing facilities. Early studies have identified innovative and emerging technologies that facilitate site investigation and align renovation and maintenance activities with business production and operation schedules. However, the selection of appropriate technologies in specific project and business environments remains a challenge. Particularly, there is no guidance for project teams who must incorporate the selected new technologies into scope management and project planning. This paper establishes a framework to guide project teams towards appropriate technology selection in renovation project planning. A decision model is developed to integrate the technology selection process into a widely used scope management tool, Project Definition Rating Index (PDRI). The model is specially designed and flexible enough to allow project teams to decide appropriate technologies according to various criteria, including cost, application area, and risk mitigation.

Keywords: Renovation, Project Planning, Project Definition Rating Index, Technology Selection, Decision Model

1. Introduction

A large volume of construction work has been carried out during the past decade in renovation projects in the United States. According to a survey conducted by the Construction Industry Institute (CII), approximately 30% of project funds spent by CII member companies were allocated for renovation and maintenance of existing facilities (CII 2009a). Nationwide, the U.S. Department of Commerce estimated that nonresidential renovation projects account for hundreds of billions of dollars annually (USDOD 2009). Consequently, a large volume of contractor work is in the renovation arena as well. As the US is taking steps to improve energy efficiency and combat global warming, the renovation construction market is widely anticipated to grow rapidly to meet the constantly increasing demand for energy efficient facilities.

Renovation projects, also named retrofit, revamp, rehabilitation, maintenance, turnover, upgrade, overhaul, reconstruction, or brownfield projects, tend to be smaller in size than typical greenfield projects. However, individual renovation projects can be quite large. In renovation projects, unique or increased risks associated with cost,

schedule, or quality appearance are not generally present in greenfield projects. The initiation of a renovation project usually involves a long process of contemplation under conditions of high uncertainty. The conditions of the existing site and in-place equipment are typically unknown. Older facilities often have unusual safety hazards, uncertain spatial characteristics such as unseen interferences, outdated or inaccurate existing condition information, legacy environmental conditions, architectural or historical concerns, or issues with dismantling or demolition.

It is arguable that these risks involved in renovation projects could be reduced in the Front End Planning. Front End Planning is defined as “the process of developing sufficient strategic information with which owners can address risk and decide to commit resources to maximize the chance for a successful project” (Gibson and Pappas 2003). CII research indicates that well-performed front end planning can reduce costs, lead to less project variability in terms of cost, schedule and operating characteristics, and increase the chance of meeting project’s environmental and operational goals. This previous research has led to tools such as the Project Definition Rating Indexes (PDRI), and the Alignment Thermometer to help teams more effectively plan projects. Additional research also has identified a few new technologies such as Penetrating Radar, 3D Laser Scanning, and Rapid Prototyping etc., that can improve the accuracy of condition investigation. However, it is still a challenge for project teams to select appropriate technologies and apply them on a renovation project because of the lack of effective tools for decision making.

This paper aims to develop a decision model to facilitate the selection process on site condition investigation technologies in renovation projects. The paper starts with a review on the scope definition rating tool PDRI and Project Condition Investigation (PCI) Technologies. Then, the paper defines the characteristics of PCI technologies and their relationships with the PDRI elements. Furthermore, a decision model is presented that combines the PDRI sheet with site condition investigation technologies. Finally, a case study is discussed to illustrate the application of the model.

2. Project Definition Rating Index

A poorly defined project can undergo considerable changes that may result in cost overruns and a greater potential for disputes (Gibson and Kaczmarowski 1995, Dumont et al 1997). The PDRI for construction projects is developed by CII as a powerful and easy-to-use tool that provides a method to measure project scope definition for completeness. It identifies and precisely describes each critical element in a scope definition package and allows a project team to quickly predict factors impacting project risk (Dumont et al 1997). The PDRI allows a project planning team to quantify, rate, and assess the level of scope definition on industrial construction projects prior to authorization for detailed design or construction. It is intended to evaluate the completeness of scope definition at any point prior to detailed design and construction.

The PDRI offers a comprehensive checklist of 70 scope definition elements in an easy-to-use score sheet format. Each element is weighted based on its relative importance to the other elements. Since the PDRI score relates to risk, those areas

that need further work can be easily isolated. Applicable industrial-type projects may include the following: Oil / Gas production facilities, Textile mills, Chemical plants, Pharmaceutical plants, Paper mills, Steel/Aluminum mills, Power plants, Manufacturing facilities, Food processing plants, Refineries, Civil/Industrial Infrastructure, and Plant upgrade/retrofit (CII 2009b).

There are three main sections of PDRI; each of them is broken down into a series of categories, which, in turn, are further broken down into elements. Adding the individual element evaluations and their corresponding weights leads to a single PDRI score for the project, which can range from zero to 1000. The lower the total score, the better definition of a project. The PDRI target score is 200 points. In other words, the project scope could be considered to be well defined if the PDRI score is below this benchmark. Nevertheless, it should be noted that the PDRI alone does not ensure project success but should be coupled with sound business planning, alignment, and good project execution to greatly improve the probability of meeting or exceeding project objectives (CII 2009b).

3. Emerging Technologies for Project Condition Investigation

New and emerging technologies and tools have great potential to help project teams mitigate risks associated with unknown existing site and equipment conditions or other factors (Rosenfeld and Shohet 1999). A number of PCI cards, which have been developed, document some of the tools currently in use. For each of the tools, the PCI cards cover the following topics: Tool Name, Alias, Description, Service Fee, Benefits/Features, Application Areas, Service Providers, Equipment Suppliers, and Other Issues.

Existing facility conditions pose a unique risk issue for renovation projects. Unknown subsurface conditions, facility configuration, and degraded equipment or systems can threaten the successful completion of a renovation project. Effective front end planning requires the project team to perform a comprehensive assessment of existing site and equipment conditions (CII 2009a). The assessment must be based on a detailed investigation of six categories of project conditions, which are shown below in Table 1.

4. Model Development

As the PCI technologies provide potential to improve project planning, research effort is needed to integrate the PCI technologies into the successful front end planning process. Especially, the integration process must consider that fact that project teams may have very different demands. For instance, some teams may identify their problems well and need a tool to help them to select appropriate PCI technologies, while others may not fully understand the site condition, or they are willing to try new technologies in their projects. Therefore, this model is specially designed to satisfy project teams' needs and defines three levels of technology selection processes, namely problem-oriented, risk-oriented and technology-oriented. Accordingly, decision criteria for technology selection are identified as application area, risk mitigation, cost effectiveness measured by performance over cost ratio, and technology match. The framework of the Decision Model for Technology Selection (DMTS) is shown in figure 1. The following sections will describe how

the proposed model facilitates project teams with PCI technology selection on renovation project planning.

Table 1: Application Areas of PCI technologies (CII 2009a)

Application Areas	Scope of Areas	Example Technologies
1. Underground Conditions	Underground or embedded utilities, structures, and other unknowns are potentially dangerous and expensive to address if found during construction.	Ground Penetrating Radar, Electromagnetic Conductivity.
2. Integrity	The current condition of existing mechanical and electrical systems, structures, and their components must be assessed in terms of their fitness for further use.	Ultrasonic Testing, Hydrostatic Isolation Technologies.
3. Restricted Access	Renovation projects many times involve tasks that must be performed in restricted or difficult areas due to safety hazards (e.g. elevation, temperature, radiation, hazardous chemicals etc.), and/or inherent security issues.	3D Laser Scanning, Photogrammetry, Rapid Prototyping.
4. Spatial Relationships	Existing facilities and equipment may have incomplete or inaccurate design or as-built documentation, or dimensions may have changed since original installation.	3D Wind Tunnel Modeling, Real-Time GPS Monitoring System.
5. Risk Identification	Unique and increased risk issues for renovation projects require detailed analysis and recognition of various uncertainties during Front End Planning.	Infrared Scanning, Liquid Penetrant Inspection.
6. Environmental Constraints	Renovation projects may require additional environmental considerations due to existing conditions such as soil conditions, endangered species, noise, dust etc.	Mass Spectrometers, Site Characterization and Analysis Penetrometer System.

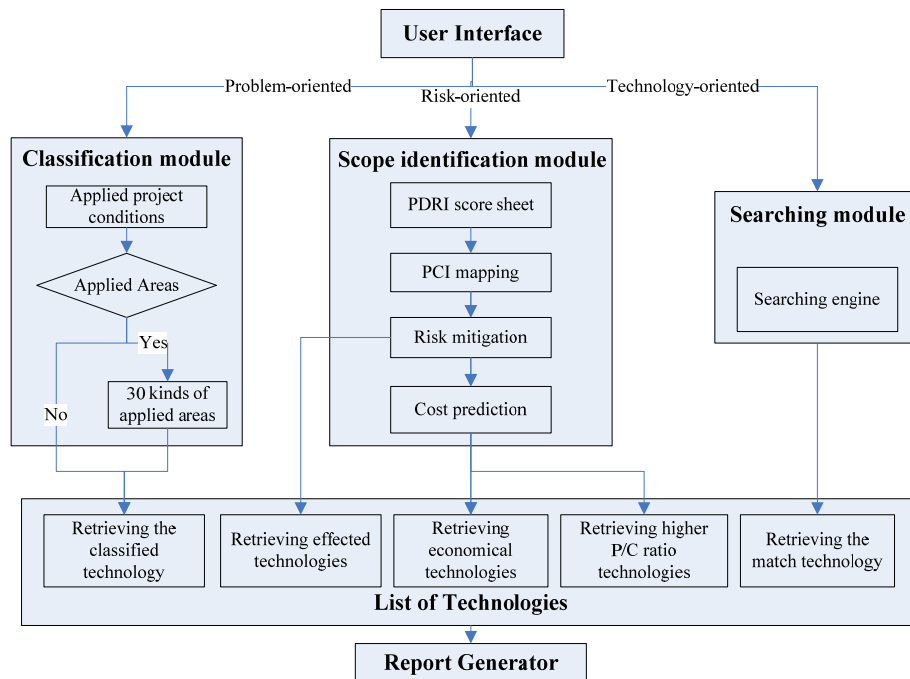


Figure 1: The framework of DMST

4.1 Problem-Oriented Decision Structure

Twenty-four (24) PCI technologies identified from previous studies (CII 2009a) have been integrated into the DMTS model. The model also allows project teams to add more emerging PCI technologies. Two decision criteria are formed at this level to classify PCI technologies, namely applied project condition and application area. Applied project conditions consist of six categories as described in section 3. Application areas, on the other hand, document 30 types of project areas where the PCI technologies could apply. When a project team is aware of project condition and has already identified risky areas, the model allows them to follow a logic procedure to locate one or several matching PCI technologies.

At this level, a project team must have conducted detailed front end planning and identified a specific condition (problem, situation, need). For example, Ground Penetrating Radar will be shortlisted when the project team identifies underground or integrity as an applied condition on the project. The results can be improved if project teams are able to define the application areas of the project condition. Application areas could be subsurface survey, structural mapping, forensic investigation or infrastructure characterization, etc. Otherwise, a shortlist of potential PCI technologies that match the applied condition is generated based on the input from previous step. Figure 2 illustrates the decision process for a PCI technology Ground Penetrating Radar. This process can be easily coded into Microsoft Excel as follows.

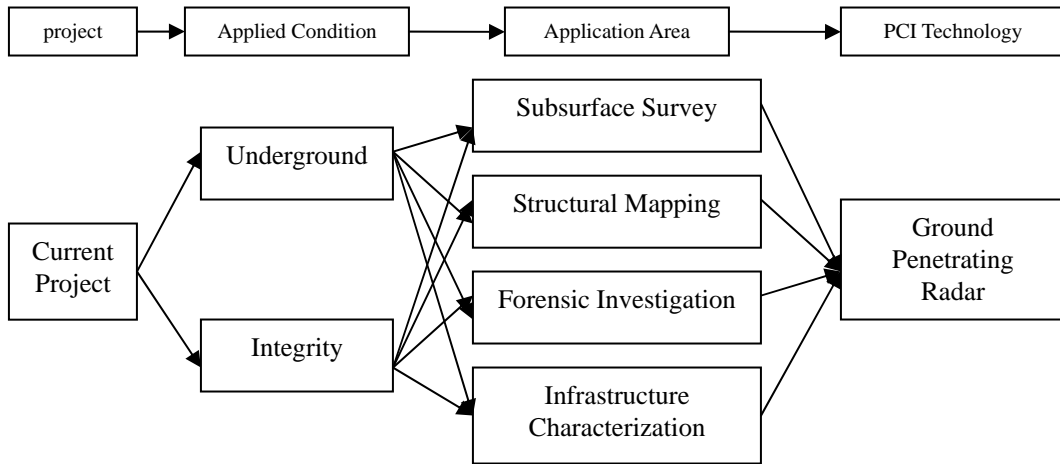


Figure 2: Classification process of Ground Penetrating Radar

=IF(AND(APC=a, OR(AA=1,AA=2,AA=3,AA=4,AA=5)),"Ground Penetrating Radar", IF(AND(APC=b, OR(AA=1,AA=2,AA=3,AA=4,AA=5)),"Ground Penetrating Radar", "")) (1)

APC = Applied Project Conditions

AA = Application Areas

a = Underground

b = Integrity

1 = Users don't know the application area

2 = Subsurface Survey

3 = Structural Mapping

4 = Forensic Investigation

5 = Infrastructure Characterization

4.2 Risk Oriented Decisin Structure

4.2.1 PDRI rating calculation

At this level, the DMTS model helps project teams mitigate project risks by incorporating technology selection with front end planning process. The team must conduct a PDRI analysis on the renovation project before the technology selection process. After the PDRI analysis is complete, the team will get a series of definition levels that cover all PDRI elements. The series can be defined as π^A , which is a 70x6 matrix for industrial renovation projects. We can define the PRDI scores matrix π^B , a 70x6 matrix, where rows of the matrix represent PDRI elements, and columns representing the scores of definition levels. A project rating matrix π^C , therefore, can be calculated by an element-by-element multiplication between matrix π^A and matrix π^B , also called dot multiplication or Hadamard Product. See equation 2 below.

$$\pi^A = \begin{bmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix}, \pi^B = \begin{bmatrix} 0 & 1 & 12 & 23 & 33 & 44 \\ 0 & 1 & 8 & 14 & 24 & 27 \\ 0 & 2 & 8 & 14 & 20 & 26 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \pi^C = \pi^A \cdot \pi^B = \begin{bmatrix} 0 & 0 & 0 & 23 & 0 & 0 \\ 0 & 0 & 0 & 14 & 0 & 0 \\ 0 & 0 & 8 & 0 & 0 & 0 \\ \dots & \dots & \dots & \dots & \dots & \dots \end{bmatrix} \quad (2)$$

A final PDRI rating score for a project can be generated. If p is the PDRI total score for a given project at a certain stage, it is equal to the multiplication of the project rating matrix π^C with two unit matrix (vectors), J^1 and J^2 . A unit matrix is an integer matrix consisting of all 1s. The dimensions of J^1 depend on the level of π or the dimension of π^C and π^B . For a industry project, J^1 is a 1x70 vector and $J^2 = [1,1,1,1,1,1]^T$

$$p = J^1 * \pi^C * J^2 \quad (3)$$

4.2.2 Mapping PCI technologies with PDRI

One of the key features of the DMTC model is to integrate technology selection into the scope management process. Especially, each PCI technology is evaluated in terms of the effectiveness of reducing risks associated with site condition and continuous operation requirements. The evaluation addresses all elements in PDRI worksheet and their scales that the PCI technology could make an improvement.

Three levels of improvement are considered in the evaluation to map project's definition level, namely no improvement, minor improvement, and major improvement. If the PCI technology is not applicable to the PDRI element or has no significant impact on improving project scope definition, no improvement with a value of 0 will be assigned. If a PCI technology significantly improves the definition level for a element, major improvement level with a value of 3 will be assigned to that element. If minor improvement is expected, a value of 1 is assigned to indicate a minor improvement on scope definition level. Then, a vector is defined to describe the values of improvement level. For example, 3D Laser Scanning technology significantly improves the definition level on some PDRI elements A3, D4, and E2. A value of 3 will be assigned (Table 2). The definition level of other elements, e.g. A1, D3, E3, are somewhat improved, therefore, a value of 1 is assigned. A mapping vector v_k is defined as

Table 2 Mapping PCI Technologies with PDRI: 3D Laser Scanning Example

Value	Improvement Level	Elements
3	Major	A3. Operating Philosophy Available vs. Required, D4. Dismantling and Demolition Requirements, E2. Design & Material Alternatives Considered/Rejected, F2. Surveys & Soil Tests, G3. Piping & Instrumentation Diagrams
1	Minor	A1. Reliability Philosophy, D3. Site Characteristics, E3. Design for Constructability Analysis, I1. Civil/Structural Requirements, I2. Architectural Requirements, M1. CADD/Model Requirements, P2. Engineering/Construction Plan & Approach
0	No	All other PDRI elements

$$v_k = [1,0,3,0,0,0, \dots] ^T,$$

Where, k indicates the PCI technology, and the values of the vector indicate the improvement level of the PCI technology on the PDRI elements has 1 or 3 if it corresponds to a PDRI element listed above, otherwise it is 0. Given a PDRI rating matrix π^C before the application of any PCI technology, the maximum scope definition improvement level (or PDRI score reduction) could be obtained. The calculation is coded in an Excel spreadsheet as follows.

- a. If $A1 < B1$, the score will show A1
- b. If $A1 = 0, B1 \neq 0$, the score will show A1
- c. If $A1 \neq 0, B1 = 0$, the score will show A1

$$=IF(A1=0,0,IF(B1=0,A1,IF(OFFSET(element,0,B1)>A1,A1,OFFSET(element,0,B1)))) \tag{4}$$

*A1= The definition level in PDRI rating matrix π^C

*B1= Improvement level of PCI technology in the mapping vector v_k

The improved project scope definition level after the use of 3D Laser Scanning is calculated as

$$P^* = J^I * \pi^C * v_k * J^2 \tag{5}$$

4.2.3 Decision on Applying New Tech

When there are several new technologies available, we can define a PDRI score improvement matrix $\Psi = [v_1, v_2, v_3, \dots v_n]$, where each column vector is a PDRI score improvement vector for a certain new technology, e.g. v_1 is the PDRI score improvement vector for 3D Laser Scanning, and v_n indicates number of new technologies used in FEP. We can define the improved PDRI score as

$$S = [p-v_1, p-v_2, p-v_3, \dots p-v_n] \tag{6}$$

Where, S is PDRI score improvement vector for all new technologies. And $S = [s_1, s_2, s_3, \dots s_n]$. Given a threshold value for PDRI score improvement, say p , any new technology with s larger than p , will be feasible based on the criteria of reducing risks. The larger reduced score the better result for reducing risk in PDRI. A feasible new technology is any technology i with $s_i > p$,

$$s_m = \text{Max } S = \text{Max } (s_1, s_2, s_3, \dots s_n) \tag{7}$$

4.2.4 Cost calculating and P/C ratio

In addition to the decision structure discussed previously, the model also incorporates technology application costs into the decision process. This feature is specially designed to meet project teams' needs for the most cost effective selection of PCI technologies. The DMTS model defines a performance-cost (P/C) ratio to measure the cost effectiveness. The higher the ratio, the more efficient the PCI technology.

$$\text{Performance-Cost (P/C) Ratio} = (p - v_k) / c_k \quad (8)$$

Where, p is the PDRI rating score before applying any PCI technology. v_k represents the improved PDRI rating score after the use of PCI technology k . And c_k depicts the application cost of PCI technology k . While, a user can follow the calculation method discussed before to obtain p and v_k , there are more complicated to accurately estimate technology application costs. The DMTS model offers two methods to integrate cost data into the decision process. The estimating methods are either based on unit price per square foot, or unit price per labor hours. Project complexity is also considered as a parameter for this decision process. The user is required to input project data into the worksheet. Then the model automatically generates a list of proper PCI technologies that are ranked from high to low performance-cost ratio.

4.3 Technology Oriented Decision Structure

This model also provides a technology searching function for users who are willing to apply innovative technologies in the project. At this level, the model identifies key terms and words of each PCI technology and indexed context. A user is able to locate specific technologies through a topic search.

5 .Application of Model

The previous sections discuss the framework of the decision model. An Excel based DMTS package has also been developed (Figure 3). This section presents an example to illustrate how the package can help project teams strengthen renovation project planning process model can be used. First, we assumed that the user knew that his project condition was underground conditions, but he/she did not know the type of applied area for the project. Therefore, the answer was 1 for the first question, and 0 for the second question in the Problem Oriented Classification Tool that was shown in figure 3. The list of technologies shows that three PCI technologies match the query. Additionally, PCI technology report will be generated through the link "Click for Report".

Users can follow the steps of questions to get three kinds of matched technologies through Risk Oriented Decision Structure. The first step is to fill out the PDRI score sheet, and the questions that follow in the next step have been described above. The assumed answers and list of matched technologies were shown with number priority which means that the first one matched technology may prove better than the second, also the second may be better than the third in figure 3. The final tool can provide technology searching function. Users can type any keywords of PCI technology details which they would like to use and get a list of appropriate PCI technologies. The example illustrates the technology selection results when a user is

Title: Renovation-001 Size: 20,000,000USD Duration: 24 months Location: Maryland Team: PM-01																																														
Problem Oriented Classification Tool <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> 1. Determine Which of the following Project Conditions are likely to influence the R&R project scope, design, and construction? Ans: <input type="text" value="1"/> </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 50%;">1=Undergroung Conditions</td> <td style="width: 50%;">4=Spacial Relationships</td> </tr> <tr> <td>2=Integrity</td> <td>5=Risk Identification</td> </tr> <tr> <td>3=Restricted Access</td> <td>6=Enviromental Constraints</td> </tr> </table> </div> <div style="border: 1px solid black; padding: 2px; margin-bottom: 5px;"> 2. Do you know which kinds of applied area in your current project? Ans: <input type="text" value="0"/> </div> <div style="border: 1px solid black; padding: 2px;"> <table style="width: 100%; border-collapse: collapse;"> <tr> <td colspan="3">0=I don't know</td> </tr> <tr> <td style="width: 33%;">1=Unsuitable for archaeological excavation</td> <td style="width: 33%;">11=Areas susceptible to environment</td> <td style="width: 33%;">21=Design and fabrication verification</td> </tr> <tr> <td>2=Work around operating units</td> <td>12=Crack detection</td> <td>22= Building Construction planning</td> </tr> <tr> <td>3=Subsurface survey</td> <td>13=Material thickness measurements</td> <td>23=Assess air flow in constructed environments</td> </tr> <tr> <td>4=Structural mapping</td> <td>14=Conductivity measurements</td> <td>24=Monitor ground information</td> </tr> <tr> <td>5=Forensic investigation</td> <td>15=Casting and forging defects</td> <td>25=Detection and analysis of volatile</td> </tr> <tr> <td>6=Infrastructure characterization</td> <td>16=Corrosion Detection</td> <td>26=Schedule risk analysis</td> </tr> <tr> <td>7=Environmental & safety assessment</td> <td>17=Paved road systems</td> <td>27=Cash flow forecasting</td> </tr> <tr> <td>8=Real time monitoring</td> <td>18=Quality control/assurance</td> <td>28=Performance measurements</td> </tr> <tr> <td>9=Structural Integrity Analysis</td> <td>19=Dimensional measurements</td> <td>29=Prevent utility disruption</td> </tr> <tr> <td>10=Inside vessels</td> <td>20=Piping system</td> <td>30=Detect explosive compounds</td> </tr> </table> </div>	1=Undergroung Conditions	4=Spacial Relationships	2=Integrity	5=Risk Identification	3=Restricted Access	6=Enviromental Constraints	0=I don't know			1=Unsuitable for archaeological excavation	11=Areas susceptible to environment	21=Design and fabrication verification	2=Work around operating units	12=Crack detection	22= Building Construction planning	3=Subsurface survey	13=Material thickness measurements	23=Assess air flow in constructed environments	4=Structural mapping	14=Conductivity measurements	24=Monitor ground information	5=Forensic investigation	15=Casting and forging defects	25=Detection and analysis of volatile	6=Infrastructure characterization	16=Corrosion Detection	26=Schedule risk analysis	7=Environmental & safety assessment	17=Paved road systems	27=Cash flow forecasting	8=Real time monitoring	18=Quality control/assurance	28=Performance measurements	9=Structural Integrity Analysis	19=Dimensional measurements	29=Prevent utility disruption	10=Inside vessels	20=Piping system	30=Detect explosive compounds	List of Technologies Matched Technologies <table style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 70%;">Hydro-Excavation</td> <td style="width: 30%; text-align: right;">Click for Report</td> </tr> <tr> <td>Ground Penetrating Radar</td> <td style="text-align: right;">Click for Report</td> </tr> <tr> <td>Electromagnetic Conductivity</td> <td style="text-align: right;">Click for Report</td> </tr> </table>	Hydro-Excavation	Click for Report	Ground Penetrating Radar	Click for Report	Electromagnetic Conductivity	Click for Report
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Figure 3 Decision Model for PCI Technology Selection Worksheet

willing to test any PCI technologies indexed with 3D. As shown in Figure 3, a list of three PCI technologies namely 3D Laser Scanning, Rapid Prototyping, and Real-time GPS Monitoring System is identified as matching technologies that have been indexed with 3D.

6. Conclusion

Renovation projects account for an increasing proportion of construction expenditure in the US and require special attention to ensure successful delivery. As compared to Greenfield projects, renovation projects present unique risks in areas such as security, existing conditions, coordination, compatibility, environmental issues etc. Better

Front End Planning, along with the application of Project Condition Investigation technologies, help project teams identify therefore mitigate special risks in renovation projects. This paper presents a decision model DMTS to integrate PCI technology selection into the renovation project planning process. The model is a flexible and user friendly Excel based decision tool. It provides three decision structures and allows project teams to select appropriate PCI technologies according their special needs. One must note that many parameters, e.g. cost, and definition level, in the DMTS model need to be regularly review to reflect the advance of new technologies. The model is specially designed to allow project teams to update the parameters and add emerging technologies for team's special needs.

7. Reference

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