Design of an Enhanced Defect Identification System for Commercial Building Construction

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Abstract **- Fairfax County of Virginia enforces the Virginia Uniform Statewide Building Code which contains the building regulations that must be complied with when constructing commercial buildings. Current inspection methods consist of inspectors physically searching for building defects with human vision while many defects ranging from structural cracks and loose nuts and bolts to inadequate sealant application and water damage go unnoticed due to varying factors such as limited line of sight and unavailability of safe access equipment. Human vision inspection procedures are also subject to additional deficiencies and complications during inspections of exterior defects as inspectors are often limited to inspect defects from the interior perimeter of the building, consequently compromising their safety and inspection quality. With an annual forecasted growth of 500,000 square feet of new construction each year, an enhanced commercial building inspection system for identifying exterior defects is in need. A stochastic simulation model was developed using distributions derived from time and motion studies to compare the time, safety, and accuracy of three design alternatives to collect, process, and analyze inspection data: (a) human vision inspection system, (b) manual use of automated defect identification system, and (c) aerial-based automated defect identification system. The design alternatives were ranked using a Multi-Attribute Utility Analysis as follows: (1) aerial-based automated defect identification system – 0.664, (2) manual use of automated defect identification system – 0.567, and (2) human vision inspection system – 0.468; the aerial-based automated defect identification system achieved a high utility score based on its improvements in inspection time, safety, and accuracy.**

Index Terms – aerial inspection, building code, construction inspection, image recognition.

CONTEXT

Building inspections identify safety hazards, major and minor defects in design specification and construction, and violations to local regulations and building codes. While inspections are regularly conducted in the construction industry, Fairfax County of Virginia puts high priority in commercial building inspections. Fairfax County is the second-largest suburban real estate market in the United States and the largest in metropolitan Washington, D.C. The County possesses 116 million square feet of office space, commercial condominiums, industrial space, and flex space, ranging from single-story to high-rise buildings [1]. With its convenient proximity to the nation's capital and major highways such as I-95, I-66, and I-395, Fairfax County is experiencing a steady economic growth, as justified by the 735,000 square feet of new construction recorded in 2010 in comparison to the 4.6 million square feet of new construction in 2015.

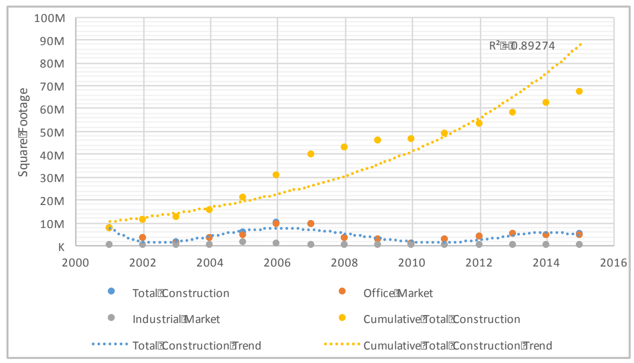

FIGURE I
NEW COMMERCIAL CONSTRUCTION BUILDING ACTIVITY IN FAIRFAX COUNTY (2001-2015)

Fairfax County enforces regulations and restrictions in construction of commercial buildings to ensure that buildings are built up to the Virginia Uniform Statewide Building Code (USBC). The Special Inspections Program, established in 1973 after a collapse of a 26-story building in Bailey's Crossroads, serves as an added layer of accountability for Architecture and Engineering firms to meet building quality and safety standards as early detection of defects is crucial as building flaws or regulation violations that are found in the later stages of construction can be costly and even life-threatening. The current building inspection system utilizes human vision carried out manually by general contractor superintendents and county inspectors to locate and identify visually observed defects such as structural cracks, misaligned roof shingles or weather-proofing plates, loose nuts and bolts, water damage, and inadequate sealant application. Unfortunately, the method of physically inspecting defects on building exteriors poses significant limitations and safety risks to the inspector. In the year 2015, the Occupational Safety and Health Administration reported that one in five worker deaths were in the construction industry, with 38.8% of those fatalities due to falls [2]. However, as the current inspection process requires inspectors to position themselves within visual line of sight to the defects, inspectors do not have other means than to observe building exteriors by leaning out between exterior framings or by fully entrusting the general contractor's workmanship.

PROBLEM STATEMENT

While continuous building inspections have been a County requirement since the 1970s, inspection methods have not seen changes since its establishment. Observation of defects on exterior walls of commercial buildings have particularly resulted in limitations from inspecting certain defects to avoid hazardous situations to inspectors such as risks of falling or injury as their access to defects are limited to the interior perimeter of buildings in the framing stages of construction.

I. Gap Analysis

As the suburban office market of Fairfax County continues to grow as justified by the 20% increase in new office space inventory within the past five years, there is a growing demand for building inspection in the commercial building construction market [3]. However, the County has not met growth in its inspector labor force or advancements in the inspection processes to reflect this market increase. The lack of uniform building defect reporting methods also limits the improvements that can be made in the inspection industry as there is no standard archive of inspection data readily available to county inspectors or general contractor superintendents. Therefore, there exists a gap between the increasing demand for new commercial building inspection and the ability of inspectors and superintendents to meet that demand without compromising inspection time, accuracy, and their safety.

STAKEHOLDER ANALYSIS

Primary stakeholders in the system serve as direct participants in the enterprise where the efficiency and outcome of building inspections result in benefit or harm.

I. Inspectors and Superintendents

Inspectors may be supplied from the County or be superintendents of the general contractors acting as inspectors procured to conduct the construction of the building. In both cases, inspectors must be certified and approved by the County either through direct employment or through prior approval and assignment. Their main objective in the system is to ensure that all buildings are constructed in accordance to the applicable building code by meeting all regulations and requirements. Tensions they face consist of time limitations in their schedules or based on the construction schedule as well as being held accountable for defects that may go unnoticed during the inspection.

II. A/E Firms and General Contractors

Architecture/engineering firms and its associates draft the appropriate building plans and specifications which is then approved by the County prior to construction of the building. General contractors are procured to carry out the construction tasks according to the approved specifications. Throughout construction, revisions of the plans are made and implemented. The objectives of the A/E firms and general contractors in the system is to construct the building within budget and on schedule. They may face tensions with each other as well as with inspectors as they will be held accountable for repairing defects and discrepancies in designs as they are identified.

NEED STATEMENT

In the current commercial building market of Fairfax County, there is a need for an enhanced defect identification system that will aid the process of commercial building inspections by reducing inspection time and improving safety, accuracy, and cost. The commercial building construction industry has been seeing a continuous growth in the recent years of its activity, therefore the inspection labor force must be met with improvements in inspection methods and procedures.

With an improved system that reduces inspection time and improves safety, accuracy, and cost of inspections inspectors and superintendents will be able to identify more defects in a set time without compromising their safety or the quality of the inspections. Particularly with a system that is able to potentially eliminate the requirement for the inspector to manually observe defects up close, inspectors will be able to reduce risks of falling or injury. A/E firms and general contractors will also be able to determine and archive construction defects for future reference and be able to hold each other accountable for design or construction flaws.

CONCEPT OF OPERATIONS

The enhanced defect identification system will consist of five operational procedures, utilizing an automated defect identification system through manual data collection methods and the use of unmanned aerial vehicles.

I. Creation of Lists of Items to Inspect

Inspectors will create a list of items to be observed and inspected for defects in the inspection by referencing the approved construction plans and specifications and the construction schedule. These defects may be structural cracks, misaligned roof shingles or weather-proofing plates, loose nuts and bolts, inadequate sealant applications, or water damage.

II. Development of Data Collection Plan

With the list of observable items, inspectors will develop a data collection plan consisting of the inspection path around the perimeter of the building framing from ground floor to the top floor. To allow an efficient inspection path, the inspector will plan on inspecting the floors one by one, in increasing floor numbers. For inspection using aerial-based vehicles, a flight path will be developed for the aircraft to spiral around the exterior perimeter of the building from ground floor to the top floor. The following figure is an example of an unmanned aerial vehicle flight plan for surveying the exterior of the building. This flight plan will be developed by the inspector to capture defects that are unreachable by the inspector from the interior framing of the building.

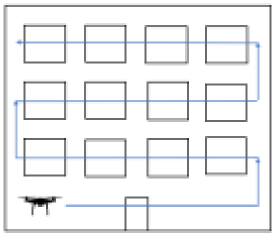

FIGURE II
SAMPLE UAV FLIGHT PLAN

III. Data Collection

The inspector will conduct the inspection and inspect areas where defects may be present, based on the list creation of observable items. With manual inspections, the inspector will manually walk around the perimeter of the interior framing. With automated inspections, the inspector will utilize the defect identification system by collecting photographs of the defect in various angles. In the aerial-based scenario, the photographs will be taken while the aerial vehicle hovers over the inspection points of interest.

IV. Defect Identification

As inspectors identify defects through human vision, notes will be made on traditional pen and paper to allow flagging of areas that require repair. If images of defects have been collected with digital photographs, the images will be processed and analyzed by the defect identification software that utilizes pixel recognition to note whether the images contain defects requiring repair.

V. Reporting and Archive

The standardization of defect categorization system enables reports to be created with minimal interrater reliability and quantitative results rather than qualitative descriptions that the manual inspection process uses. These reports and associated inspection data can be stored for long-term for future reference for similar building projects as well as maintenance inspections through the life of the building. Archive platforms include Fairfax County servers or cloud storage options such as Amazon Web Services Simple Storage Services (S3) and Amazon Glacier.

DESIGN ALTERNATIVES

With consideration of the current inspection, two additional design alternatives were considered. The current inspection method utilizes human vision inspection requiring inspectors to manually walk through the interior of the building for inspection of exterior walls. The second design alternative considers the use of automated defect identification system through collection of digital photographs while inspectors are still required to walk through the interior perimeter of the building with a camera. The third design alternative utilizes an aerial inspection method with an automated defect identification system using the aircraft camera and paired live-view modes to eliminate the inspector's need for manual walk-throughs while providing accessibility to exterior defects from the outside perimeter of the building.

I. Human Vision Inspection (manual)

The first design alternative, Human Vision Inspection, is how the building inspections are carried out today. The human vision inspection requires inspectors to manually walk around the interior perimeter of the building to inspect defects on the exterior walls under limited visual line-of-sight or subjecting themselves to risks of falling or injury. Due to physical limitations on the inspectors restricted access to exterior framing of buildings, many defects go unnoticed. In addition, the accuracy of the inspection relies heavily on the visual conditions of the defect as well as the inspector's claim on whether if an observed item is deemed defective. This raises concerns for interrater reliability as one inspector may consider an item to be defective while another inspector may pass the it to be sufficient. Defects are also recorded in a qualitative and descriptive manner as there are no uniform measurement or archive methods used in defect categorizations to measure key characteristics such as size, depth, and severity of defects.

II. Manual Inspection with Automated Defect Identification System (manual)

The second design alternative, Manual Inspection paired with an Automated Defect Identification System, combines the current inspection method and the introduction of pixel recognition. Inspectors will be required to walk around the interior perimeter of the building to inspect the exterior framing defects, however will use a camera to collect digital photographs of areas being observed for post-processing for pixel recognition. Cameras may be mounted on extenders to allow additional visual accessibility. Once images are taken, they will be post-processed on a computer and analyzed through a defect identification software to identify and record the defect type and characteristics.

III. Aerial-based Identification with Automated Defect Identification System (manual)

The third design alternative, Aerial-based Inspection with Automated Defect Identification System eliminates the need for inspectors to manually walk through the buildings being inspected. Inspectors can create a set flight path with utilizing waypoints to sweep around the building for inspection. Through the use of unmanned aerial vehicles and the equipped camera and live-view modes, inspectors will be able to observe buildings remotely. This allows the inspectors to remove themselves from risks of falling while having the gained accessibility to exterior defects as the aerial vehicles can fly around the exterior framing of the building for a direct visual line-of-sight to exterior defects. Unmanned aerial vehicles can also spiral between floors, reducing travel time in inspections as well as hover over areas that require additional observations to allow capturing multiple images from varied angles. Captured images will then be available to be analyzed at real-time with the live-view mode or be stored for post-processing with the defect identification software. With continued use and advanced proficiency, inspectors can expect faster data collection with flexibility in accessibility to exterior defects. However, this design alternative requires additional batteries as feasible aircraft designs allow for approximately 25 minutes of flight time, as well as vehicle insurance and registration with the Federal Aviation Administration. The inspector will also be required to obtain a pilot certification to operate the unmanned aerial vehicle.

SIMULATION

A stochastic simulation was used to estimate the the overall inspection time, safety, and accuracy of the three design alternatives and compare the two proposed designs to the traditional system of manual inspection using human vision.

I. Simulation Input

Various input values for the simulation consisted of data collected from time and motion studies in the field to mirror the current inspection system and the proposed design alternatives.

- **Properties of Defects:** Properties of defects to be identified were also observed to reflect descriptions of required visual line of sight and the likelihood of occurrence of each defect.

TABLE I

PROPERTIES OF BUILDING DEFECTS

Defect Type	Description of Required Visual	Required Angle	Likelihood of Occurrence
Structural cracks	Approximately linear, darker in color than surrounding area, greater than 3 cm in length	90° front facing	40% of defects
Misaligned roof shingles or weather-proofing plates	Casts geometrically inconsistent shadow and profile, greater than 5 cm	45° side angle	5% of defects
Loose nuts/bolts	Inconsistent geometry, less than 3 cm	45° side angle	20% of defects
Inadequate sealant application	Approximately linear, greater than 3 cm, darker in color than surrounding area	90° front facing	25% of defects
Water damage	Darker in color than surrounding area, creates round profile, greater than 5 cm	45-90° facing	10% of defects

- **Unmanned Aerial Vehicle:** Utilizing the DJI Phantom 3 Pro quadcopter, various time and speed values were collected to appropriate the input data for use of such aircrafts in a building inspection environment, with the maximum velocity threshold set to 4.7 meters per second to avoid potential fatalities caused by falling aerial vehicles.

$$KE = \frac{1}{2}\, mv^2, where\ KE = 250J. \quad (1)$$

$$v = \sqrt{\frac{2*250J}{m}}, where\ m = 22.68kg \quad (2)$$

TABLE II

OBSERVED INPUT VALUES FOR UAVS

Description	Mean, μ	St. Dev, σ
Time required for aerial vehicle pilot to set up, calibrate, and test aircraft	300 sec	100 sec
Time required for battery switch for aerial vehicle	300 sec	100 sec
Vehicle's flight speed inspecting for defects	1.0 m/s	0.3 m/s
Vehicle's flight speed ascending between floors	2.0 m/s	0.3 m/s
Vehicle's flight speed descending between floors	2.0 m/s	0.3 m/s

- **Manual Inspection:** Time and speed values were collected from observation of the human vision inspection process through manual testing and measurement recordings.

TABLE III

OBSERVED INPUT VALUES FOR MANUAL INSPECTION

Description	Mean, μ	St. Dev, σ
Time required for inspector to arrive at floor 1 from field office	600 sec	300 sec
Inspector's walking speed manually inspecting for defects	0.48 m/s	0.04 m/s
Inspector's walking speed up a staircase of average 27° gradient	0.57 m/s	0.05 m/s
Inspector's walking speed down a staircase of average 27° gradient	0.77 m/s	0.05 m/s

- **Camera/Sensor:** The camera capability was also tested to observe the relationship between the distance of the camera from an image being photographed and the quality of the photograph taken, using the same quality camera as that of the DJI Phantom 3 Pro. A photograph of a figure of various sizes were taken at varied distances then reviewed on a computer for visibility ratings from 0% to 100% clarity. Through this experiment it was determined that defects of size 2.5 centimeters or greater could be moderately identified at a distance of 2 meters away. The following table includes the allowable visual distance per each defect size with highlighted cells indicating furthest distances between the defect and the camera that allows for maximum clarity.

TABLE IV

ALLOWABLE VISIBILITY ON 12MP UAV CAMERA

	0.5 cm	1.0 cm	1.5 cm	2.0 cm	2.5 cm	3.0 cm	4.0 cm	5.0 cm
0.5 m	90%	100%	100%	100%	100%	100%	100%	100%
1.0 m	85%	100%	100%	100%	100%	100%	100%	100%
1.5 m	55%	90%	100%	100%	100%	100%	100%	100%
2.0 m	40%	80%	90%	100%	100%	100%	100%	100%
2.5 m	25%	50%	60%	90%	100%	100%	100%	100%
3.0 m	5%	20%	45%	70%	80%	90%	100%	100%
4.0 m	0%	5%	20%	40%	70%	75%	98%	100%
5.0 m	0%	0%	10%	25%	45%	50%	90%	100%

III. Design of Simulation

Defects were characterized by the time required to identify the defect, the safety risk the inspector would be subject to by inspecting the defect, and the accuracy in which the defect could be inspected in consideration of accessibility and visibility constraints in each alternative. Safety risk values were determined from a scale of 1 (low risk – favorable) to 7 (high risk – unfavorable) and accuracy values were determined from a scale of 1 (low accuracy – unfavorable) to 7 (high accuracy – favorable).

TABLE V

OBSERVATION TIMES PER DEFECT OCCURRENCE

Defect Type	Design Alt. 1	Design Alt. 2	Design Alt. 3
Structural cracks	μ = 180s σ = 30s	μ = 100s σ = 10s	μ = 60s σ = 30s
Misaligned roof shingles or weather-proofing plates	μ = 180s σ = 30s	μ = 90s σ = 30s	μ = 60s σ = 15s
Loose nuts and bolts	μ = 300s σ = 100s	μ = 350 σ = 100s	μ = 200s σ = 30s
Inadequate sealant application	μ = 300s σ = 100s	μ = 250s σ = 50s	μ = 200s σ = 30s
Water damage	μ = 120s σ = 10 s	μ = 60s σ = 10s	μ = 60s σ = 15s

TABLE VI

RISK ALERT FACTORS PER DEFECT OCCURRENCE

Defect Type	Design Alt. 1	Design Alt. 2	Design Alt. 3
Structural cracks	μ = 6.8 σ = 1.1	μ = 5.2 σ = 2.1	μ = 2.1 σ = 1.2
Misaligned roof shingles or weather-proofing plates	μ = 5.3 σ = 2.2	μ = 4.1 σ = 1.2	μ = 1.3 σ = 0.5
Loose nuts and bolts	μ = 6.6 σ = 1.9	μ = 5.2 σ = 1.7	μ = 2.1 σ = 1.2
Inadequate sealant application	μ = 6.2 σ = 3.1	μ = 3.2 σ = 1.6	μ = 2.1 σ = 1.1
Water damage	μ = 3.1 σ = 0.4	μ = 1.1 σ = 0.3	μ = 4.2 σ = 0.4

TABLE VII

ACCURACY FACTORS PER DEFECT OCCURRENCE

Defect Type	Design Alt. 1	Design Alt. 2	Design Alt. 3
Structural cracks	μ = 3.7 σ = 1.3	μ = 5.2 σ = 1.9	μ = 6.1 σ = 2.1
Misaligned roof shingles or weather-proofing plates	μ = 4.1 σ = 1.4	μ = 5.2 σ = 1.4	μ = 6.6 σ = 1.1
Loose nuts and bolts	μ = 3.2 σ = 1.1	μ = 4.7 σ = 1.2	μ = 6.1 σ = 2.1
Inadequate sealant application	μ = 4.2 σ = 1.6	μ = 5.8 σ = 1.2	μ = 5.5 σ = 1.1
Water damage	μ = 6.1 σ = 2.1	μ = 6.2 σ = 1.5	μ = 5.3 σ = 1.4

With JavaScript programming, building dimensions were formulated using various building widths, lengths, and floor numbers which then determined the interior and exterior perimeters of the building inspectors or the unmanned aircraft would inspect defects from. The interior perimeter and exterior perimeter were given a difference of 3 meters to allow for the thickness of exterior framing and walls as well as the average distance between the building and the aerial vehicle flight path. The inspector's walking speeds, aircraft's flight speeds, and time required for the aircraft's battery switch were included in the simulation with the use of random number generators to reflect distributions for varied values.

Three functions were created to simulate each of the design alternatives. The first two design alternatives considered the interior perimeter as the inspector would manually walk through the inside of the building and observing defects on the exterior walls. The third design alternative considered the exterior perimeter of the building as the aircraft would fly around the exterior of the building and hovering at various locations where defects are to be observed. Elapsed inspection times, safety risk values, and accuracy values for each of the design alternatives were observed for 1000 iterations per building dimension.

DESIGN OF EXPERIMENT

It was hypothesized that either manual inspection with automated defect identification system (design alternative 2) or aerial inspection with automated defect identification system (design alternative 3) would see a minimum of 20% improvement in time, safety, and accuracy than that of the traditional system, human vision inspection (design alternative 1). The 20% goal was determined to be an adequate improvement as a reflection of the average growth in new commercial building construction seen in the last five years in Fairfax County.

RESULTS

Varied building dimensions of 3 to 6 floors were observed to output elapsed time, safety risk, and accuracy values to be compared among the three design alternatives.

- **Time:** A notable difference can be observed between the elapsed time of the human vision inspection compared to that of the two design alternatives utilizing automated defect identification system; 17.6% for its manual use and 44.4% for the aerial-based system, allowing for post-processing of digital photographs.

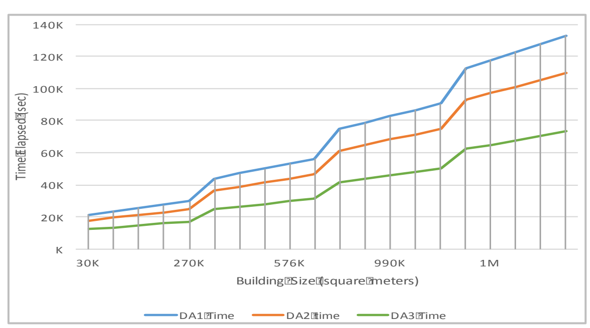

FIGURE III

RESULTING ELAPSED TIME OF INSPECTION SIMULATION

- **Safety Risk Value:** Human vision inspection resulted in the highest total safety risk value, indicating that the process posed more dangerous threats to the inspector's safety than that of the manual and aerial-based use of the automated defect identification system which resulted in 25.4% and 51.7% of improvement, respectively.

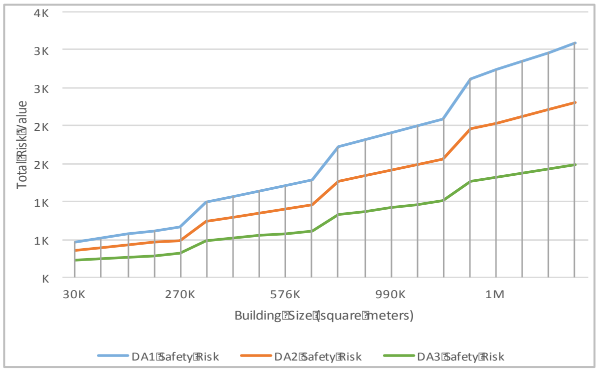

FIGURE IV
RESULTING SAFETY RISK VALUE OF INSPECTION SIMULATION

- **Accuracy Value:** The aerial-based automated defect identification system resulted in the highest accuracy level due to flexibility in visual line-of-sight with the aid of unmanned aerial vehicles and hover technology. The average accuracy improvement seen in this design was 36.3% while the manual use of automated defect identification system resulted in a 26.5% accuracy improvement.

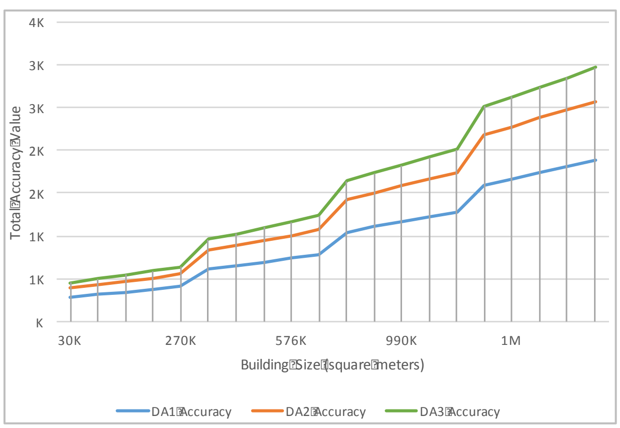

FIGURE V
RESULTING ACCURACY VALUE OF INSPECTION SIMULATION

ANALYSIS

From the obtained simulation results, additional analysis was conducted to compare each design alternative on three attributes by Analytic Hierarchy Process using Logical Decisions® Multi-Attribute Utility Analysis: (a) time – weight of 0.20, (b) safety risk value weight of 0.50, and (c) accuracy value – weight of 0.30.

The AHP weight matrix was developed to reflect the weights of each of the three attributes for utility analysis.

l-max = 3.000 C.I. = 0.000 C.R. = 4.27e-009	Accuracy	Safety Risk	Time
Accuracy	0.300	0.600	1.500
Safety Risk	1.667	0.500	2.500
Time	0.667	0.400	0.200

TABLE VIII
AHP ATTRIBUTE WEIGHT MATRIX

Sensitivity analysis was conducted by incorporating the average values of the obtained simulation outputs in consideration of the pre-determined weights from. Rankings based on the combination of utility attributes resulted in the following result: (1) aerial-based automated defect identification – 0.664, (2) manual use of automated defect identification system – 0.567, and (3) human vision inspection system – 0.468. This resulted in the third design alternative of aerial-based automated defect identification system to be 30% higher in the utility score, most sensitive to safety risk factors.

FIGURE VI
RANKING OF ALTERNATIVES FROM SENSITIVITY ANALYSIS OF UTILITY

Based on the simulation and analysis of its results, the use of aerial-based defect identification system can provide large improvements in the current building inspection market and increase capacity for more inspections with added safety and accuracy than that of the current process.

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