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Airfield Pavement Management Framework using a Multi-Objective Decision Making Process

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Submitted by:

Hao Wang
Associate Professor

Lukai Guo
Postdoctoral Associate

Xiaodan Chen
Graduate Research Assistant

Department of Civil and Environmental Engineering,
Rutgers, The State University of New Jersey
Piscataway, NJ 08854

External Project Manager

Jeff Gagnon, Federal Aviation Administration (FAA)

In cooperation with

Rutgers, The State University of New Jersey
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16. Abstract

Airfield pavement management system uses pavement condition indexes to evaluate pavement conditions for timely planning of maintenance and rehabilitation. Using the comprehensive FAA PAVEAIR database, this study aims to investigate the consistency and relationship of three indexes: pavement condition index (PCI), structural condition index (SCI), and foreign object damage index (FOD). The statistical analysis results show that the service life of airfield pavement estimated by PCI is significantly longer than the ones estimated by FOD and SCI in general. However, pavement surface type (asphalt or cement concrete) and branch uses (runway, taxiway, or apron) can affect the comparison results between these condition indexes. The study findings indicate that the use of PCI, SCI, and FOD for planning of M&R treatments in airfield pavement management system may not be fully replaced by each other, although correlations were found between them. In addition, it is suggested that different thresholds of pavement condition indexes may be needed by airport authorities for defining the service life runway, taxiway, and apron pavements since their importance levels are different. The study results can be further used in life-cycle cost analysis and selection of M&R alternatives in airfield pavement management system. The ultimate goal is to consider multiple criteria in decision making of airfield pavement management, such as extended pavement life, cost, safety, and sustainability.

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Table of Contents

INTODUCTION 1

OBJECTIVE AND SCOPE 2

AIRFIELD PAVEMENT CONDITION INDEX 2

Pavement Condition Index (PCI) 2

Structure Condition Index (SCI) 3

Foreign Object Damage (FOD) 4

AIRFIELD PAVEMENT CONDITION DATABASE 5

DATA ANALYSIS METHODS 7

Estimation of Pavement Life 7

Survival Function with Kaplan-Meier Estimator 8

Cox Proportional Hazard Model 9

RESULTS AND ANALYSIS 11

Relationship between Different Pavement Condition Indexes 11

Survival Curves of Pavement Life Estimated Using Different Condition Indexes 13

Effects of Pavement Surface and Branch Use on Pavement Life 15

Statistical Analysis Results from Cox Proportional Hazard Model 16

CONCLUSIONS 19

RECOMMENDATIONS 20

List of Figures

Figure 1 Database of pavement sections evaluated with different condition indexes 6
Figure 2 Total number of pavement sections evaluated by PCI, SCI, and FOD (every 10 years) . 7
Figure 3 Frequency distributions of estimated service life by PCI, SCI, and FOD........................ 8
Figure 4 Service life of airfield pavement estimated by PCI, SCI, and FOD............................... 14
Figure 5 Survival curves of pavement sections with AC and PCC surfaces 15
Figure 6 Survival curves of pavement sections in different branch uses...................................... 16
Figure 7 Example of Decision Making Framework in Airfield Pavement Management System 21

List of Tables

Table 1 Airfield Pavement Distresses for Calculation of PCI, SCI, and FOD Index 4
Table 2 Regression analysis results between SCI vs. PCI and FOD vs. PCI 12
Table 3 Correlations between pavement life estimated by PCI, SCI, and FOD 13
Table 4 Statistic results from Cox Proportional Hazards Model 17
Table 5 Effects of branch use on service life of airfield pavement 18
Table 6 Effects of pavement type on service life of airfield pavement 19

INTODUCTION

Airport authorities have constantly collected pavement condition data and utilize life-cycle cost analysis to select construction and maintenance alternatives. The current pavement condition assessment focuses on fatigue cracking and rutting, which affect structural integrity of pavement. In airfield pavement management, it is necessary to consider non-structural distresses such as low friction and surface distortion, which affect safety of aircraft operations.

The current FAA Advisory Circular 150/5380-7B recommends using pavement condition index (PCI) to assess airfield pavement condition for planning of maintenance and rehabilitation (M&R) treatments (*1*). PCI is an index covering all general pavement distresses related to both structural and functional pavement performance. Considering that structural and functional performance of airfield pavement may deteriorate differently. Two pavement sections with the same PCI may have different deteriorations and need different M&R treatments. For example, the load-related structural distresses are critical for assessing the structural capacity of airfield pavement under aircraft traffic loading. In this case, structural condition index (SCI) can be an alternative index to help airport authorities determine the time and type of pavement repair.

In the airfield, some pavement distresses, such as block cracking and patching, can create loose components which may cause potential damage to aircraft engine and tires. If such pavement distresses increase considerably and affect the safety of aircraft operation, the proper maintenance treatment is needed. This type of damage on the aircraft engine is known as foreign object damage (FOD). The total cost caused by FOD can be up to $12 billion counting the indirect costs from delays, additional fuel consumptions, and plane shifts (*2*). Among different sources causing FOD, the loose foreign objects generated from pavement distresses can be eliminated by timely M&R treatments.

Since the pavement distresses and the corresponding failure thresholds of each condition index are different, it is challengeable to compare the ability of using different condition indexes on estimating the service life of airfield pavement. Garg et al. (2004) evaluated the operational life of airport pavements based on PCI and SCI. It was found that the average SCI for airfield pavements older than 20 years was above 80, while runways had the highest SCI close to 90 and aprons had the lowest SCI around 82 (*3*). This verified that the FAA pavement thickness design standards satisfied the 20-year design life requirement. The study also found that compared to SCI, PCI represented showed larger difference of pavement condition between flexible and rigid pavements. It raised the importance of improving construction and material standards for flexible pavements (*3*). Li et al. (2010) analyzed the interrelation between PCI and FOD to study the feasibility of using FOD potential index in airfield pavement management. They found that some pavement sections with PCI values showing good pavement condition still required maintenance since the FOD potential reflected poor pavement condition against aircraft (*4*). However, this finding was only based on limited pavement sections at one commercial airport and one general aviation airport.

OBJECTIVE AND SCOPE

The aim of this study is to investigate the consistency and relationship of PCI, SCI, and FOD on evaluating service life of airfield pavement. To reach this goal, three detailed objectives are completed using proper analysis methods. First, the interrelation between PCI, SCI, and FOD were analyzed using regression analysis. Second, the life estimations of airfield pavement using different condition indexes were compared using correlation test, survival curves, and Cox proportional hazard models. Third, the effects of pavement surface type and branch use on the life estimation of airfield pavement were analyzed using statistical analysis.

AIRFIELD PAVEMENT CONDITION INDEX

Pavement Condition Index (PCI)

Pavement condition index (PCI) is a rating index of pavement condition based on visual survey of pavement distresses. The detailed procedure of pavement survey and PCI calculation mainly follows ASTM D5340-03, Standard Test Method for Airport Pavement Condition Index Survey (*5*). Basically, PCI is determined by the type, severity, and density of distress, as show in Equation 1.

$$\mathrm{PCI} = 100 - \max \mathrm{CDV} = 100 - \max\ \mathrm{g}\left(q, \sum_{i=1}^{m_s} \sum_{j=1}^{n_j} f\left(T_i, S_j, D_{ij}\right)\right) \quad (1)$$

Where,

m_s = total number of pavement distress types;

n_j = severity level of the i^{th} distress;

$f(T_i,S_j,D_{ij})$ = function of deduct value determined by distress type T_i at severity level S_j with density D_{ij};
q = number of entries with deduct values greater than 5; and
$g(q,T_i,S_j,D_{ij})$ = function of corrected deduct value.

As can be seen from Equation 1, once T_i and S_j are collected by visual survey and D_{ij} are calculated by the distress quantity divided by the area of sample unit, the deduct value for each distress type at each severity level can be quantified through the curves provided in ASTM D5340-03 with a function of $f(T_i,S_j,D_{ij})$. Then, through adjusting the deduct values which are greater than 5 to equal to 5, a series of decreasing total deduct values can be obtained. Based on those decreasing total deduct values with the corresponding q, a series of corrected deduct values (CDV) can be obtained through another group of curves provided in ASTM D5340-03 with a function of $g(q,T_i,S_j,D_{ij})$. After that, PCI can be calculated through 100 deducted by the maximum value among those CDVs. It is clear that the scale of PCI is from 100 to 0, with 100 reflecting excellent pavement condition.

According to ASTM D5340-03, the rating scales of PCI can be further divided to three levels of pavement condition: good condition with PCI from 100 to 71, fair condition with PCI from 70 to 56, and poor condition with PCI smaller than 55. In this study, the threshold of PCI to define the end of airfield pavement service life is set as 55 (*5*).

Structure Condition Index (SCI)

Pavement distresses can be further categorized by structural distresses (e.g., transverse, longitudinal, corner cracking, corner break, pumping, shrinkage crack, spalling-joints, spalling-corner, shattered slab) and functional distresses (e.g., corrugation, faulting, heave/swell, bleeding) based on whether the distress can affect pavement bearing capacity or not. Structural distresses can get more attentions by pavement engineers regarding pavement structure designs. The structural condition index (SCI) is calculated using the same equation for of PCI (Equation 1) but only considers structural distresses. The threshold of SCI defining the structural failure of pavement is set as 80 for concrete pavement by FAA AC 150/5320-6F (*6*). This SCI threshold has been used by one previous FAA study to define the structural life of airfield pavement (*3*).

Foreign Object Damage (FOD)

The FOD index is calculated using the similar equation for PCI (Equation 1) but only considers the pavement distresses that can potentially lead to loose foreign objects. Additional modification factors to some distress deduct values are required to be added to the calculation of FOD index, including using 0.6 for deduct value of alligator cracking and 4.0 for deduct value of joint seal damage (*7*). The specific distresses involved in calculating FOD index is regulated in the Air Force Civil Engineer Support Agency Engineering Technical Letter 04-9 (*8*). The threshold of FOD index regarding the unacceptable damages on the aircraft is set as 40 after converting it to the consistent rating scale as PCI and SCI (*8;9*). The total FOD potential can be converted based on the FOD index, the specific aircraft category (F-16, KC-135, or C-17), and the pavement type (concrete pavement or asphalt pavement). Among these three aircraft categories, the KC-135 category is normally used for commercial airports since it contains the A-320, B-737, B-757, and other similar passenger aircraft (*7*).

The detailed list of pavement distresses used to calculate PCI, SCI, and FOD are listed in Table 1, respectively, for flexible and rigid pavements. The major difference between PCI, SCI, and FOD is the types of pavement distress considered in the calculation of index values. The PCI counts all 32 pavement distress types; while the FOD ignores some pavement distress types (8 of 32) that have no potential risk of generating loose foreign objects. On the other hand, the SCI focused on a small group (8 of 32) of pavement structural distresses.

Table 1 Airfield Pavement Distresses for Calculation of PCI, SCI, and FOD Index

Pavement Distress Types	Pavement Types	PCI	FOD	SCI
Alligator Cracking	Flexible	√	√	√
Bleeding	Flexible	√		
Block Cracking	Flexible	√	√	
Corrugation	Flexible	√		
Depression	Flexible	√		
Jet Blast Erosion	Flexible	√	√	
Joint Reflection Cracking	Flexible	√	√	
Longitudinal/Transverse Cracking	Flexible	√	√	

Oil Spillage	Flexible	√	√	
Patching	Flexible	√	√	
Polished Aggregate	Flexible	√		
Raveling	Flexible	√	√	
Weathering	Flexible	√	√	
Rutting	Flexible	√		√
Shoving	Flexible	√	√	
Slippage Cracking	Flexible	√	√	
Swelling	Flexible	√		
Blow Up	Rigid	√	√	
Corner Break	Rigid	√	√	√
Durability Cracking	Rigid	√	√	
Linear Cracking	Rigid	√	√	√
Joint Seal Damage	Rigid	√	√	
Small Patching	Rigid	√	√	
Large Patching	Rigid	√	√	
Popouts	Rigid	√	√	
Pumping	Rigid	√	√	
Scaling	Rigid	√	√	
Settlement	Rigid	√		
Shattered Slab	Rigid	√	√	√
Shrinkage Cracking	Rigid	√		√
Joint Spalling	Rigid	√	√	√
Corner Spalling	Rigid	√	√	√

AIRFIELD PAVEMENT CONDITION DATABASE

The pavement condition database used in this study were extracted from FAA PAVEAIR, which is a public web-based airport pavement management system maintained by FAA. This database contains a large number of airport networks. Each airport network is divided into several branches and each branch is divided into pavement sections with different pavement surface types. The pavement surface types are asphalt concrete (AC) and Portland cement concrete (PCC), while the branch uses of pavement sections include apron, runway, and taxiway. In each pavement section, multiple inspections were conducted over the years.

Up to 2095 general airport networks available in the FAA PAVEAIR database were selected in this study. Among those general airport networks, all of them record PCI to evaluate airfield pavement condition, while only 80 of them use SCI and 65 of them use FOD as alternative indexes to evaluate airfield pavement condition additionally. For completing the objectives in this study, the entire database used is further divided into four sub-databases by those indexes, including PCI-based database, SCI-based database, FOD-based database, and all-in-one database. The first three databases contain the pavement sections evaluated by either of three condition indexes (PCI, SCI, and FOD), while the all-in-one database only includes the pavement sections evaluated by all three indexes. The detailed size of pavement sections in each category is listed in Figure 1.

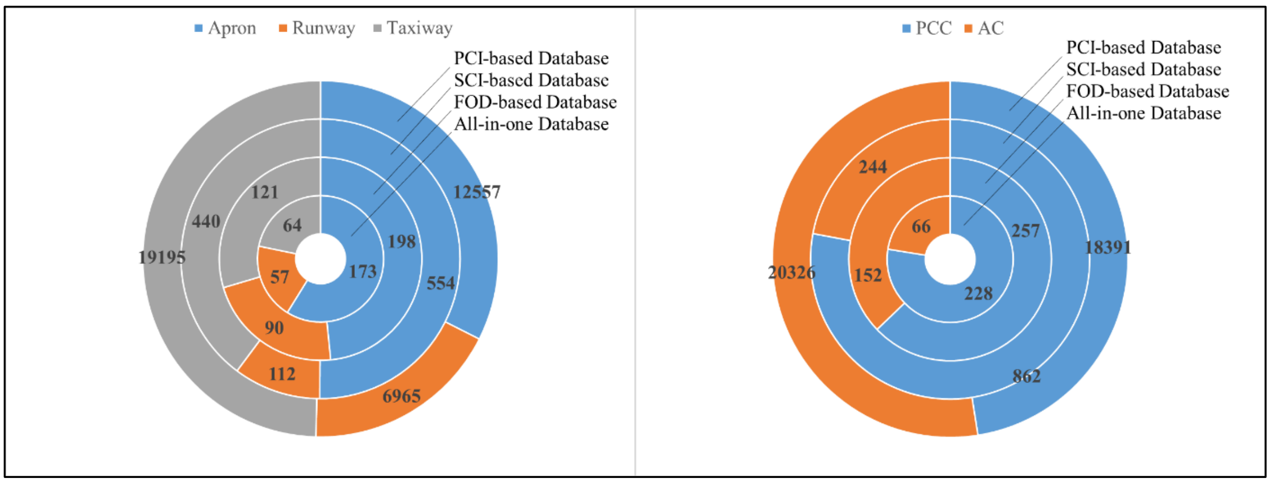

Figure 1 Database of pavement sections evaluated with different condition indexes

FAA PAVEAIR database provides the date of inspection on each pavement section. The total numbers of samples evaluated within each ten years are listed in Figure 2. It shows that the inspections of airfield pavement condition started since 1940s and increased exponentially after 1990. This long range of observation period assures that the service life of airfield pavement can be sufficiently analyzed.

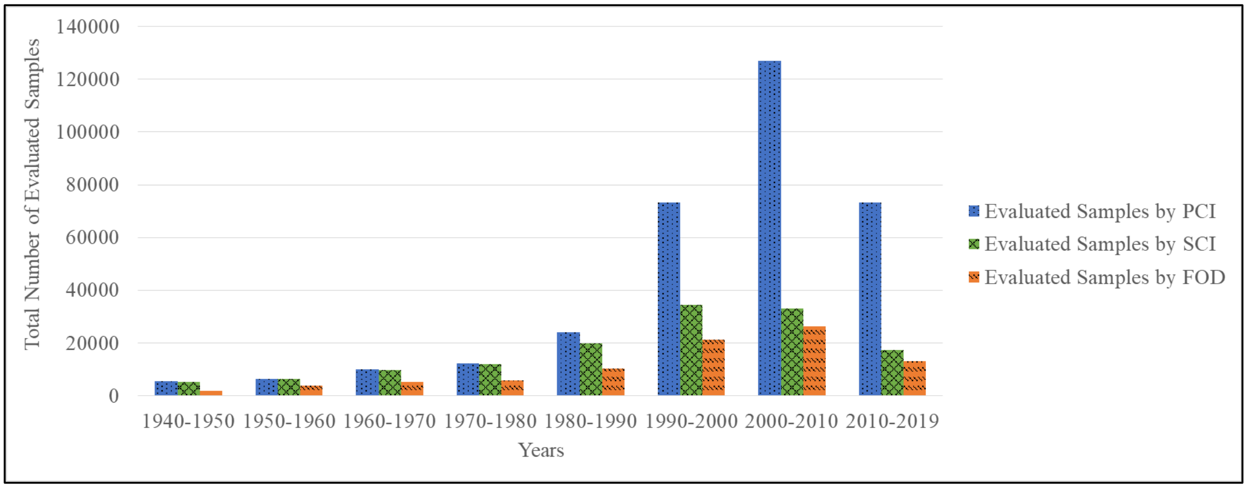

Figure 2 Total number of pavement sections evaluated by PCI, SCI, and FOD (every 10 years)

DATA ANALYSIS METHODS

Estimation of Pavement Life

One critical challenge of estimating pavement life is to properly estimate the specific year in which airfield pavement condition index reaches the failure threshold value (55 for PCI, 80 for SCI, and 40 for FOD in this study). A two-point interpolation method was applied to estimate pavement life before failure thresholds. The ideal situation of using two-point interpolation method is that the failure threshold falls in the middle of two condition points that are recorded in the database. If there was no condition worse than the threshold condition, the two condition points that were closest to the failure threshold were selected for two-point interpolation. For the pavement sections that were repaved multiple times, the service period prior to the latest M&R treatment was used in the analysis because this period recorded the entire life cycle of pavement. Quality check of raw data was conducted before analysis. The data preprocessing mainly includes exclusion of pavement sections that start with condition index less than 100 or have increasing values of index without M&R treatments.

The airfield pavement service life of each pavement section was estimated based on PCI, SCI, and FOD, respectively. The frequency distributions of pavement life are displayed in Figure 3. The pavement sections having estimated service life greater than 50 years are excluded in this study due to their small sample size and the potential measurement errors. The results show that the pavement service life estimated based on PCI or FOD had peak values occurring at 15 to 20 years, while the peaks move to the range of 0 to 10 years if the pavement service life is estimated based on SCI. The estimated pavement service life spanned a large range as the database contains a large number of airports subject to different traffic and climate conditions.

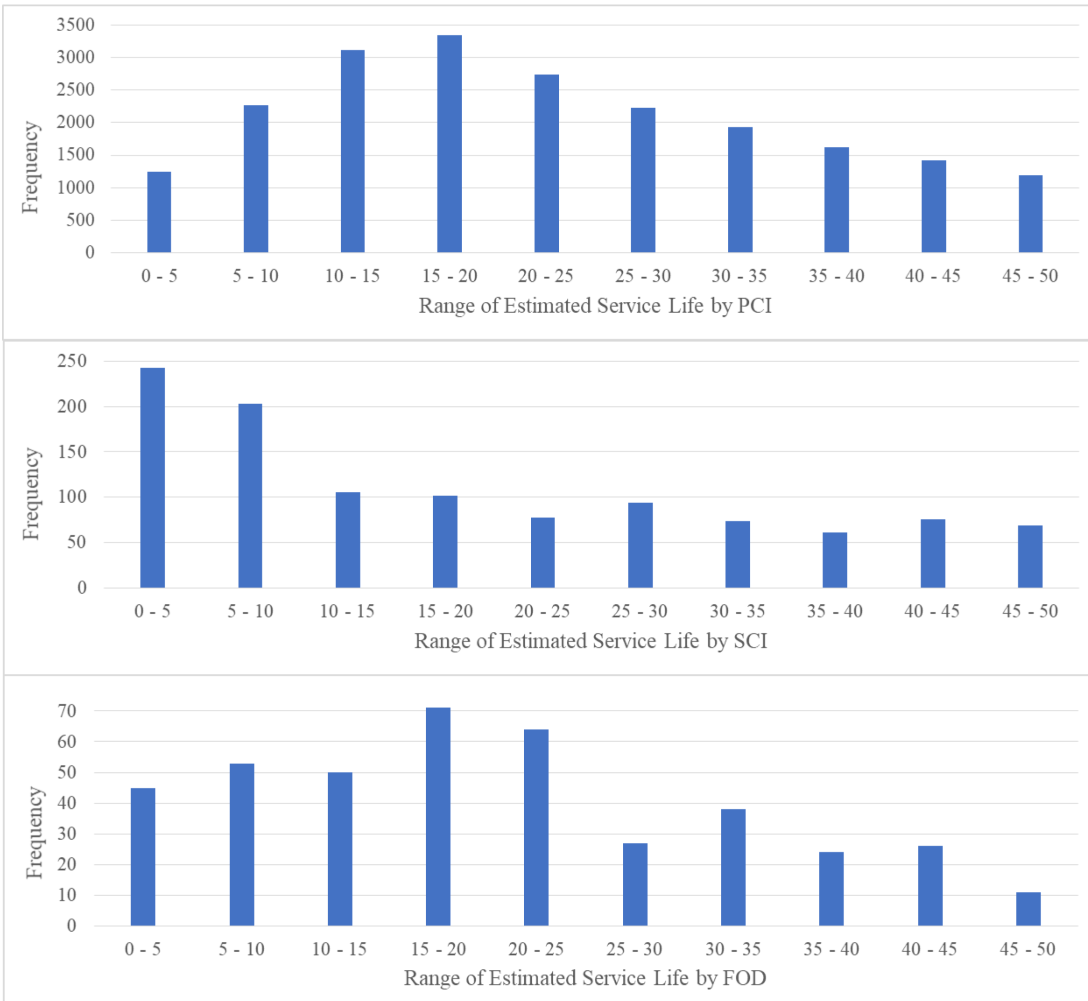

Figure 3 Frequency distributions of estimated service life by PCI, SCI, and FOD

Survival Function with Kaplan-Meier Estimator

Survival analysis is generally defined as a "time to event" analysis to estimate the probability or the percentage of a group of subjects (e.g., patient, employee, construction) to experience an event of interest (e.g., die, leave a company, structural failure) over time. The survival function S(t) is the probability of observing a survival time, T, which is greater than one stated time value, t. It can be expressed as S(t)=Pr(T>t). In a group of cases developed by time, the survival time of each case is being approached and the S(t) will dynamically decrease from one at the beginning to zero at the infinite end (*10*). One default estimator of the survival function is the Kaplan-Meier estimator, which can be expressed as Equation 2. The reliability of survival analysis results mainly depends on the observed group size and the observation durations (usually by years).

$$\hat{S}(t) = \prod_{t_i \le t} \frac{n_i - d_i}{n_i} \tag{2}$$

Where,

n_i is the total sections having the condition better than the threshold at a survival time t_i; and

d_i is the total sections falling to the condition worse than the threshold at a survival time t_i.

Survival analysis has been used to evaluate pavement performance and its relationship with traffic, climate, and pavement structure. Wang et al. (2005) conducted survival analysis using long-term pavement performance (LTPP) database to study fatigue cracking on flexible pavements with various influential variables, including pavement layer thickness, traffic, and climatic factors (precipitation intensity and freeze-thaw cycles) (*11*). Wang and Allen (2008) developed a staged survival analysis method to predict the expected service life of asphalt overlays after resurfacing, and determine the optimal timing of resurfacing (*12*). Dong and Huang (2012) used survival analysis to investigate the major factors of developing different cracks on resurfaced-asphalt pavements based on LTPP database (*13*). Anastasopoulos and Mannering (2015) implemented survival analysis specifically on the performance of pavement overlay and found that some influential factors had varying effects on pavement service life, such as drainage condition, rehabilitation costs, and weather (*14*).

Cox Proportional Hazard Model

Although the Kaplan-Meier estimator can generate survival curves in multiple categorical groups for comparison purpose, Cox proportional hazard model provides one way to test the statistical significance of risk factors on affecting the survival curves. When the underlying time random variable is continuous, the survival function can be expressed by the cumulative hazard function H(t) as $S(t)=e^{-H(t)}$. Similar to S(t), one estimator, Nelson-Aalen estimator of H(t), can be expressed in Equation 3.

$$\widehat{H}(t) = \sum_{t_i \le t} \frac{d_i}{n_i} \tag{3}$$

The corresponding hazard function at the observed survival time t_i is expressed in Equation 4.

$$\tilde{h}(t_i) = \frac{d_i}{n_i} \tag{4}$$

The hazard function can be further expressed in a more general function as a product of two functions. One represents the hazard function changed by the survival time, t, and another one represents the hazard function adjusted by the subject covariates, $x\beta$, as shown in Equation 5.

$$h(t, x, \beta) = h_0(t) r(x, \beta) \tag{5}$$

Since the hazard function $h_0(t)$ is only changed by the time, the ratio of two hazard functions $h(t, x_1, \beta)$ and $h(t, x_0, \beta)$ can only depend on the ratio of $r(x_1, \beta)$ and $r(x_0, \beta)$. In other words, the hazard function under any time-dependent distribution form will not affect the estimation of subject covariates, $x\beta$. In 1972, Cox suggested $r(x, \beta) = exp(x\beta)$ and parameterized the hazard function, as shown in Equation 6.

$$h(t, x, \beta) = h_0(t) e^{x\beta} \tag{6}$$

The ratio of two hazard functions representing two samples (hazard ratio, HR) is proportional in Cox function, as shown in Equation 7.

$$HR(t, x_1, x_0) = \frac{h_0(t) e^{x_1 \beta}}{h_0(t) e^{x_0 \beta}} = e^{\beta(x_1 - x_0)} \tag{7}$$

As can be seen from Equation 7, the coefficient β reflects the hazard ratio between two cases having x_1 and x_0. It means that the risk of sample with x_1 is e^{β} times the risk of sample with x_0 to end its life (or reach to any other expected events). Therefore, higher β represents higher risks.

Compared to other statistic models, instead of using the maximum-likelihood function to obtain the proper parameters β_i to fit the statistic model, a partial-likelihood function which only depends on the parameter of interest is a more common method to fit the proportional hazard model. The partial likelihood can be expressed in Equation 8.

$$l_p(\beta) = \prod_{i=1}^{m} \frac{e^{x_i \beta}}{\sum_{j \in R(t_i)} e^{x_j \beta}} \tag{8}$$

Where,

x_i denotes the value of covariate for the subject with ordered survival time t_i;

$R(t_i)$ denotes the summation over the set of subjects where their life is still not ended at t_i.

For evaluating the significance of the coefficient in the proportional hazard model, there are three available well-developed tests, including the partial likelihood ratio test, the Wald test, and the score test (*10*). In most cases, the results from those three tests are consistent. If not, the partial likelihood ratio test is preferred. In this study, all three above tests were performed to decide the proper categorical variables in Cox Proportional Hazard Model.

- The partial likelihood ratio test, denoted G, counts the log partial likelihood of the model with or without containing the covariate: $G = 2\{L_p(\hat{\beta}) - L_p(0)\}$;
- The Wald statistic with its p-value, denoted z, uses the ratio of the estimated coefficient to its estimated standard error: $z = \frac{\hat{\beta}}{\widehat{SE}(\hat{\beta})}$;
- The score test, denoted z*, uses the ratio of the derivative of the log partial likelihood to the square root of the observed information all evaluated at $\beta = 0$: $z^* = \left.\frac{\partial L_p/\partial \beta}{\sqrt{I(\beta)}}\right|_{\beta=0}$.

Cox proportional hazard model is also widely used to study the influential factors on pavement service life. Yu et al. (2008) applied this model to search the factors on affecting the service life of asphalt overlays in Ohio and assist decision making of pavement M&R and budget allocation (*15*). Nakat and Madanat (2008) used Cox proportional hazard model to study the factors affecting crack initiation in pavement overlays, which were helpful for selecting proper pavement rehabilitation policies in Washington (*16*). Svenson (2014) used Cox proportional hazard model to test the effect of maintenance activities on roadway condition in Sweden, also considering other factors, such as pavement type, road width, speed limit, and climate zone (*17*).

RESULTS AND ANALYSIS

Relationship between Different Pavement Condition Indexes

To investigate the possible relationship between PCI with other two indexes, linear regression analysis was conducted with SCI and FOD as the dependent variables and PCI as the independent variable. The regression analysis results are shown in Table 2. Based on the t-statistic of regression model, PCI shows significantly linear relationship with SCI or FOD for the pavement sections either categorized by pavement surface type (AC and PCC) or branch use (apron, taxiway, and runway). In general, the linear relationships had the adjusted R-square values greater than 0.80, except for the pavement section with AC surface. Compared to SCI, the linear relationships between PCI and FOD had relatively higher adjusted R-square values. This indicates that the PCI can be converted to FOD index in good confidence.

Although the above regression results show significant relationships between these three indexes, the consistency of using different condition indexes on estimating airfield pavement service life is still required to be verified since the threshold values of these three indexes defining poor pavement condition are different. The change rates of different pavement condition indexes over time can be also different.

Table 2 Regression analysis results between SCI vs. PCI and FOD vs. PCI

	SCI			FOD		
	f(PCI)	t stat	Adjusted R^2	f(PCI)	t stat	Adjusted R^2
AC	0.758PCI+27.035	24.91	0.53	0.931PCI+7.711	51.01	0.94
PCC	0.635PCI+36.610	55.30	0.82	0.970PCI+2.611	66.34	0.87
Apron	0.718PCI+29.096	45.35	0.82	0.966PCI+2.810	49.90	0.84
Taxiway	0.688PCI+32.090	26.61	0.80	0.911PCI+8.967	57.81	0.95
Runway	0.626PCI+37.550	28.20	0.80	0.954PCI+4.629	82.97	0.97
All data	0.686PCI+32.057	59.59	0.81	0.941PCI+5.504	87.39	0.90

Correlation analysis was conducted between the airfield pavement life estimated by different condition indexes. The correlation coefficients and t-statistic results are summarized in Table 3. It was clear to see that the pavement life estimated by three condition indexes have significantly positive correlations between each other. Through comparing the Pearson correlation coefficients, it was found that the service life of airfield pavement estimated based on PCI and FOD were highly correlated with each other under any category.

Table 3 Correlations between pavement life estimated by PCI, SCI, and FOD

Data set	Index	Correlation (t-statistic)		
		FOD	PCI	SCI
General	FOD	1		
	PCI	0.807* (12.411**)	1	
	SCI	0.555 (15.211)	0.497 (7.056)	1
Runway	FOD	1		
	PCI	0.874 (4.869)	1	
	SCI	0.691 (5.747)	0.542 (2.160)	1
Apron	FOD	1		
	PCI	0.774 (9.393)	1	
	SCI	0.463 (11.647)	0.452 (5.998)	1
Taxiway	FOD	1		
	PCI	0.813 (6.535)	1	
	SCI	0.656 (8.225)	0.569 (3.400)	1
AC	FOD	1		
	PCI	0.817 (7.483)	1	
	SCI	0.585 (10.311)	0.485 (4.828)	1
PCC	FOD	1		
	PCI	0.851(9.845)	1	
	SCI	0.595 (11.945)	0.522 (5.935)	1

* correlation coefficient; **t-statistic

Survival Curves of Pavement Life Estimated Using Different Condition Indexes

Figure 1 compares the survival curves of airfield pavement sections based on PCI with a threshold of 55, FOD with a threshold of 40, and SCI with a threshold of 80. Considering the standardized rating scale of PCI and the large size of PCI-based database available in this study, the survival curve using PCI reflects the general condition of airfield pavement nationally. In general, the PCI-based survival curve keeps higher survival percent than the ones based on SCI and FOD, which can be mainly contributed by the various distresses and thresholds considered for different indexes.

Therefore, it is highly possible that a pavement section is evaluated as poor condition based on SCI or FOD while the PCI still has an acceptable value.

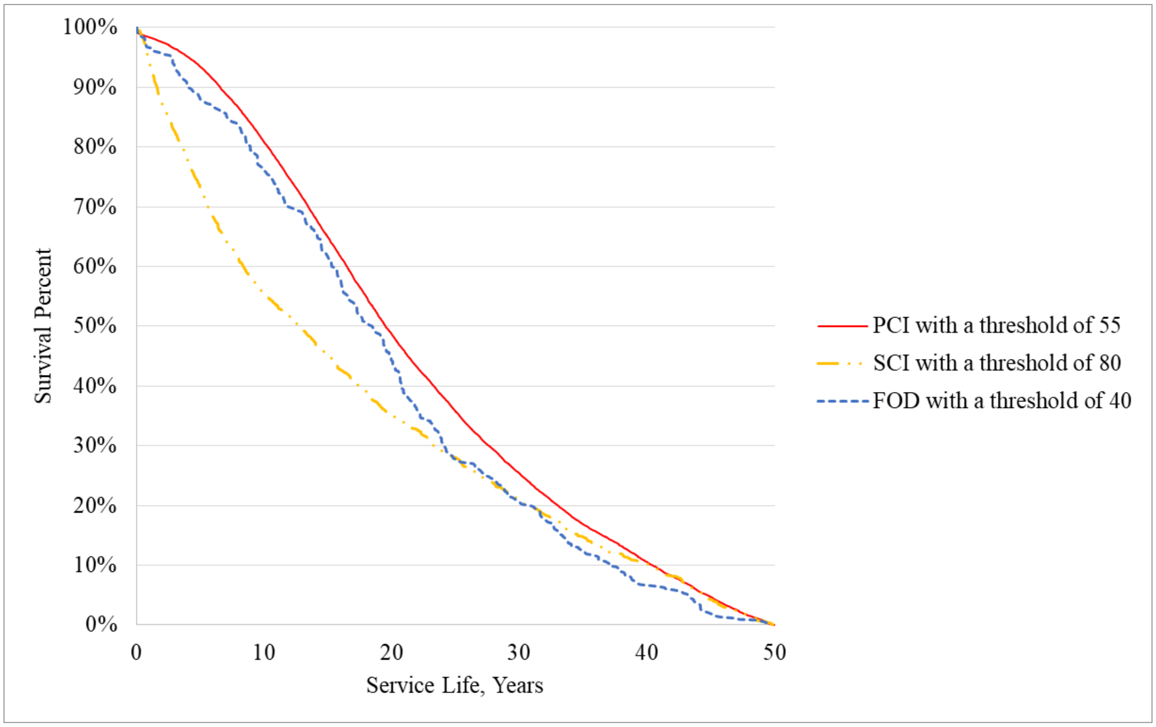

Figure 4 Service life of airfield pavement estimated by PCI, SCI, and FOD

For the pavement sections having the service life shorter than 20 years, the FOD-based survival curve is closer to the PCI-based survival curves. However, the pavement life estimated from SCI is shorter than the ones estimated from PCI. In other words, PCI may underestimate the pavement condition with its current rating scale for scheduling M&R treatments. Therefore, SCI can be an unreplaceable index to evaluate airfield pavement condition, especially regarding the possible early structural distresses on the airfield pavement. On the other hand, the trend was changed for the pavement sections having longer service life. The service life estimated by SCI is getting closer to the one by PCI; while the pavement life estimated by FOD is shorter. This observation indicates that for long-life pavement, the major reason to end its service life can be caused by functional distresses.

Effects of Pavement Surface and Branch Use on Pavement Life

Pavement structures with AC and PCC surfaces can have different pavement distresses. Each pavement distress may shorten the pavement service life at certain degradation level. Therefore, the weights of these pavement distresses counted to evaluate pavement condition by PCI, SCI, and FOD (deduct values in the calculation equation) are different. Figure 5 displays the survival curves of pavement service life estimated from different pavement condition indexes after dividing the data for AC and PCC surfaced pavement sections. The results show if the pavement condition is evaluated by PCI or SCI, PCC surfaced pavement sections generally have longer service life than AC surfaced pavement sections regardless of branch use type. This finding is consistent with the result concluded by previous FAA study (*6*). However, if FOD is used to evaluate airfield pavement condition, this comparison result between PCC and AC surfaced pavement sections turns to be opposite. It indicates that AC surfaced pavement may have less potential of having foreign object damage than PCC surfaced pavement.

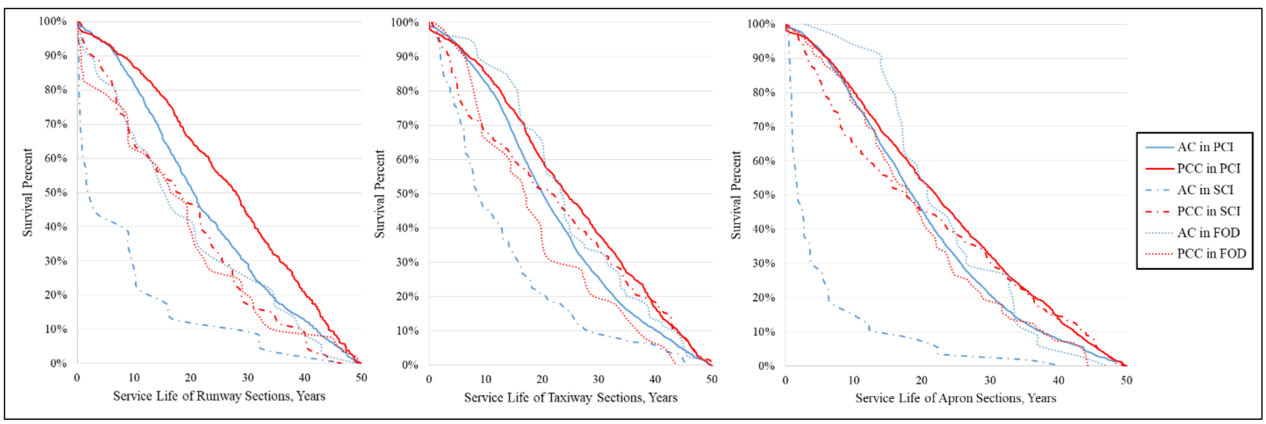

Figure 5 Survival curves of pavement sections with AC and PCC surfaces

Branch uses involved in the database include apron, taxiway, and runway. Runway is the region for landing and takeoff of aircraft. Apron is the region for parking the aircraft to load or unload goods and passengers. And taxiway is the area for aircraft to travel from and to runway and apron. Due to their different intended uses, pavement sections in runway, taxiway, and apron can have different aircraft load conditions (e.g. speed and payload), which affect the service life of pavement sections.

Figure 6 displays the survival curves of AC and PCC surfaced pavement sections located in runway, taxiway, and apron, respectively. The differences between these survival curves of runway, taxiway, and apron pavement sections can only be clearly identified for service life of PCC surfaced pavements estimated using PCI or AC surfaced pavements estimated using SCI. Apron sections appear to have generally shorter service life than the ones in taxiway and runway. The comparisons of service life between runway and taxiway pavement sections varied by the pavement condition index. Runway sections have shorter service life than taxiway sections if only the structural distresses are counted in SCI, but longer service life if all pavement distresses are included in PCI for condition evaluation.

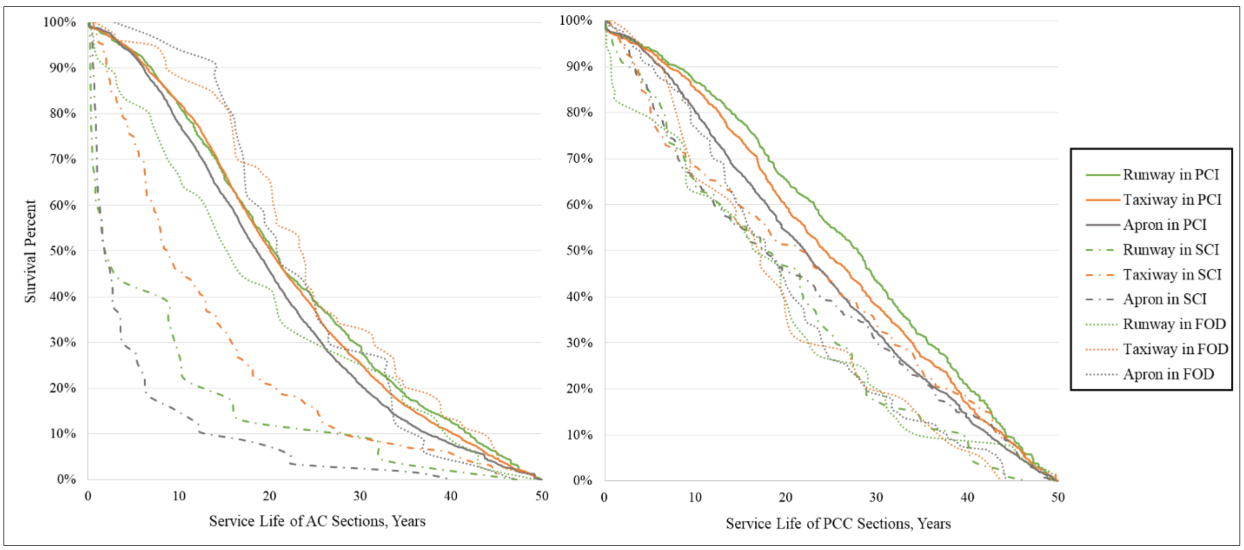

Figure 6 Survival curves of pavement sections in different branch uses

Statistical Analysis Results from Cox Proportional Hazard Model

The observations of survival curves provide straightforward comparison information on the service life of airfield pavement estimated by PCI, SCI, and FOD. The specific type of pavement surface and branch use was found affecting the service life of airfield pavement. To unbiasedly compare different pavement condition indexes on estimating service life of airfield pavement, Cox proportional hazard model was used considering all possible interactions between different variables. Two index-related category variables, SCI and FOD, are compared with PCI as the base. Besides the category variable indicating the condition index used in each case, two other categorical variables, pavement surface type and branch use, are considered in the model with PCC surface and runway as the base categories, respectively. The index-related category variable can be used to statistically check the possible significant relationship between PCI with the other two indexes on the estimated pavement service life. Through adding the multiplication of the index-related category variable with other two variables into the statistic models, any significant interactions can be investigated. Meanwhile, after considering significant interactions in the model, the significance of index variable by itself can turn to be more convincible.

Table 4 summarizes statistical analysis results from Cox Proportional Hazards Models. The coefficient of FOD and SCI shows that, if pavement section is within runway and paved by PCC, the possibilities of evaluating airfield pavement as poor condition by FOD and SCI are $e^{0.386}$ and $e^{0.583}$ times the possibility of that by PCI, respectively. In other words, the service life of airfield pavement estimated by PCI is significantly longer than the ones estimated by FOD and SCI in general. This is consistent with the observation results from survival curves.

However, pavement surface and branch use can also affect the comparison results between these indexes, except that branch use have insignificant effects on the service life estimated by FOD and PCI. As shown in Table 4, if the pavement section is located at taxiway or apron, the possibilities of evaluating airfield pavement as poor condition by SCI can be dropped to $e^{0.583-0.363}$ or $e^{0.583-0.457}$ times the possibility of that by PCI respectively. This means that the difference between service life estimated by SCI and PCI can be generally shortened. On the other hand, if the pavement surface type is AC, the possibilities of evaluating airfield pavement as poor condition by SCI and FOD can be changed to $e^{0.583+0.641}$ or $e^{0.386-0.480}$ times the possibility of that by PCI, respectively. In other words, the service life estimated by PCI turns to be shorter than that by FOD, and meanwhile, the difference between service life estimated by SCI and PCI can be extended.

Table 4 Statistic results from Cox Proportional Hazards Model

Variable	Coeff.	Std. err.	z	Pr()>|z|
FOD	0.386	0.063	6.103	0.000
SCI	0.583	0.097	6.028	0.000
AC	0.248	0.012	20.073	0.000
Taxiway	0.076	0.017	4.538	0.000
Apron	0.192	0.018	10.799	0.000
AC × FOD	-0.480	0.103	-4.649	0.000
AC × SCI	0.641	0.090	7.134	0.000
Taxiway × SCI	-0.363	0.107	-3.385	0.000

Apron × SCI	-0.457	0.105	-4.347	0.000

To better evaluate the effect of pavement surface type on airfield pavement service life estimated using different indexes, a series of Cox proportional hazard models were run the sub-databases divided by three branch uses (runway, taxiway, and apron). The statistical analysis results from Cox proportional hazard models are displayed in Table 5. These results are consistent with the observation results from survival curves, showing that PCC surfaced pavement has statistically significantly longer service life than AC surfaced pavement if the condition is evaluated by SCI or PCI. The results also indicate that, if the pavement condition is evaluated by FOD, the advantage of AC surfaced pavement over PCC surfaced pavement is only significant when the pavement section is located at taxiway.

Table 5 Effects of branch use on service life of airfield pavement

FOD	Apron			Taxiway			Runway		
		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	AC	-0.243	0.199	***AC***	***-0.489***	***0.013***	AC	-0.037	0.863
SCI	Apron			Taxiway			Runway		
		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	AC	***0.945***	***0.000***	***AC***	***0.667***	***0.000***	***AC***	***0.639***	***0.028***
PCI	Apron			Taxiway			Runway		
		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	AC	***0.482***	***0.000***	***AC***	***0.456***	***0.000***	***AC***	***0.387***	***0.000***

Similarly, cox proportional hazard models were run on PCI-based database, SCI-based database, and FOD-based database to test the effects of section branch uses on airfield pavement service life. The statistical results from Cox proportional hazard models are shown in Table 6. It is worth pointing out that, for the categorical variables related to branch use, since only one category can be initially selected as base category, all categories were tried as the base category and compared with each other based on Likelihood ratio test, Wald test, and Score test to select the proper base category among these categorical variables. As a result, runway and apron are selected as the base category under certain scenarios, respectively, as noted in Table 6.

Table 6 confirms the observation results from survival curves. The effect of branch use on airfield pavement service life is not significant if pavement condition is evaluated by FOD. Apron pavement have significant shorter service life than taxiway and runway pavement in general, which is also consistent with the result concluded by previous FAA study (*6*). However, runway turns to have the shortest service life for PCC-surfaced pavement if SCI is used. This finding reflects that for PCC surfaced pavement, the structural distresses on runway degrades its service life more than those on apron or taxiway.

Table 6 Effects of pavement type on service life of airfield pavement

	AC (Runway as base)			PCC (Runway as base)		
FOD		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	Taxiway	-0.310	0.121	Taxiway	0.172	0.426
	Apron	-0.100	0.674	Apron	0.094	0.574
	AC (Apron as base)			PCC (Runway as base)		
SCI		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	Taxiway	-0.878	0.000	Taxiway	-0.352	0.004
	Runway	-0.545	0.030	Apron	-0.236	0.043
	AC (Apron as base)			PCC (Apron as base)		
PCI		Coeff.	Pr()>|z|		Coeff.	Pr()>|z|
	Taxiway	-0.164	0.000	Taxiway	-0.133	0.000
	Runway	-0.242	0.000	Runway	-0.113	0.000

CONCLUSIONS

This study investigated the consistency and relationship of three pavement condition indexes (PCI, SCI, and FOD) for estimating airfield pavement service life. It was found that PCI had significant linear relationship with SCI and FOD, although confidence level of fitting model varied. A relatively high and statistically significant correlation was observed between the service life of airfield pavement estimated by PCI and FOD.

The analysis results from survival curves and cox proportional hazard models both show that the service life of airfield pavement estimated by PCI is significantly longer than the ones estimated by FOD and SCI in general. However, pavement surface type and branch uses can affect the comparison results between these condition indexes. PCC surfaced pavement generally has longer service life than AC surfaced pavement. On the other hand, apron sections have the shortest service life compared to runway and taxiway sections. However, this study points out that, if the pavement condition is evaluated by FOD, the advantage of PCC surfaced pavement over AC surfaced pavement turns to be opposite on taxiway. Meanwhile, PCC surfaced pavement sections on runway has the shortest pavement life if evaluated by SCI.

The study findings indicate that the use of PCI, SCI, and FOD for planning of M&R treatments in airfield pavement management system may not be fully replaced by each other, although correlations were found between them. In addition, different thresholds of pavement condition indexes may be needed by airport authorities for defining the service life runway, taxiway, and apron pavements since their importance levels are different. It is noted that the potential sources of FOD also include personnel, environment, and equipment in the airfield. Only the pavement related FOD is considered in this study.

RECOMMENDATIONS

Airfield pavement service life can be defined not only by structural failure, but also reaching the unacceptable function for aircraft operation safety. It is important for airport authorities to select the appropriate pavement condition index that provides the best indication of service life. The study results can be further used in life-cycle cost analysis and selection of M&R alternatives in airfield pavement management system. An example of decision making framework in airfield pavement management system is shown in Figure 7 (*18*). The ultimate goal is to consider multiple criteria in decision making of airfield pavement management, such as extended pavement life, cost, safety, and sustainability.

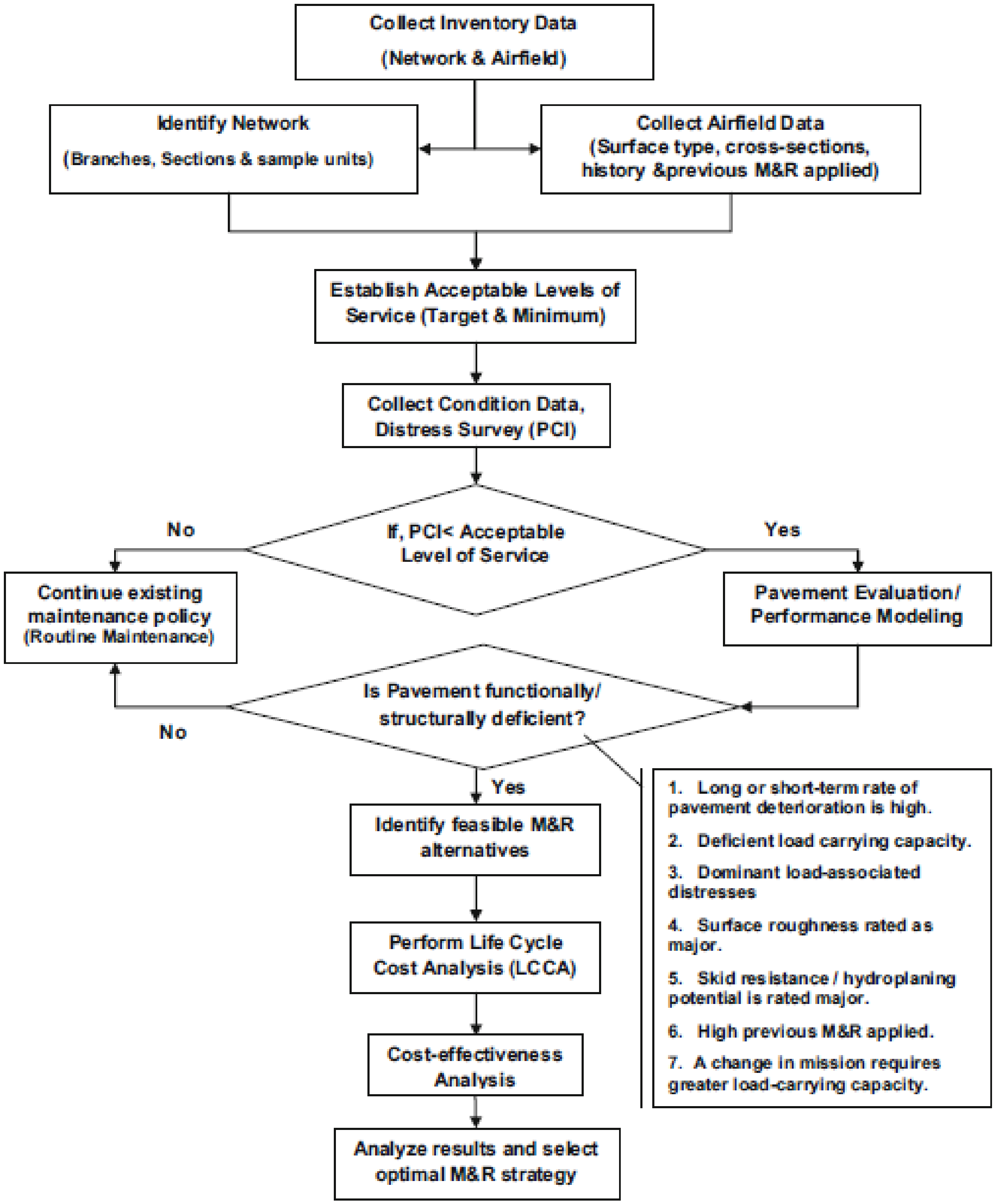

Figure 7 Example of Decision Making Framework in Airfield Pavement Management System

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