DEVELOPING A CONCEPT FOR EVALUATING DEFECT LEVEL IN VISUAL QUALITY INSPECTION THROUGH DIGITAL IMAGE PROCESSING AND FUZZY LOGIC THEORY

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การพัฒนาแนวความคิดสำหรับประเมินหาระดับความบกพร่องในการตรวจสอบคุณภาพด้วยสายตาโดยการประมวลผลภาพดิจิตอลและทฤษฎีฟัซซี่ลอจิก

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การตรวจสอบคุณภาพงานด้านสถาปัตยกรรมมีหลายรายการที่ใช้วิธีการตรวจสอบด้วยสายตา โดยเฉพาะงานที่เกี่ยวข้องกับความสวยงาม ผู้ตรวจสอบไม่สามารถระบุปริมาณของค่าความบกพร่องได้ การประเมินดังกล่าวใช้เพียงแค่ความรู้สึกที่ขึ้นอยู่กับประสบการณ์ของแต่ละบุคคล เพราะขาดมาตรฐานอ้างอิงในการประเมิน โดยความแตกต่างของมุมมองในการประเมินคุณภาพนำไปสู่ความไม่แน่นอนและก่อให้เกิดข้อโต้แย้งระหว่างบุคคลที่เกี่ยวข้องในการตรวจสอบ ดังนั้นวัตถุประสงค์ของงานวิจัยนี้คือนำเสนอแนวคิดการพัฒนาระบบประเมินข้อบกพร่องเพื่อสนับสนุนการตรวจสอบคุณภาพด้วยสายตาในด้านความสวยงามของงานสถาปัตยกรรม ระบบแบ่งออกเป็นสององค์ประกอบหลักคือ (1) ระบบตรวจหาตำแหน่งและปริมาณข้อบกพร่อง (2) ระบบการประเมินระดับข้อบกพร่อง ระบบแรกประยุกต์ใช้เทคนิคการประมวลผลภาพดิจิตอลเพื่อวิเคราะห์คุณลักษณะข้อบกพร่องและหาปริมาณของข้อบกพร่อง ระบบที่สองมาตรฐานการประเมินข้อบกพร่องสำหรับใช้ในองค์กรพัฒนาขึ้นโดยใช้ระบบฟัซซี่ลอจิก การตัดสินใจโดยใช้กระบวนการลำดับชั้นเชิงวิเคราะห์ และแนวคิดการจัดการองค์ความรู้ กรณีศึกษาที่ถูกเลือกมาพัฒนาระบบต้นแบบคือการตรวจสอบงานปูกระเบื้อง ผลของการนำระบบไปทดลองใช้ในหน่วยงานก่อสร้างจริงแสดงให้เห็นว่าระบบมีค่าความแม่นยำสูงสุดเท่ากับ 79% เมื่อเปรียบเทียบกับตำแหน่งที่บกพร่องจริง ซึ่งมากกว่าค่าความแม่นยำของผู้ตรวจสอบ ประโยชน์ที่ได้รับจากระบบคือ ช่วยเพิ่มความน่าเชื่อถือของกระบวนการตรวจสอบด้วยสายตาโดยลดการตัดสินใจที่ใช้เพียงแค่ความรู้สึกของแต่ละบุคคลในประเด็นของความสวยงาม และช่วยลดข้อโต้แย้งเกี่ยวกับการตัดสินใจยอมรับระดับความบกพร่อง

ภาควิชา วิศวกรรมโยธา ลายมือชื่อนิสิต..

สาขาวิชา วิศวกรรมโยธา ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก.................

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Several items in defect check list of the quality inspection on architectural works only use subjective visual inspection, especially those involving aesthetic faults. The inspectors are not able to quantify the value of defect. Subjective evaluations depend on individual experience because they lacks of the quality evaluation standard. The different perception on quality evaluation leads to unreliable results and causes conflicts between people involved in quality inspection. Therefore, the objective of this research is to present a concept of developing defect evaluation system for supporting the visual quality inspection in aesthetic issue of architectural work. The system is divided into two main components: (1) the defect detection and quantification system, (2) the defect level evaluation system. First, the digital image processing technique is applied to analyze the defect feature and quantify the defect value. Second, the standard of defect level evaluation using within organization is developed by using Fuzzy logic, AHP and Knowledge Management concepts. The inspection of tiling work was chosen as a case study for developing a prototype system. The result of the implemented system on an actual construction site was given the most accuracy of position detection at 79% when compared with actual defect positions. The result from defect level evaluation system is more reliable than it from inspectors. The potential benefits of the system are to increase the reliability of visual quality inspection by reducing the subjective human judgment of aesthetic faults, and to reduce conflict about acceptable judgment of defect level.

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CHAPTER I
INTRODUCTION

1.1 Background

The construction business is a highly competitive environment, and quality is a key element for a business's success and survival. Besides cost and time, quality of the product is a key to customer satisfaction with regard to the performance of construction projects. Therefore, many construction companies are looking for processes that will provide superior quality to meet their customer's needs. Quality control is an important element to achieve this and inspection is one of the most essential components in the quality control process. Inspection is the act of measuring or carefully examining a product's quality and preventing defects to ensure that the final product meets specifications, is fit for use and fulfills the customer's requirements (Juran and Gryna, 1980; Pesante-Santana, 1997). Moreover, effective quality inspection can avoid the very large costs and delays that are associated with having to redo work that does not meet specifications (Hendrickson, 1998).

Generally, quality inspection can be performed during the work-in-process and end-product stages. During the work-in-process stage, inspection is used to check work preparation for each procedure to reduce the number of defects in the final product. One example of this is a steel and formwork installation inspection before pouring concrete in structural work. Inspection during the end-product stage aims to detect defects or construction errors that must be remedied to improve the quality of the final product including aesthetic issues in architectural work. Inspection during both stages is therefore essential for quality control to ensure that the quality of the end product meets the customer's requirements (Bannister, 1991).

However, the current quality inspection process still encounters conflicts regarding the judgment of acceptable defect levels between people involved in the construction process such as inspectors, contractors and the customer. The evaluation of the quality of inspection processes for construction work can be divided into two categories consisting of measurable and subjective attributes (Arditi and Gunaydin, 1997; Toakley and Marosszeky, 2003). These processes are shown in Figure 1.1. Measurable attributes include material, construction and functional requirements. These must conform to a contract document that includes the standards, sampling and specifications to adhere to in the construction work. Because these attributes can be measured, mechanical instruments are frequently used to enhance observations for human judgment. Instruments such as gauges are used to determine thread sizes, gap thicknesses, angles between parts, hole depths, and weld features. Thus, the quality of the work can be understood, controlled and evaluated by comparing measurements with initial specifications. In contrast, subjective attributes relate to aesthetic faults which are especially common in architectural work. Quality inspection in this area usually makes use of subjective visual inspections. A person's ability to judge aesthetic faults is limited in that it cannot quantify the value of a given defect. Subjective evaluation depends on individual experience and differing perceptions which may not be based on a uniform standard. In fact, the same person might even make different judgments on different days (Shingo, 1986). Moreover, it is not possible for a person to determine all the possible defects that can occur in a project. Therefore, certain methods must be devised to solve the problem of subjectivity in quality evaluation due to the inherent limitations of human perception.

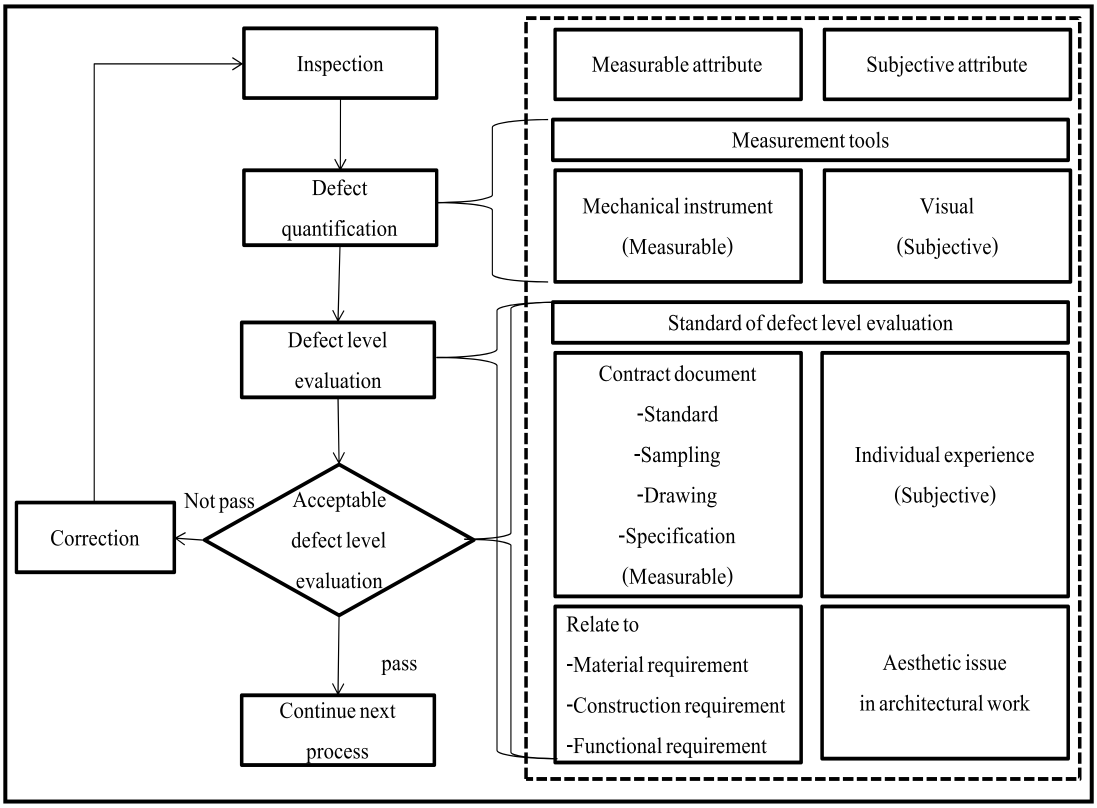

Figure 1.1 Quality evaluation in inspection processes

From above discussion, the subjective attributes lead to the unreliability of quality evaluation, which need to be overcome. We make to explore the methods from the review of related literature. We have derived an understanding of the capability of digital image processing techniques, fuzzy logic theory, AHP and principle of knowledge management. The digital image processing technique can be used to analyze the feature of defect from digital image that limitation of human vision cannot quantify defect value. The digital image processing technique is used the damage inspection in several concrete structures such as road, tunnel and bridge

(Georgopoulos, Loizos and Flouda, 1995; Lee, 2004; Yu, Jang and Han, 2007; Furuta, Namura, Nakatsu, Hattori, and Adachi; 2009; Lee, Chang and Skibniewski, 2006). Moreover, the image processing can be applied to inspect the defect level in the architectural work such as air pockets detection in architectural concrete (Zhu and Brilakis, 2008) and defect positions detection on materials in manufacturing (Boukouvalas, Kittler, Marik, Mirmehdi and Petrou, 1995; Srikanteswara, 1997; Ghazvini, Monadjemi, Movahhedinia and Jamshidi, 2009; Silvestre and Brito, 2009; Ruz, Estevez and Ramirez, 2009). Next, the fuzzy logic theory is used in various cases of decision making problem in subjective attributes and ambiguity such as evaluation of customer satisfaction, concept of a comfortable temperature, and separating height value between short and tall (Zadeh, 1965; Zimmermann, 1991; Fasanghari and Roudsari, 2008). Moreover, AHP, and principle of knowledge management can be used also to support the problem solving of subjective attributes (Saaty, 1980; Huizingh and Virolijk, 1994; Sahoo, 1998; Tiwana, 2001; Alavi and Leidner, 2001; Bahra, 2001). For more details are described in Chapter 4.

Although many researchers intend to study for overcoming the subjective attributes, few researchers have focused on evaluating the intensive defect level of the subjective attributes of aesthetic issues during the construction stage. The quality evaluation in aesthetic issue likes fuzziness which is difficult to quantify defect value and classify defect level. In real practice, the classification in each defect level has the tolerate vagueness. Therefore, our study aims to present a concept of developing a system for evaluating aesthetic defect levels of architectural work. The proposed system is used within an organization to overcome the conflict in different perception from subjective attributes.

1.2 Problem statements

In current practice, the aesthetic evaluation process for defects using visual quality inspection in the construction process encounters the following problems:

1.2.1 Unreliability of current methods of aesthetic evaluation of defects

Judgments of aesthetic qualities in visual quality inspection are evaluated using human sensory systems e.g. touch or vision. It is difficult to identify defect levels or to quantify defects precisely. Sensory mediated methods are unreliable and result in largely subjective judgments.

1.2.2 Problems of multiple-standards in defect level evaluation

The decision making process in aesthetic evaluation of defect levels is subject to multiple-standards depending on the experience of each person. Different people will make different judgments and the same person might even have different judgments on different days (Shingo, 1985). Lack of precise evaluating criteria often leads to conflicting judgments between project participants who are involved in visual quality inspection.

1.2.3 Failure to retain and use previous decisions in visual quality evaluation for continued product quality and knowledge improvement

During the construction process, the inspector encounters different scenarios and problems as the project progresses. Retention and incorporation of the lessons learned from previous problem solving decisions helps the inspector refine his knowledge base which can be applied, along with workers' skill sets, to achieve continuous quality improvement. Moreover, the knowledge of quality standards can supplement the inspector's inexperience in quality assessment.

1.3 Research objectives

The research objective is to present a concept of developing defect evaluation system for supporting the visual quality inspection in aesthetic issue of architectural work. The defect evaluation system will help to reduce the subjective human element in judgments of an aesthetic nature which often rely heavily on an individual's experience. It will increase reliability by using digital image processing (DIP), fuzzy logic and a clearly defined knowledge base to overcome limitations arising from the subjectivity of human perception. Accordingly, the sub-objectives of this dissertation are:

1.3.1 To develop a conceptual framework for the defect evaluation system.

1.3.2 To develop a knowledge-based system related to defect level classification.

1.3.3 To develop a prototype of the defect evaluation system.

1.3.4 To demonstrate the reliability of the method through comparison with the results of defect evaluation by human inspectors alone.

1.4 Scope of research

This research was carried out with the following predetermined limits:

1.4.1 The focus is on aesthetic issues in architecture work using visual quality inspection.

1.4.2 The system concept does not intend to evaluate all quality requirements using only image processing techniques. The focus is instead on supporting visual quality inspection with respect to certain quality requirements.

1.4.3 Use of case studies on defects in tiling work.

1.4.4 Data from housing projects.

1.5 Research methodology

The research methodology employed in this study will be as follows.

1.5.1 Preliminary research

1.5.1.1 Field observation of visual quality inspection methods in current use and problems of human subjective judgment in aesthetic issues.

1.5.1.2 Review previous literature and research on integrated systems in development; an overview of quality inspection in construction projects; digital image processing (DIP); use of a decision support system (DSS) and knowledge management system (KMS); description of the basic concepts, benefits, implementation, integration and limitations of the system.

1.5.1.3 Review previous literature and research on the use of information technology tools and the Matlab (DIP and Fuzzy logic toolbox) programs for system development. Indicate the advantages and limitations of these technologies.

1.5.2 Conceptual framework development from literature review and observational data.

1.5.3 System design and development

1.5.3.1 Tool development for defect detection and quantification from image feature analysis.

1.5.3.2 Development of quality standards knowledge base to support defect level evaluation using own organization or project.

1.5.3.3 Development of defect level evaluation system.

1.5.4 Implementation, experimental system, verification and validation

1.5.5 Presentation of results, conclusions, and future research.

1.6 Research contributions

1.6.1 The research outcome will be a new concept to support visual quality inspection in construction work. The product of this research will be divided into three main parts as follows.

1.6.1.1 A new conceptual framework applying DIP, Fuzzy logic and KMS to develop a defect evaluation system for an organizational use to support visual quality inspection in architectural work.

1.6.1.2 Two new algorithms proposed to support the system and used in a case study of tiling work: one algorithm for gap size inspection and another for right angle inspection.

1.6.1.3 Prototypes for the defect detection and quantification system, and the defect level evaluation system for tiling inspection.

1.6.1.4 A new concept to develop a knowledge based model and evaluation mechanism derived from fuzzy logic theory to use as the standard of defect level evaluation in aesthetic issues for an organizational use. The evaluation standard increases the reliability of visual quality inspection.

1.6.1.5 Information from the results of the experimental system demonstrating the applicability, problems and limitations of the proposed evaluation concept on an actual construction site will be of use to other researchers.

1.6.2 Potential benefits of the system in engineering work.

1.6.2.1 The concept of applying a defect detection and quantification system can increase the reliability of visual inspection of defect positions because a person's ability to judge aesthetic faults is limited. People have some limitation in quantifying defect values. So, inspectors using a visual inspection method cannot cover all defect positions, especially in the case of massive products or large areas, and respective evaluations may not be consistent. The proposed system can detect defect positions more thoroughly and consistently than unaided human visual inspection. Moreover, the proposed system can quantify defect values. These defect values can be applied to classify defect levels as an evaluation standard in each organization and used it for continuous quality improvement.

1.6.2.2 The proposed defect level evaluation system can increase the reliability of visual inspection. As traditional visual methods of defect level evaluation of aesthetic architectural issues depend on the inspectors' individual experience, each one will have a different perception without an evaluation standard. Such evaluations may also be inconsistent. The proposed defect level evaluation system evaluates the defect level using a uniform standard leading to greater reliability and consistency when used on actual building projects.

1.6.2.3 The evaluation standard is based on input from all major participants in a project or organization to ensure the reduction of sources of conflict among project participants who are involved in evaluating work defects such as inspectors, contractors and customers.

1.6.2.4 The proposed system can be used to improve inspector knowledge, workers' skills and quality of product. The quality standard knowledge base can support inspectors who inexperienced in quality evaluation decision making.

1.6.2.5 The proposed conceptual framework can be used to develop defect level evaluation systems for quality inspection in other types of work.

CHAPTER II
LITERATURE REVIEW

This chapter presents a literature review of related research. First, an overview of quality management in construction projects is described. Second, basic concepts, benefits, the implementation and integration of digital image processing (DIP), a decision support system (DSS) and knowledge management system (KMS) in construction quality management are explained. Next, the use of information technology tools and MATLAB applications (DIP and Fuzzy Logic toolbox) for system development will be explained. Finally, issues related to integrated systems are discussed.

2.1 Overview of quality management in construction projects

In the present highly competitive construction industry, quality is a key element for success and survival. Besides cost and time, a high quality product with regards to the performance of construction projects, is an important requirement for customer satisfaction. Therefore, many companies and researchers have attempted to determine which strategies are most effective to ensure quality in building projects.

Previous research has presented several issues which are causes of low quality in the construction industry. For example, Arditi and Gunaydin (1997) point to many characteristics that are different between the construction and manufacturing industries. Some of their conclusions are described as follows:

- Each construction project is unique. The conditions differ from site to site. While manufacturing installations are typically fixed. Therefore, similar conditions exist for production in different locations.
- The life-cycle of a construction project is longer than the manufactured products.
- There is no clear quality control standard in evaluating overall construction quality as there is in the manufacturing industry. Quality in construction projects is usually the outcome of a subjective evaluation.
- The construction industry has more participants e.g. owners, designers, general contractors, subcontractors, material suppliers, etc.
- These factors can lead to uncertainty in decision making situations and be difficult to control.

Figure 2.1 shows general components of the construction process including input, production and output processes. In reality, all parties are trying to achieve good performances of the output process to be seen in completed projects. Successful projects are those with high quality, and end products completed under budget and in time. However, many projects encounter problems which result in poor performance outcomes due to a lack of inspection of input and production processes, for example, low quality materials, or lack of knowledge, experience and motivation of manpower (labor), and mistakes in design (Josephenson and Hammarlund, 1999). Another cause of poor outcomes is a production process using unsuitable construction methods and management (Ledbetter, 1994).

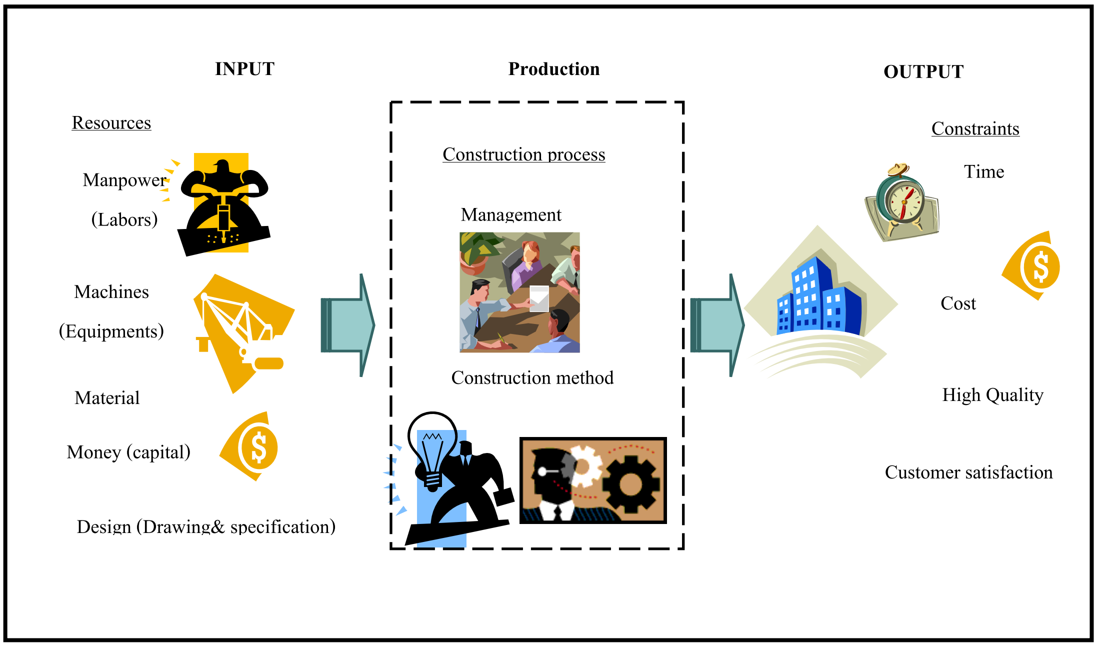

Figure 2.1 General components in the construction process
(modified from Hashiholan (2006) and Kubal (1994))

These issues make it difficult to achieve high performance and a high quality end product for customer satisfaction. Therefore, the construction industry needs efficient quality management procedures. Quality inspection is an essential part of the process to meet customers' requirements and to limit factors which can lead to poor performance outcomes. A poor quality product is still possible when these processes are without inspection, despite good input processes such as high quality materials or proper construction methods. Every aspect of the construction process needs quality control.

This section will give an overview of quality management in construction projects. It includes definitions of quality from several perspectives and industries, basic concepts of quality management, the need for quality inspection standards, problems in current practice, and improvement of quality management systems.

2.1.1 Definitions

2.1.1.1 Quality

The word “quality” is frequently used to describe goods or services. It means different things to different people (Kubal, 1994). In general usage, quality has come to mean “better quality”, and better quality often means richer, finer, and more costly materials, better methods or a better appearance (Banister, 1991). Quality has been defined as fitness for use, or the extent to which a product meets the customer’s requirements (Juran and Gryna, 1980).

In the field of construction, “quality” has a different meaning than it has in general usage. The Design & Construction Quality Institute (DCQI) gives four definitions of quality depending on the role of the user. For an owner, quality means fitness for an intended purpose. For a designer, it means conformance to certain requirements. For a contractor, it means reliance and strict adherence to a plan. To operational and facilities management people, it means the ability to maintain an acceptable, predictable performance. In addition, quality for the inspector is defined by Banister (1991) as “meeting the established requirement”. These standard requirements are established in the project design. The design, embodied by the drawings and specifications, establishes the relative quality of the materials and the level of workmanship. Quality is not judged by the product’s cost, but by its expected performance in relation to desired standards (Kubal, 1994).

In another work, Arditi and Gunaydin (1997) defined “quality” as meeting the legal, aesthetic and functional requirements of a project. Chamberlin (1995) defined “quality” as conformance to established requirements. Quality is a critical factor in determining project acceptance and resultant contractual payment levels based on relationships between material/construction characteristics and performance.

2.1.1.2 Quality standards

A standard is a procedure, product or criterion that is accepted as a basis for comparison. It is established by determining the technical and non-technical elements of the procedure or product. In codes, handbooks and manuals, standards are defined as those procedures developed and approved for determining whether requirements are satisfied and regarded as proper for use(McKechnic, 1972).

Quality standards in construction projects refer to: (1) codes and standards, (2) drawings and specifications.

(1) Codes and standards have a primary purpose to protect the health and safety of the public. The design professional must be knowledgeable about provisions of codes and standards before starting the design process because building

codes directly control the minimum standards of many components of a building project, and are responsible for much of the quality of the finished product. Determining which codes and standards apply to a project should be an issue addressed early in the design phase to avoid having to redo plans and specifications which can result in considerable cost and delay. Stasiowski and Burstein (1994) underline that quality design begins with sound engineering and scientific principles and must satisfy the criteria of applicable codes and standards as well as the owner's project requirements.

International standards are used to regulate the types of goods and services that flow between nations. One main purpose of international standards is to work towards harmonizing technical regulations of different nations. Examples of such organizations are the ASME, ASTM, the British Standards Institution (BSI), the Canadian Standards Association (CSA), and the German National Standards Organization (DIN). Many of the standards adopted by these organizations are incorporated into international standards through the ISO (Yates and Aniftos, 1997).

(2) Drawings and specifications are contract documents that guide the physical construction of the project by the contractor by providing technical information on materials, performance requirements of the constructed facility, and quality requirements. Drawings show the design concept, size and scope of the job, number and size of materials or items to be used in the process, and how they are assembled into a final project (Oberlender, 1993). There are often inconsistencies between a project's drawings and specifications. The quality of the drawings and specifications received from the designer has a great effect on quality in the design and construction phases, and consequently the quality of the constructed facility.

2.1.1.3 Quality inspection

This process is called "inspection" or "on site observation". It is the act of measuring or examining carefully the quality of a product (Pesante-Santana, 1997). It means looking at what the contractor is doing and determining. It must meet the standards that they have been contracted to provide. The accepted standards are enumerated in the contract documents including the agreement, conditions of the contract, drawings and specifications.

2.1.2 Quality management: basic concepts

What constitutes acceptable levels of quality in the construction industry has been a problem for a long time because of a lack of efficient quality management procedures. Many have attempted to apply quality management strategies from the manufacturing industry to the construction industry for increased productivity, decreased product cost and improved product reliability.

Total quality management (TQM) is one of several strategies that has been applied in construction projects (Ledbetter, 1994), although some have argued it could only be applied to mass produced goods. The principle of TQM focuses on process improvement, customer and supplier involvement, teamwork, and training and education in an effort to achieve customer satisfaction, cost effectiveness, and defect-free work by continuously improving performance (Arditi and Gunaydin, 1997). It includes a quality assurance (QA) and quality control (QC) program. Quality assurance involves establishing project related policies, procedures, standards, training, guidelines, and system necessary to produce quality. These developments are the responsibility of the designer and builder in each project. Quality control is a part of quality assurance which is a set of specific procedures involved in the quality assurance process (Ferguson and Clayton, 1988). These procedures include planning, coordinating, developing, checking, reviewing, and scheduling work. They are used to monitor the process and reduce the possibility of changes, mistakes, and omissions. As a result, it can eliminate the problems that lead to conflict, disputes and unsatisfactory quality performance (Juran, 1988, and Wick and Veilleux, 1993).

Inspection is one of the essential processes in quality control necessary to assure a construction product of high quality. Inspection can occur during the construction and operation stages. During the construction phases, the main contractor's staff usually takes the role of checking work preparation and ensuring the quality of the final construction product. This process is a minimum requirement of the specifications. Inspection at this phase also involves the consultant who investigates and approves the quality of the work of the main contractor. Quality assurance procedures must apply from the beginning of a project. Inspection should look at all periods of construction to ensure high quality in both work-in-process and end-products in order to reduce defects in the final product. Construction errors are identified in a punch list during final inspection (Banister, 1991). After the construction project has been built and operated for a period of time, it is necessary to check the quality of a number of construction elements. At this point, inspection aims to maintain and ensure the property of construction during operational phases (O'Brien, 1997).

2.1.2.1 Types of quality inspection

An inspection is most generally an organized examination or formal evaluation exercise. It involves measurements, tests, and gauges applied to certain characteristics in regard to an object or activity. The results are usually compared to specified requirements and standards to determine whether the item or activity is in line with targets. There are two types of inspection: (1) destructive testing technique and (2) nondestructive testing (NDT) technique.

(1) Destructive testing technique is that in which testing is carried out to the failure of the specimen in order to understand its structural performance or material behavior under different loads. These tests are generally much easier to carry out, yield more information, and are easier to interpret than nondestructive testing. Destructive testing is most suitable, and economic, for objects which will be mass produced, as the cost of destroying a small number of specimens is negligible. It is usually not economic to do destructive testing where only one or very few items are to be produced, for example, in the case of a building. Some types of destructive testing are stress tests, crash tests, hardness tests and metallographic tests.

(2) Nondestructive testing (NDT) technique is an analysis technique used in scientific fields to determine the state or function of a system by comparing a known input with a measured output. It does not use invasive approaches like disassembly or failure testing because NDT does not require the disabling or sacrifice of the specimen or system of interest. It is a highly-valuable technique that saves both money and time in product evaluation, troubleshooting, and research. NDT methods include acoustic testing, liquid penetrate testing, and radiographic testing. NDT can be used with any isolated input / output system, and is a commonly-used tool in forensic engineering, mechanical engineering, electrical engineering, civil engineering, systems engineering, and medicine.

Inspections are usually non-destructive. Non-Destructive Examination (NDE) or Non-Destructive Testing (NDT) describes a number of technologies used to analyze materials for either inherent flaws or damage from use. Some common methods are visual, Liquid or Dye Penetrate, Magnetic Particle, Radiography, Ultrasonic, eddy Current, Acoustic Emission and Thermography. In addition, many non-destructive inspections can be performed by a precision scale, or, when in motion, a check weigher.

Visual inspection is by far the most common nondestructive testing (NDT) technique. Visual inspection is the process of examination and evaluation of systems and components using human sensory perception systems aided only by mechanical enhancements to sensory input such as magnifiers, dental picks, stethoscopes, and the like. The inspection process may be performed using such methods as looking, listening, feeling, smelling, shaking, and twisting. It includes a cognitive component wherein observations are correlated with knowledge of structure and with descriptions and diagrams from the service literature.

2.1.2.2 Components of the quality inspection process

The components of the quality inspection process to support the decision making process for quality evaluation are shown in Figure 2.2.

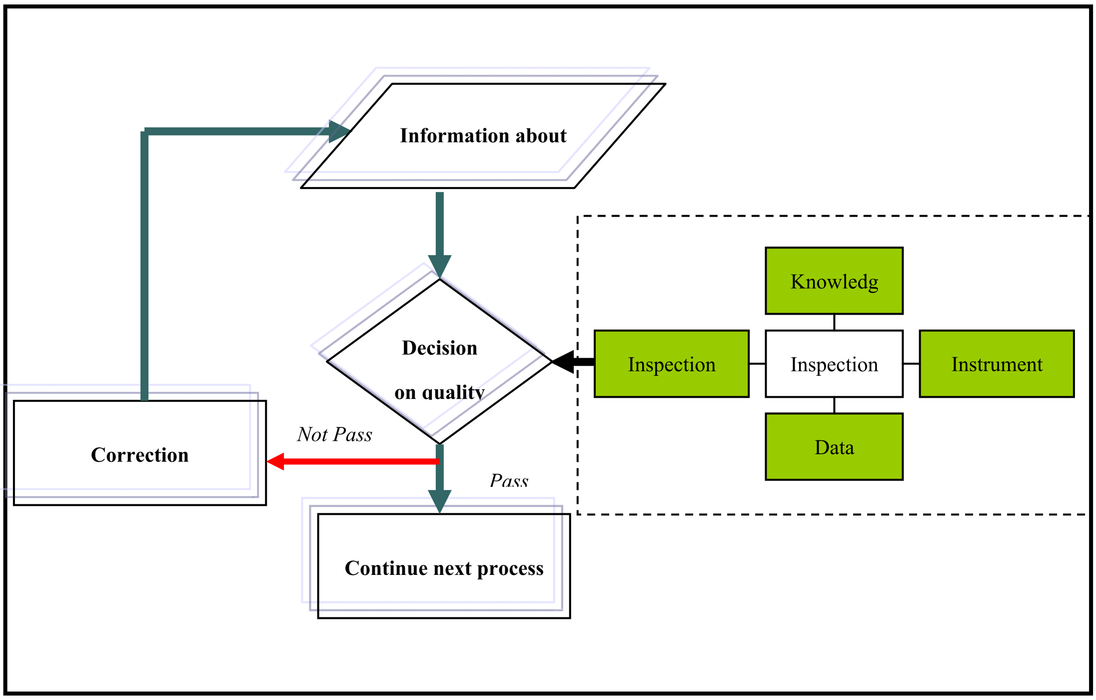

Figure 2.2 Components of the quality inspection process
(modified from Sunkho (2001))

(1) The inspection elements or items to be inspected. The following items are taken from the example of a housing project. Main items are as follows:

- Lay-out
- Piling
- Foundation
- Structural work (beams, columns and floors); inspection of materials, formwork, concrete placement pre-work and placement, reinforcing
- Roofing
- Finishing (painting, tile, ceiling, etc.)

(2) Inspection data.

(3) Instruments or devices used to collect data. The instruments or technologies used are usually non-destructive for instance, a Schmidt hammer, a Hammer test, and a Seismic test. Other mechanical devices help to improve the precision of an inspector's visual observations. As specifications and tolerances become closer, calipers and micrometers become necessary. There is variety of

gauges available to help determine thread sizes, gap thicknesses, angles between parts, hole depths, and weld features (Matzkanin).

(4) Knowledge of the specific inspection process. Inspection process knowledge can be divided into two types: explicit knowledge and tacit knowledge. Explicit knowledge is derived from standards, codes of practice, specifications and drawings. It is easily used for decision making. On the other hand, tacit knowledge relies on individual experience. It is difficult to convert tacit knowledge to explicit knowledge and to transfer it to other people (Tiwana, 2001).

2.1.3 Problems in the quality inspection process as currently practiced in the construction industry

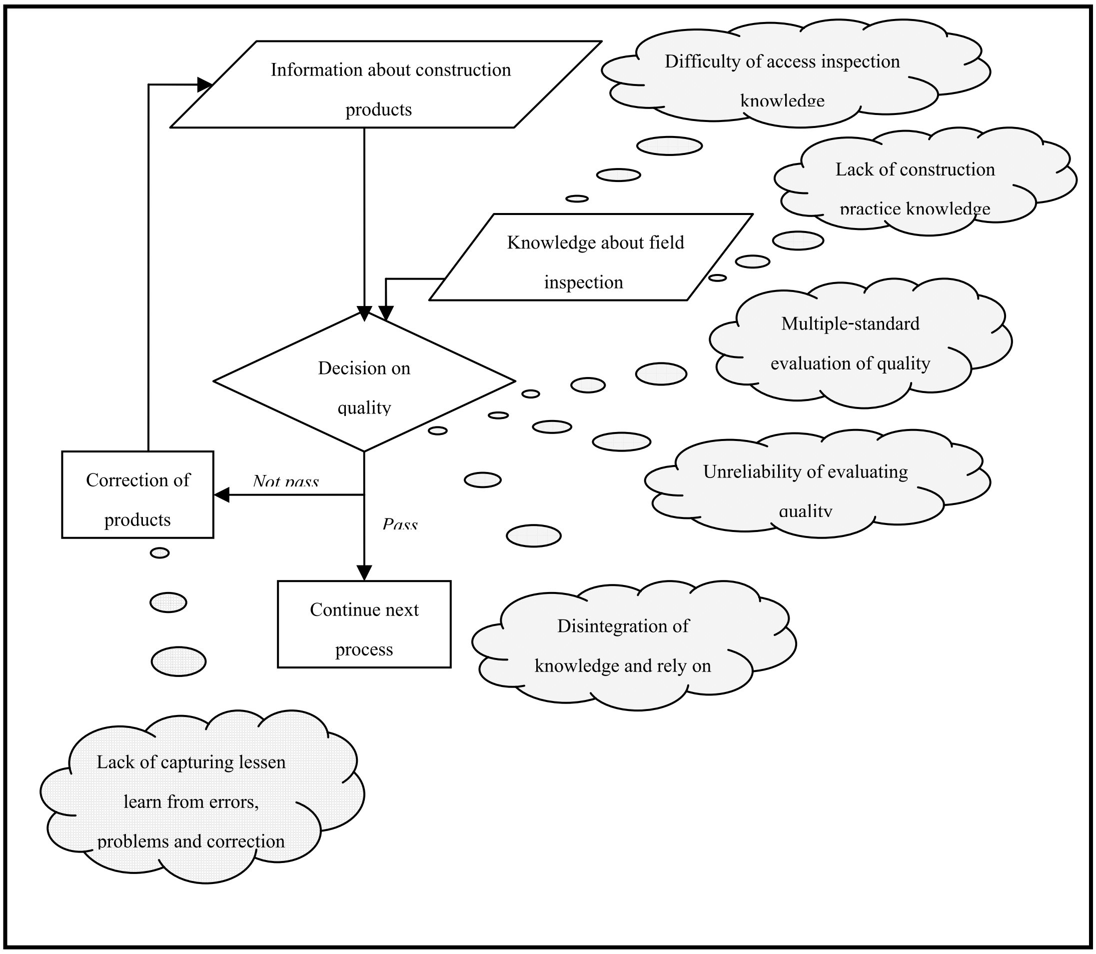

Figure 2.3 Problems in the inspection process as currently practiced

Although inspection is an important part of the construction process, many problems related to quality inspection implementation remain. They can be divided into four main points: (1) inspector inexperience and lack of know-how leads to difficulties solving field construction problems; (2) an incomplete inspection system, such as an incomplete checklist, unsystematic data collection, and inefficiency due to the use of a traditional checklist, making it difficult to recheck quality information; (3) lack of assessment standards to support decision making leading to multiple-standards and unreliability. In this case, inspection is made more complicated due to subjectivity of decision making criteria which leads to inconsistency in the quality of inspection. This, in turn, leads to owner dissatisfaction with production quality. This problem can affect the company in the long term with respect to quality management; and finally, (4) failure to retain lessons learned from errors, problems and correction techniques used in past to improve the product. Without integration of past problem solving approaches and good practical knowledge, it is difficult to improve quality inspection standards. Moreover, lack of shared inspection knowledge can impede the continued improvement of a staff's skills and work processes resulting in lack of attention to inspection leading to problems such as having to redo work, delays, unreliable standards of quality inspection, and customer dissatisfaction (Gordon, Akinci et al., 2007).

2.1.4 Need for quality inspection standards

Although quality inspection standards are based on requirements specified in building contract documents, problems regarding judgments of defect levels remain. The construction project may not meet the customer's requirements despite being completed on time under budget and perfectly functional. By its nature, quality evaluation in a building project can be seen as having two attributes: the measurable and the subjective (Arditi and Gunaydin, 1997; Toakley and Marosszeky, 2003). Measurable attributes relate to materials, construction and functional requirements. These conform to contract specifications including standards, sampling and specific construction jobs. As these can be measured, they frequently use mechanical instruments to enhance sensory input for human judgment. Instruments such as gauges are used to determine thread sizes, gap thicknesses, angles between parts, hole depths, and weld features. Thus, judgment of work quality can be understood, controlled and evaluated by comparing measurements with contract specifications. In contrast, subjective attributes relate to aesthetic issues especially in finished work. Satisfaction on an aesthetic level depends on customer perceptions which vary considerably (Kubal, 1994). These aesthetic aspects are difficult or impossible to quantify in contracts. When inspectors rely on individual experience in making judgments of work quality, the result is multiple-standards and unreliability in defect level evaluation and even variability in judgments by the same person on different days (Shingo, 1985). Knowing the requirements of quality standards is important to support planning for evaluation in quality inspection. Recognizing them can help inspectors accurately detect defects that need to be remedied (Boukamp and Akinci, 2007; Gordon, Akinci and Garrett, 2008).

In conclusion, conflicts about acceptable levels of defect arise as a result of the subjective nature of evaluating without clear standards of evaluation leading to different perceptions by different project participants in quality inspection such as inspectors, contractors and customers. Therefore, reliance on subjective attributes in quality evaluation needs to be minimized.

2.1.5 Quality inspection process improvement

Previous researchers have tried to overcome the above-mentioned problems in several ways. Many attempts have been made to design an integrated system with the use of quality management principles, innovation and technology advancement to improve system efficiency.

- Examples of information technology applications to enhance the development of a quality inspection system can be grouped as follows:

(a) Data collection, e.g. personal digital assistance (PDA), radio frequency identification (RFID), laser scanners and digital image processing (DIP). RFID is an automated data collection system. It helps to collect data accurately, and reduce inspection obstacles in difficult environments. Laser scanners help to collect 3D images. DIP helps to evaluate the digital camera that collects data for visual inspection. Personal digital assistance (PDA) is designed to help in the collection of inspection data on construction sites. It can reduce sources of confusion in documents.

(b) Communication/data exchange e.g. Internet, wireless sensor networks or web portals. This technology can help reduce time and cost of communication. It is used with PDA and databases for data exchange in real time.

Akinci, Boukamp, Gordon, Huber, Lyons and Park (2006), Boukamp and Akinci (2007), Gordon, Akinci and Garrett (2008) explain the importance of knowing the requirements of quality standards for inspection planning to help inspectors accurately detect defects. They developed an automated planning process of construction specifications and goals to support inspection and quality control in on-site construction. They applied a laser scanner and an embedded sensor system to collect automated data.

Georgopoulos, Loizos and Flouda (1995), Lee (2004) and Lee, Chang and Skibniewski (2006) attempted to overcome the limitations of a subjective visual evaluation process by human inspectors. They developed an automatic procedure replacement using computer visualization and digital image processing (DIP) technologies. These are popular information technology applications in the infrastructure field. The objective is to inspect for infrastructure deterioration such as steel bridge coating and pavement cracks. It can be used to determine optimum infrastructure maintenance strategies in operational stages.

Sunkpho, Garrett, Smailagic, Siewiorek and Liu (1998) and Sunkpho (2001) attempted to reduce the complications of document and information input for inspector decision making. They designed a prototype wearable computer-based tool and suggested the use of PDA in infrastructure inspection. This prototype includes the field context and intelligent support for field data collection and decision making. The benefits are improvement in checklist completion, systematic data collection and knowledge for inexperienced inspectors.

Wang (2008) proposed the RFID-based Quality Inspection and Management (RFID-QIM) System to enhance the effectiveness of communication and the flexibility of information flow in real time of the concrete specimen inspection process by integrating the automated data collection technology of RFID with PDA and web portals.

Chin, and Kim (2004) applied a database to improve productivity of the quality system (QS) process during the construction phase by presenting a process-based quality management information framework.

Navon (2000) developed a floor-tiling robot for quality control by using sensors and a video camera to allow accurate placement of tiles in straight lines at uniform distances.

Although several attempts have been made to apply advanced technologies to enhance the effectiveness of systems and reduce the limitations of human inspectors, there are few studies focusing on the problem of the subjectivity of human judgment in visual quality inspection regarding aesthetic issues. Current practice encounters the following problems:

(1) Unreliability of methods in aesthetic evaluation of defects

The subjective attribute of aesthetic judgments in visual quality inspection is currently evaluated using human sensory systems such as touch or visualization. This leads to difficulty identifying defect levels and absolute defect quantity. Therefore, relying on subjective judgment is an unreliable method of quality inspection.

(2) Problems of multiple-standards in defect level evaluation

Decision making on defect levels in aesthetic issues is characterized by multiple-standards depending on individual experience. Different people will have different standards of judgment and the same person might make different judgments on different occasions (Shingo, 1985). Lack of evaluation criteria leads to conflict between project professionals involved in the process of visual quality inspection.

(3) Failure to integrate previous decisions in visual quality evaluation for continuous quality product and standardized knowledge improvement

During the construction stage, the inspector may encounter different scenarios and problems. Integration of lessons learned from previous decisions helps the inspector's knowledge base, worker skill and product quality improvement. Moreover, the knowledge base of quality standards provides support for inspectors inexperienced in quality evaluation decision making.

Therefore, we have endeavored to develop a method to evaluate defect levels to reduce human subjective judgments and enhance the reliability of visual quality inspection of aesthetic issues. The following sections will explain the basic concepts and benefits of the tools used in the research while the final section will demonstrate the integrated system.

2.2 Digital image processing (DIP)

2.2.1 Basic concepts of digital image processing

Digital image processing (DIP) in computer vision are the computerized processes which help to translate the quality of images into suitable forms with objective, easy feature analysis for image understanding (Yodrayub, 2007). Digital image processing can be roughly divided into four levels of computerized processes in the continuum that is shown in Figure 2.4. Representations are depicted as shaded rounded rectangles.

Two levels are often distinguished: Low-level image processing and high-level image understanding (Gonzalez, Woods and et al., 2004; Yodrayub, 2007; Sonka, Hlavac and Boyle, 2008).

(1) Low-level processing involves primitive operations of image acquisition, image compression and pre-processing methods for noise filtering, edge extraction and image sharpening, and enhancement of object features which are relevant to understanding the image.

(2) High-level processing attempts to imitate human cognition and the ability to make decisions according to the information contained in the image. The ability to interpret for image understanding is the heart of the method. When a person tries to understand an image, previous knowledge and experience is brought to the current observation. The human ability to reason allows representation of long-gathered knowledge and its use to solve new problems. Mathematical methods such as neural networks (Lee, 2004; Hata, Tanaka and et al., 2007), and fuzzy logic (Furata, Namura and et al., 2009), pattern recognition, expert systems (Silvestre and Brito, 2009), and artificial intelligence (AI) are widely applied at this level.

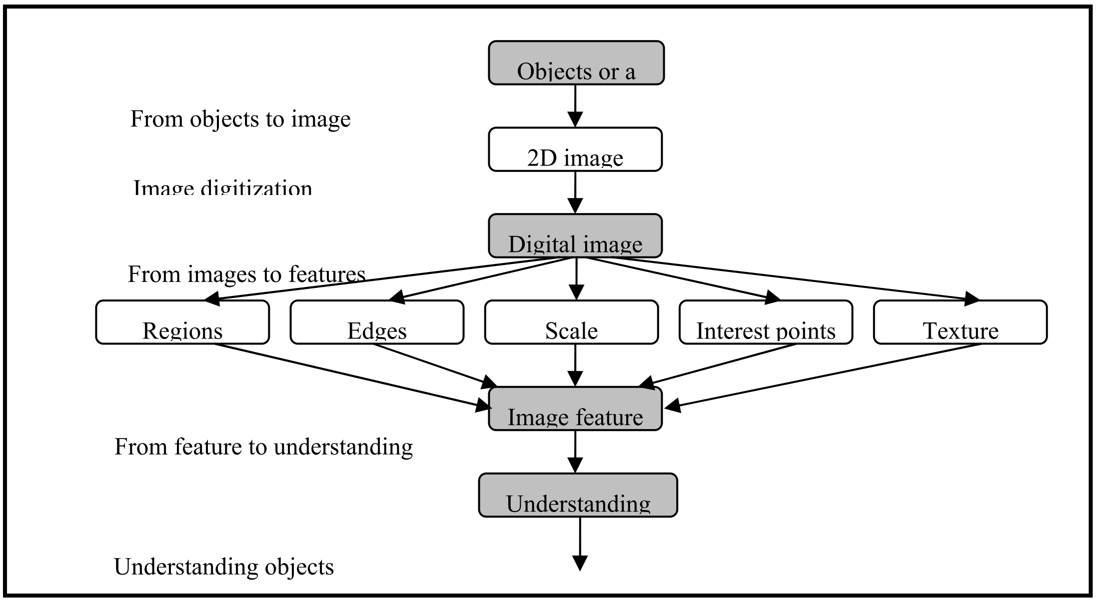

Figure 2.4 Four levels of digital image processing
(modified from Sonka, Hlavac and Boyle, 2008)

In addition to examples of proposed algorithms, Lee, Chang & Skibniewski (2006) applied the digital image processing method to find percentages of rust on steel bridge surface coatings by using statistical data extracted from a scatter plot of a digital image of a coating. Georgopoulos, Loizos & Flouda (1995) determined the X, Y co-ordinates of the cracking on an image to interpret type, severity and density of pavement cracks.

Table 2.1 Levels of perception and relevant processes (Georgopoulos, A., Loizos, A., and Flouda, A., 1995)

Level	Process	Result
Low	Sensing Preprocessing	Image-acquisition Noise reduction Detail enhancement
Medium	Segmentation Description	Divide image into areas of interest Determination of size and shape
High	Recognition Interpretation	Identification of objects Image understanding

2.2.2 Benefits of digital image processing

Interest in digital image processing methods stems from two principal application areas: (1) improvement of pictorial information for human interpretation and (2) the processing of scene data for autonomous machine perception (Gonzalez and Woods, 1992).

(1) Improvement of pictorial information for human interpretation.

- In medicine, computer procedures enhance contrast or code intensity levels into colors for easy interpretation of x-rays and other biomedical images.

- Geographers use the same or similar techniques to study pollution patterns from aerial and satellite imagery. Image enhancement and restoration procedures are used to process degraded images of unrecoverable objects or experimental results too expensive to duplicate.

- In archeology, image processing methods have successfully restored blurred pictures that were the only available records of rare artifacts lost or damaged after being photographed.

- In physics and related fields, computer techniques routinely enhance images of experiments in areas such as high-energy plasmas and electron microscopy.

- Similarly, successful applications of image processing concepts can be found in astronomy, biology, nuclear medicine, law enforcement, defense, and industry applications.

(2) Processing of scene data for autonomous machine perception.

- In this case, interest focuses on procedures to extract image information in a form suitable for computer processing. Often, this information bears little resemblance to visual features that human beings use in interpreting the content of an image. Examples of the types of information used in machine perception are statistical moments, Fourier transform coefficients, and multidimensional distance measures.

- Typical problems in machine perception that routinely utilize image processing techniques are automatic character recognition, industrial machine vision for product assembly and inspection, military recognizance, automatic processing of fingerprints, screening of x-rays and blood samples, and machine processing of aerial and satellite imagery for weather prediction and crop assessment.

The manufacturing industry is characterized by mass production that requires automatic processing in quality inspection to enhance speed and accuracy. Moreover, some of the limitations of human visual inspection include subjectivity of judgment, inspector inexperience, inaccurate data, and long and complicated inspections. It is difficult to set criteria for sensory inspection because different people will make different judgments and the same person might make different judgments on different days (Shingo, 1986). The advanced technologies of automatic processing can help to overcome the limitations of human inspection systems and can set standards of memorized quality criteria. However, unlike humans, who are limited to the visual band of the electromagnetic (EM) spectrum, imaging machines cover almost the entire EM spectrum, ranging from gamma to radio waves. They can also operate on images generated by sources that humans are not accustomed to associating with images. These include ultrasound, electron microscopy, and computer-generated images. Thus, digital image processing encompasses a wide and varied field of applications (Gonzalez, Woods and Eddins, 2004). In summary, digital image processing is suitable for use with mass production, small objects, etc. (Yodrayub, 2007).

2.2.3 Digital image processing for quality management in construction

Digital image processing (DIP) is applied in several cases in the construction industry. For examples, the damage inspection in several concrete structures by using digital image processing technique, Georgopoulos, Loizos and Flouda (1995), and Lee (2004) conducted studies to quantify defects and to classify crack types in road infrastructures. The results of these studies helped to optimize infrastructure maintenance strategies during the operation stage. Digital image processing (DIP) is a popular information technology in this field. In the same, Yu, Jang and Han (2007) studied to propose a system by using digital image processing technique for detecting and measuring cracks in a tunnel to provide objective crack data to be used in evaluating safety. Furuta, Namura, Nakatsu, Hattori, and Adachi (2009) studied to apply for evaluating damage level of bridge. Lee, Chang and Skibniewski (2006) studied the inspection of the deterioration of a steel bridge coating by quantifying the amount of rust on the steel surface. Moreover, the image processing can be applied to inspect the defect level in the architectural work. For example, Zhu and Brilakis (2008) studied to detect air pockets in architectural concrete for quality assessment. Mostly, the previous researches intended to apply image-processing technique to detect defect positions on materials in manufacturing such as wood defect classification, defects on tile (cracks, bumps, depressions, holes, dirt, drops, water drop, ondulations, colour and texture) (Boukouvalas, Kittler, Marik, Mirmehdi and Petrou, 1995; Srikanteswara, 1997; Ghazvini, Monadjemi, Movahhedinia and Jamshidi, 2009; Silvestre and Brito, 2009; Ruz, Estevez and Ramirez, 2009).

The current study required digital image processing methods to enhance the reliability of a visual quality inspection system. We used DIP to enhance image quality and identify defect value and level in aesthetic issues. Both high- and low-level processing are used in our research. Because it is very difficult to avoid noise and control lighting during image capture, low-level pre-processing is used for easier high-level analysis. We use the morphological method to correct for non-uniform illumination by extracting unnecessary background images for easy edge detection. High-level processing in this study uses algorithms of logical and mathematical models to analyze the defects of an object of interest from the digital image. Image processing algorithms are used to replace human reason and to overcome the subjectivity of human judgment (Sonka and Hlavac, 2008).

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2.2.4 Digital image processing using MATLAB

At present, there are a number of programs that can perform digital image processing such as Visual basic, Java and MATLAB. This research chose to use MATLAB because it is the most popular program in the field. It has a ready-application called “image processing toolbox”. Also, the image processing toolbox in MATLAB version 2008 has more ready applications. It is easier to apply compared with other programs. The details of MATLAB are described in section 2.5

2.3 Decision support system (DSS)

We envision the need for evaluation standards to support the decision making process in visual quality inspection. Such standards can ensure a quality standard to meet customer requirements and reduce sources of conflict between those involved in quality evaluation. Therefore, we make use of a decision support system (DSS) which can be applied as a tool to develop quality evaluation criteria.

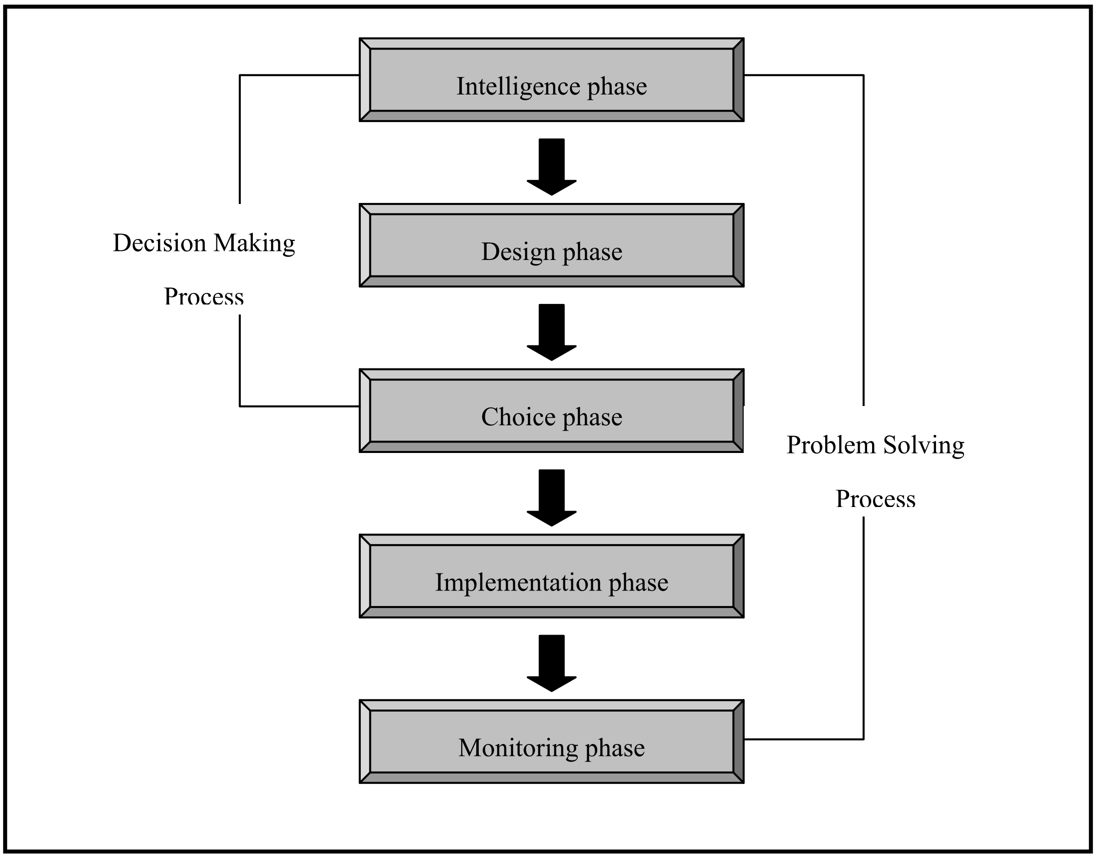


Figure 2.5 Decision making and problem solving process

2.3.1 Definitions and basic concepts of decision making

Decision making is a process of choosing among two or more alternative courses of action for the purpose of attaining a goal or goals (Turban, Aronson, Liang and Sharda, 2007).

The problem has three characteristics (Pakdeewattanakul, 2007):

(1) Class of decision maker; individual (personal decision) or group decision.

(2) Structure of the problem; structured, unstructured, and semi-structured problems.

(3) Organization management; decision-making strategy, management control or tactical decisions, and operational decisions.

The decision making process includes five phases which we derive from the decision making process of Simon and the problem solving process of Huber shown in Figure 2.5: (1) intelligence phase (2) design phase (3) choice phase (4) implementation phase (5) monitoring phase.

2.3.2 Definitions and basic concepts of the decision support system

Gorry and Marton (1971) defined a decision support system as "interactive computer-based systems, which help decision makers utilize data and models to solve unstructured problems".

Keen and Morton (1978) explain that decision support systems couple the intellectual resources of individuals with the capabilities of the computer to improve the quality of decisions. It is a computer-based support system for management decision makers who deal with semi-structured problems.

Table 2.2 Evolution of a decision support system (Pakdeewattanakul, 2007)

Years	Evolution of system
1950-1959	Transaction processing system: TPS, Information reporting, Management Information System: MIS.
1960-1970	Office Automation System: OAS
1970-1980	Decision Support System: DSS
1980-1990	Expert System: ESS
1990-1999	Artificial Intelligence: AI
1999-Present	Intelligent Agent

Doherty (1986) defined a decision support system (DSS) as a set of computer-based tools used by a manager in connection with his or her problem-solving and decision-making duties.

Development of the decision support system concept comes from the need to apply information technology (IT) to enhance efficiency in decision making. The evolution of the system is shown in Table 2.2.

The characteristics and capabilities of the DSS are as follows (Marakas, 1999):

- Supports semi-structured or unstructured decision contexts.
- Supports all levels of management from top executives to line managers.
- Supports individual and group decision making.
- Intended to support decision makers rather than replace them.
- The decision maker is system controller.
- Supports all phases of the decision making process.
- Focuses on the effectiveness of the decision-making process rather than its efficiency.
- Uses underlying data and models.
- Facilitates learning on the part of the decision maker.

- Interactive and user-friendly.
- Supports multiple independent or interdependent decisions.
- Supports decision making in continuous problems.

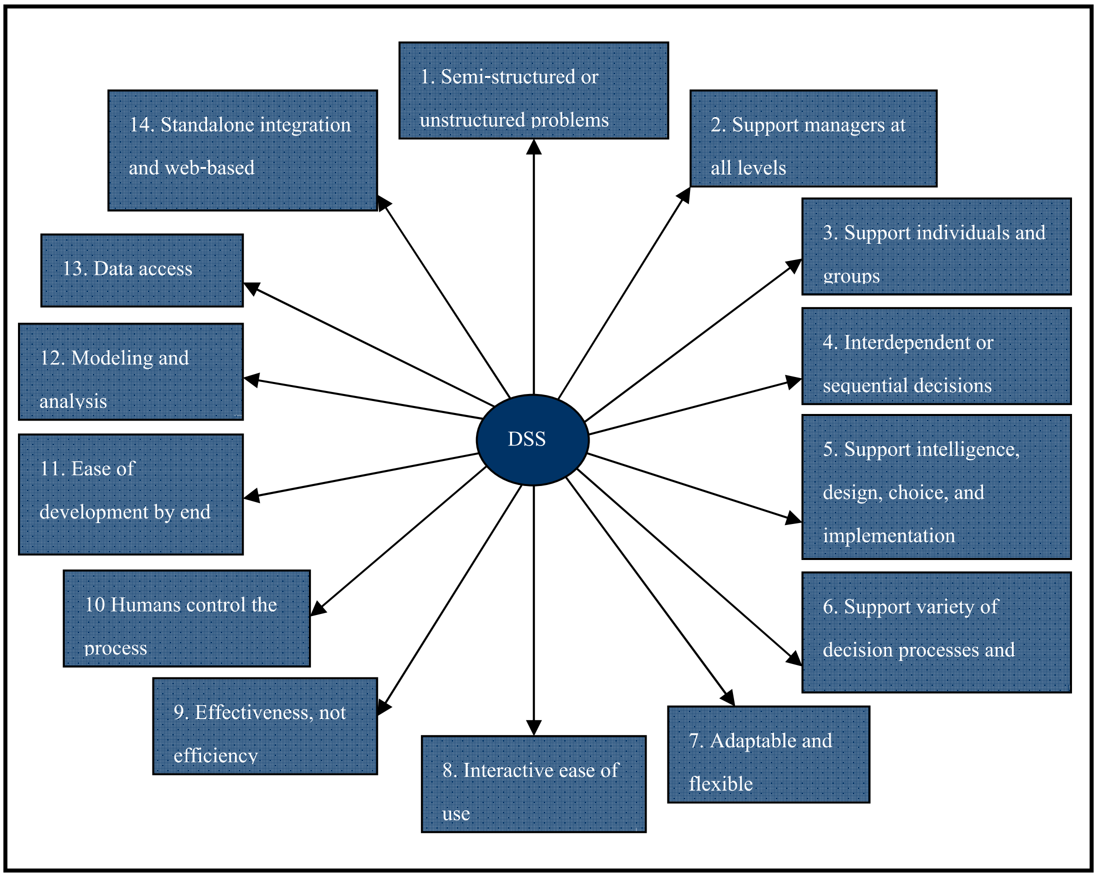


Figure 2.6 Key characteristics and capabilities of DSS
(Turban, Aronson, Liang and Sharda, 2007)

The DSS application can be composed of the data management system, the model management system, user interface system and knowledge-based management system as shown in Figure 2.7.

- The data management system contains external and internal data. It is composed of the DSS database, software called the database management system (DBMS), a data directory, a query facility and extraction.

- The management system controls the model to make it suitable within the particular decision making context e.g. financial, statistical, management science, or other quantitative model. It is composed of a model base, model base management system (MBMS), modeling language, model directory, model execution, integration, and command processor.

- The user interface system is that part used to communicate with and command the DSS.
- The knowledge-based management system supplies the required expertise to solve complex problems (semi-structured or unstructured) and provide relevant information.

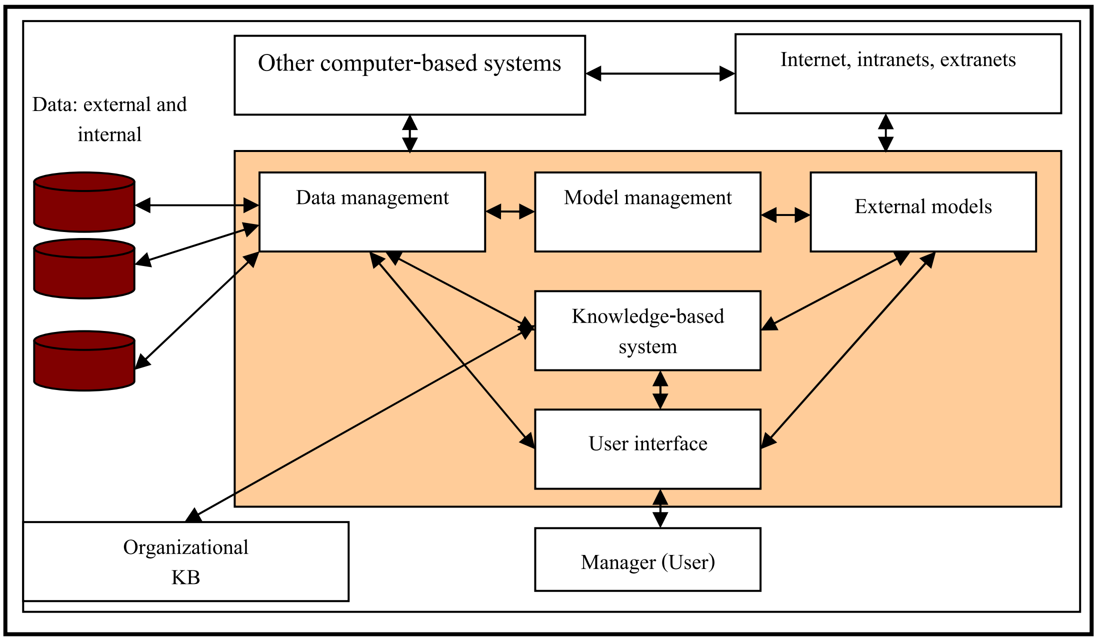


Figure 2.7 A Schematic view of DSS (Turban, Aronson, Liang and Sharda, 2007)

Turban, Aronson, Liang and Sharda (2007) relate specific MSS technologies to the decision making process in Figure 2.8. They provide the data that drive the decision making process.

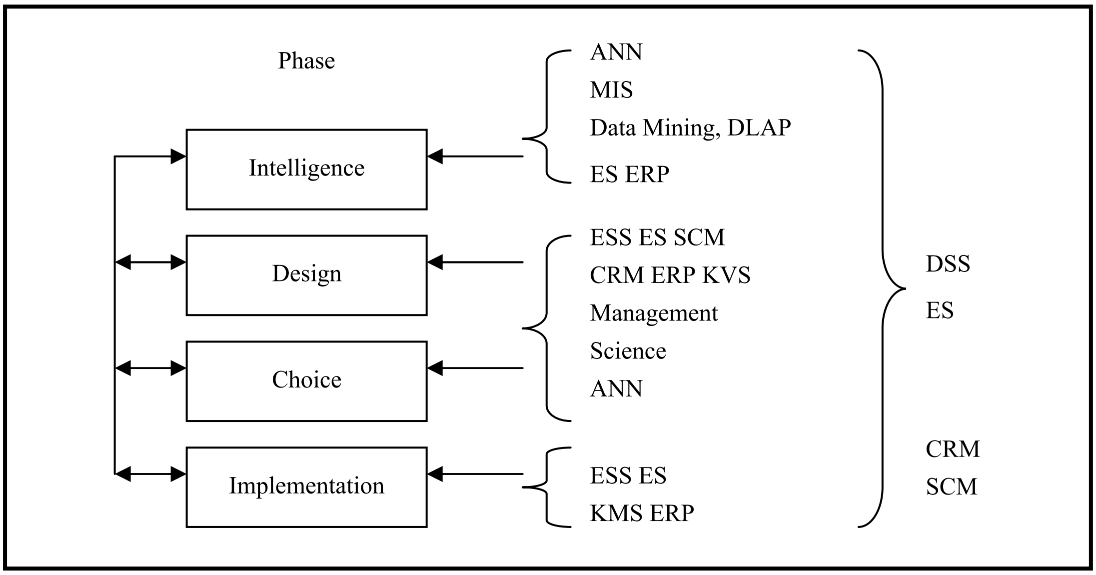


Figure 2.8 DSS support (Turban, Aronson, Liang and Sharda, 2007)

2.3.3 Benefits and limitations of the decision support system

Marakas (1999) argued that we must acknowledge and understand the benefits and limitations of using a DSS. They are as follows:

2.3.3.1 Benefits

- Extends the decision maker's ability to process information and gain knowledge.
- Extends the decision maker's ability to tackle large-scale, time-consuming, complex problems.
- Shortens the time associated with making a decision.
- Improves the reliability of the decision process or outcome.
- Encourages exploration and discovery on the part of the decision maker.
- Reveals new approaches to thinking about a problem or decision context.
- Generates new evidence in support of a decision or confirmation of existing assumptions.
- Creates a strategic or competitive advantage over competing organizations.

2.3.3.2 Limitations

- The DSS cannot yet be designed to include distinctly human decision-making talents such as creativity, imaginativeness or intuition.
- The power of a DSS is limited by the computer system upon which it is running, its design, and the knowledge it possesses at the time of use.
- Language and command interfaces are not yet sophisticated enough to allow for natural language processing of user directives and inquiries.
- DSS are normally designed to be narrow in scope of application, thus inhibiting their generalizability to multiple decision-making contexts.

2.3.4 Decision support systems in construction quality management

In construction projects, many problems are encountered that require decisions. A decision support system (DSS) is used to provide support in several fields for maximum benefit as:

- Evaluation of contractor prequalification and selection (Russell and Skibniewski, 1988, Abudayyeh, Zidan, Yehia and Randolph, 2007).
- Deciding which construction method to select e.g. Pan's (2008) use of the fuzzy AHP (Analytical Hierarchy Process) model to select a suitable bridge construction method.

- Decision-making and assessment tool for design and construction of high-rise building drainage systems (Cheng, He and Yen, 2008).
- Housing evaluation (Jesus, Rodrigues and Antunes, 2007).
- Determining a budget for a project (Lai, Wang, 2008).

Quality management also uses a DSS. For example, Leu and Tzeng (2000), Garrett, Smailagic, Siewiorek, Liu and Sunkpho (2001) used the decision support system concept to improve ineffective field quality inspection processes for the following:

- Lack of reference information when an inspector is performing quality inspection.
- Excessive paper documents which are difficult to control and trace.
- Provide an alternative to manual analysis of quality data which is difficult for inexperienced inspectors.
- Provide a quality inspection program independent from a construction CPM program.

Leu and Tzeng (2000) established a CPM-based construction quality inspection and decision-aid system (CQIDS) which consists of three subsystems:

(1) The data subsystem containing information about quality standards, shop drawings, checklists, and methods of taking corrective action.

(2) The decision subsystem containing statistical algorithms to automatically facilitate quality data analysis and experience-related information to assist in managing activities affecting quality.

(3) A user interface e.g. pen-based input, popup windows, and digital cameras.

This system is capable of identifying problems, selecting relevant quality data, selecting specifications and evaluating alternative corrective action methods when quality objective variances occur.

Garrett, Smailagic, Siewiorek, Liu and Sunkpho (2001) designed a wearable computer-based prototype that includes the field context and intelligent support for field data collection and decision making. Its advantages are that it facilitates checklist completion, systematic data collection and knowledge acquisition for inexperienced inspectors.

A sub-objective in our research was to develop a quality evaluation list and criteria to support the decision making system, especially decision making of semi-structured problems. Although some items are selected from drawings and contract specifications, previous experience is required to support the assessment of quality defect levels of aesthetic issues. Therefore, we envision the use of an AHP method to determine relative importance (weight) and fuzzy logic to identify defect levels. Moreover, concepts of DSS apply information technologies, fuzzy logic and the knowledge-base to support decision making in visual quality inspection.

2.3.5 Fuzzy logic

Fuzzy logic theory was introduced by Zadeh in 1965 to provide a mathematical framework to handle uncertainties, tolerate vagueness or ambiguity in many decision-making problems (Zimmermann, 1991). Fuzzy logic (Zadeh, 1973) can be treated as a mechanism that mimics human inference processes with fuzzy information. It is a tool with the ability to compute using words to model the qualitative human thought process in the analysis of complex systems and decisions. Therefore, fuzzy logic is appropriate for unstructured decision making (Liu, 2007). Fuzzy theory is widely applicable in information gathering, modeling, analysis, optimization, control, decision making and supervision (Fasanghari and Roudsari, 2008). In the past decade, the fuzzy technique has been divided into two broad fields: (1) fuzzy set/fuzzy logic and (2) hybrid fuzzy techniques (those that combine fuzzy set/fuzzy logic with other techniques) such as fuzzy neural network, neurofuzzy and fuzzy reasoning, fuzzy expert system, fuzzy analysis and fuzzy clustering. The applications can be divided into four main categories including: (1) decision making (2) performance (3) evaluation/assessment and (4) modeling. Fuzzy membership functions and linguistic variables in particular can be used to set applications to solve problems encountered in the construction industry based on the nature of construction which is widely regarded as complicated, full of uncertainties, and contingent on changing environments (Chan and Yeung, 2009). Table 2.3 shows the application of fuzzy set/fuzzy logic in construction management from 31 papers which are summarized by Chan and Yeung (2009).

The notion of fuzzy set is highly intuitive and transparent as it captures the essence of the way in the real world is perceived and described. We encounter categories of objects whose belongingness to a given category (concept) is always a matter of degree. There are numerous examples in which we find elements whose allocation to a concept we want to define can be satisfied to some degree. For instance, we may qualify an indoor environment as comfortable when its temperature is kept around 20ºC. If we observe a value of 19.5ºC, it is very likely that we still feel quite comfortable. The same holds if we encounter 20.5ºC- people usually do not discriminate changes in temperature within the range of 1ºC. A value of 20ºC would be fully compatible with a concept of a comfortable temperature which can be described as being cool or warm respectively.

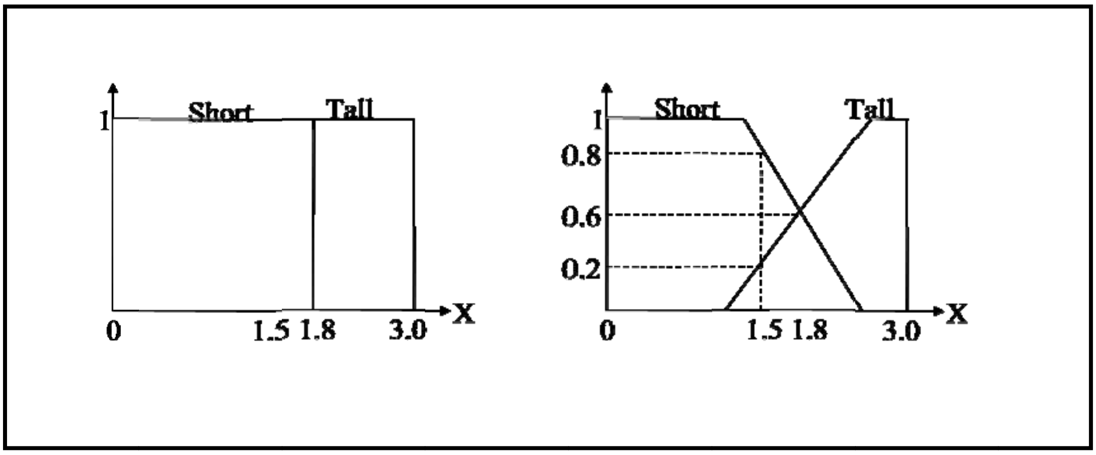


Figure 2.9 Boolean (two-valued) membership in characteristic functions and gradual membership represented by membership functions (fuzzy sets) (Pedrycz and Gomide, 2007).

Similar phenomena occur when we are dealing with the concept of people's height. Figure 2.9 shows the difference between the concept of Boolean (two-valued) membership in characteristic functions and gradual membership represented by membership functions (fuzzy sets) which demonstrate vagueness in separating height value between short and tall (Pedrycz and Gomide, 2007).

Fuzzy logic theory includes important concepts e.g. linguistic variables, fuzzy sets and membership functions, and fuzzy logic system (Owais, 2009).

1) ***Linguistic variables, values and terms:*** linguistic variable accepts linguistic values which are words (linguistic terms) with associated degrees of membership in the fuzzy set. For example, linguistic variable age, the term set T(age) may be defined: T(age) = {"young", "not young", "not so young", "very young",…, "middle aged", "not middle aged",…, "old", "not old", "very old", "more or less old", "quit old",…, "not very young and not very old",…}.

2) ***Fuzzy sets and membership functions:*** each linguistic term is associated with a fuzzy set, each of which has a defined membership function. Formally, a fuzzy set A in U is expressed as a set of order pairs: A = {(x, μ_A(x))| x in U}. μ_A(x) is the membership function which provides the degree of membership of x. This indicates the degree to which x belongs in set A, where U is the universe of discourse.

3) ***Fuzzy logic system:*** the fuzzy logic system has a direct relationship to fuzzy concepts. The most popular fuzzy logic systems can be classified into three types: pure fuzzy logic system, Takagi and Sugeno's fuzzy system, and fuzzy logic system with fuzzifier and defuzzifier. The last type is the most widely used one. Figure 2.10 shows the basic configuration of a fuzzy logic system with fuzzifier and

defuzzifier which was first proposed by Mamdani, 1974. The four main functional components are as follows:

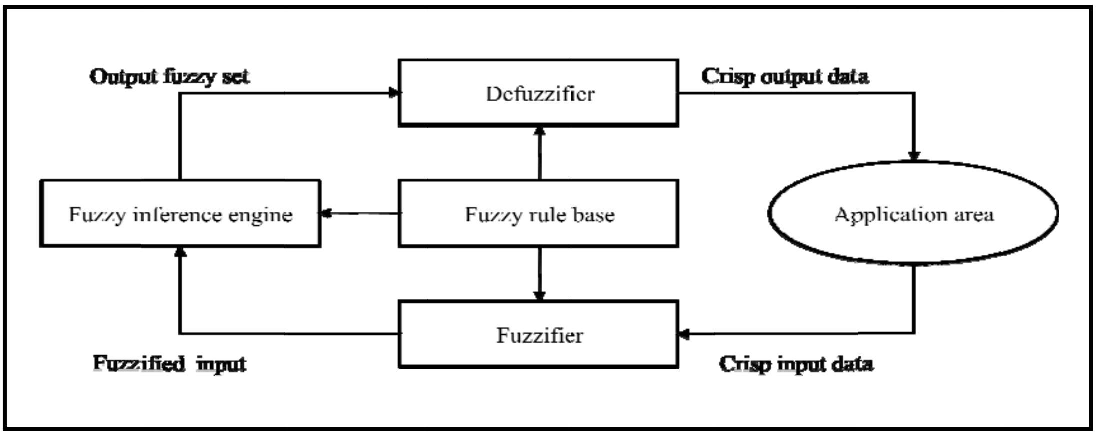


Figure 2.10 Fuzzy logic system with fuzzifier and defuzzifier (Wang, 1994)

3.1) Fuzzifier: converts a crisp input to a fuzzy set.

3.2) Fuzzy rule base: Fuzzy logic systems use fuzzy IF-THEN rules. A fuzzy IF-THEN rule is of the form “IF X1 = A1 and X2 = A2…and Xn = An THEN Y = B” where Xi and Y are linguistic variables and Ai and B are linguistic terms. The ‘IF’ part is the antecedent or promise while the ‘THEN’ part is a consequence or conclusion. The collection of fuzzy IF-THEN rules is stored in the fuzzy rule base, which is known as the inference engine.

3.3) Fuzzy inference engine: once all crisp input values are fuzzified into their respective linguistic values, the inference engine accesses the fuzzy rule base to drive linguistic values for the intermediate and output linguistic variables. The inference engine performs two main operations: aggregation and composition. Aggregation is the process of computing for the values of the IF (antecedent) part of rules while composition is the process of computing for values of the THEN (conclusion) part of the rules.

3.4) Defuzzifier: converts fuzzy output into crisp output.

This principle is related to subjective judgments of acceptable defect levels in aesthetic issues. We apply the fuzzy logic method to develop the evaluation model. This fuzzy evaluation is based on knowledge mining from the previous experience of experts.

Table 2.3 Applications of fuzzy set/fuzzy logic in construction management research (Chan and Yeung, 2009)

Journal	Author(s)	Theory/ concept	Field/ application	Relevance/ classification
JCEM	Singh, D, and Tiong, R.L.K. (2005)	Fuzzy sets	Contractor selection	Decision making; performance evaluation
JCEM	Seo, S., Aramaki, T., Huang, Y., and Hanaki, K. (2004)	FST	Environmentally sustainable building	Decision making; assessment
JCEM	Tam, C.M., Tong, T.K.L., Leung, A.W.T., and Chiu, G.W.C. (2002b)	Fuzzy sets	Site preparation	Decision making
JCEM	Fayek, A. (1998)	FST	Competitive bidding strategy	Decision making; assessment
CME	Wang, R.C., and Liang, T.F. (2004)	Fuzzy sets	Project management decisions	Decision making
CME	Zhang, H., and Tam, C.M. (2003)	Fuzzy sets	Dynamic resource allocation	Decision making
CME	Li, H., and Shen, Q. (2002)	FST	Sustainable housing	Decision making
CME	Ng, S.T., Luu, D.T., Chen, SE., and Lam, K.C. (2002)	FST	Procurement selection criteria	Decision making
IJPM	Wang, W., Hawwash, K.I.M., and Perry, J.G. (1996)	FST	Contract type selector	Decision making
IJPM	Lin, C.T., and Chen, Y.T.(2004)	Fuzzy logic	Bid/no-bid	Decision making
JCEM	Zheng, D.X.M., and Ng, S.T.(2005)	Fuzzy sets	Project management; risk management; productivity	Time and cost performance

Table 2.3 Applications of fuzzy set/fuzzy logic in construction management research (Chan and Yeung, 2009) (continued)

Journal	Author(s)	Theory/ concept	Field/ application	Relevance/ classification
JCEM	Bonnal, P.,Gourc, D., and Lacoste, G. (2004)	Fuzzy sets	Project scheduling	Time performance
JCEM	Lorterapong, P., and Moselhi, O. (1996)	Fuzzy sets	Project network analysis	Time performance
CME	Kishk, M. (2003)	FST	Whole-life costing	Cost performance
ECAM	Zhang, H., Li, H., and Tam, C.M. (2004)	FST; fuzzy logic	Activity duration	Time performance
IJPM	Baloi, D., and Price, A.D.F. (2003)	FST	Risk management	Performance
JCEM	Oliveros, A.V.O., and Fayek, A.R.(2005)	Fuzzy logic	Project management; activity delay analysis	Time performance
JCEM	Knight, K., and Fayek, A.R. (2002)	Fuzzy logic	Cost control; project management	Cost performance; decision making
CME	Okoroh, M.I., and Torrance, V.B.(1999)	FST; fuzzy logic	Subcontractor selection	Modeling
IJPM	Wei, C.C., and Wang, M.J.J.(2004)	FST	Selection of ERP system	Modeling
IJPM	Tseng, T.L., Huang, C.C., Chu, H.W., and Gung, R.R. (2004)	Fuzzy sets	Multi-functional project team formation	Modeling
IJPM	Leu, S.S., Chen, A.T., and Yang, C.H. (2001)	FST	Construction time-cost trade-off	Modeling
JCEM	Choi, H.H., Cho, H.N., and Seo, J.W. (2004)	Fuzzy sets	Risk management	Assessment

Table 2.3 Applications of fuzzy set/fuzzy logic in construction management research (Chan and Yeung, 2009)(continued)

Journal	Author(s)	Theory/ concept	Field/ application	Relevance/ classification
JME	Sanchez, M., Prats, F., Agell, N., and Ormazabal, G. (2005)	Fuzzy sets	Value management	Evaluation; decision making
ECAM	Kumar, V.S.S., Hanna, A.S., and Adams, T. (2000)	FST	Assessment of working capital requirement	Assessment
IJPM	Holt, G.D. (1998)	FST	Contractor selection	Evaluation
JCEM	Zayed, T.M., and Halpin, D.W. (2004)	Fuzzy logic	Productivity	Quantitative assessment (performance)
JCEM	Chao, L.C., and Skibniewski, M. (1998)	Fuzzy logic	Construction technology	Evaluation
CME	Tah, J.H.N., and Carr, V. (2000)	Fuzzy logic	Construction project risk management	Assessment
ECAM	Shang, H., Anumba, C.J., Bouchlaghem, D.M., and Miles, J.C. (2005)	Fuzzy logic	Intelligent risk assessment system	Assessment
BIJ	Ma, H., Deng, Z., and Solvang, W.D. (2004)	Fuzzy logic	Distributor benchmarking	Benchmarking/ Assessment

Note: JCEM = Journal of Construction Engineering and Management, ASCE; CME = Construction Management and Economics; IJPM = International Journal of Project Management; JME = Journal of Management in Engineering, ASCE; ECAM = Engineering, Construction and Architectural Management; and BIJ = Benchmarking: An International Journal.

2.4 Knowledge management system (KMS)

Knowledge management is an important component in the decision support system. Decision-makers solve problems by using knowledge and experience. Sufficient knowledge or experience and good knowledge management will lead to success.

2.4.1 Definitions of the knowledge management system

Nonaka and Takeuchi (1995) defined KM as the substantiated understandings and beliefs in an organization about the organization and its environment. They also differentiated between two types of knowledge: explicit and tacit. Explicit knowledge is codified, easily translated and facts and information easily shared; it exists in reports and other documents. Tacit knowledge is personal knowledge that is hard to confirm and share with others; it is the private understanding and knowledge that people have about issues, problems, services, and products. A major task of KM is to turn tacit knowledge into explicit knowledge.

Tiwana (2002) defined knowledge management as a changing mix of workers' experience, values, expert insight, and intuition that provides an environmental framework for evaluating and incorporating new experiences and information. It resides in the minds of workers, but is often expressed in the culture of the organization, including its routines, processes, systems, and norms. This definition is similar to many definitions for human capital.

Mcnabb (2007) defined knowledge management as a set of processes, practices, and management philosophies that exist to collect, process, store, and make available organizational knowledge to be more proficient in competition. Tacit knowledge is knowledge held in the minds of the men and women who hold, use, and share what they know about things and how to do what they do. Explicit knowledge is knowledge that has been or can be written down and contained in documents and other media.

Joch (2004) defined knowledge management as managing information to make the most of knowledge in an organization in order to benefit from finding and applying innovative answers to old and new questions. Information and communications technology constitutes one of the three chief building blocks of knowledge management. The other two are the people who use knowledge and the processes that have been developed to enable and enhance knowledge capture and sharing.

2.4.2 Basic concept of a knowledge management system

Objectives of a knowledge management are as follows (Pakdewattanakul, 2007):

- To create a knowledge repository.
- To create knowledge explication.
- To capture and share knowledge.
- To manage knowledge assets.

We must also know about knowledge management characteristics and things that knowledge management does not do for organizations (Tiwana, 2002).

- KM is not knowledge engineering. Rather, KM falls into the domains of management and information systems. It is not computer science.
- KM is not only about digital networks. It is about management processes. Technology is an enabler, but it is not a driver.
- KM is not about a one-time investment in technology. It is a future-oriented investment that requires consistent attention and evaluation.
- KM is not about "enterprise-wide Infobahn". KM should not be confused with enterprise information systems. The primary focus is on helping the right people have access to the right knowledge at the right time.

2.4.3 Components of knowledge management systems development

A model of a total knowledge management system has five components or subsystems as shown in Figure 2.11.

2.4.3.1 Information process subsystem

The need is to manage large amounts of data and to transform that data into the type and amount of information needed by decision makers. This is one of the earliest drivers of the knowledge management discipline. All raw data is meaningless until it is coded, transformed, shaped into graphic communications forms, evaluated and interpreted, recorded and published, and eventually filed for future reference. This information is one kind of input needed by a knowledge management system. It remains processed data until it is put to some use by people somewhere. Then it becomes knowledge, specifically, the kind known as explicit knowledge. Explicit knowledge is the content of reports and manuals, films, radio scripts, charts and graphs, and speeches and books. The second type of knowledge is tacit knowledge. It often skips the information stage because it is knowledge that exists in the minds of human beings. It is knowledge gained from experience, from doing and acting. It is difficult to convert tacit knowledge to explicit knowledge. Knowledge creation occurs when people use what they know or have learned to perform what for them is a creative or innovative task. Clearly, knowledge is created by human experience which can result from doing, or learned by reading about phenomena, by watching a film or video, and from listening to a narrative or someone tell a story about their experience.

An information technology-based information process subsystem of hardware and software tools facilitates the transformation of data into information, and of information into knowledge. The processes in this subsystem revolve around designing and investing in the technology architects need to support the knowledge management system.

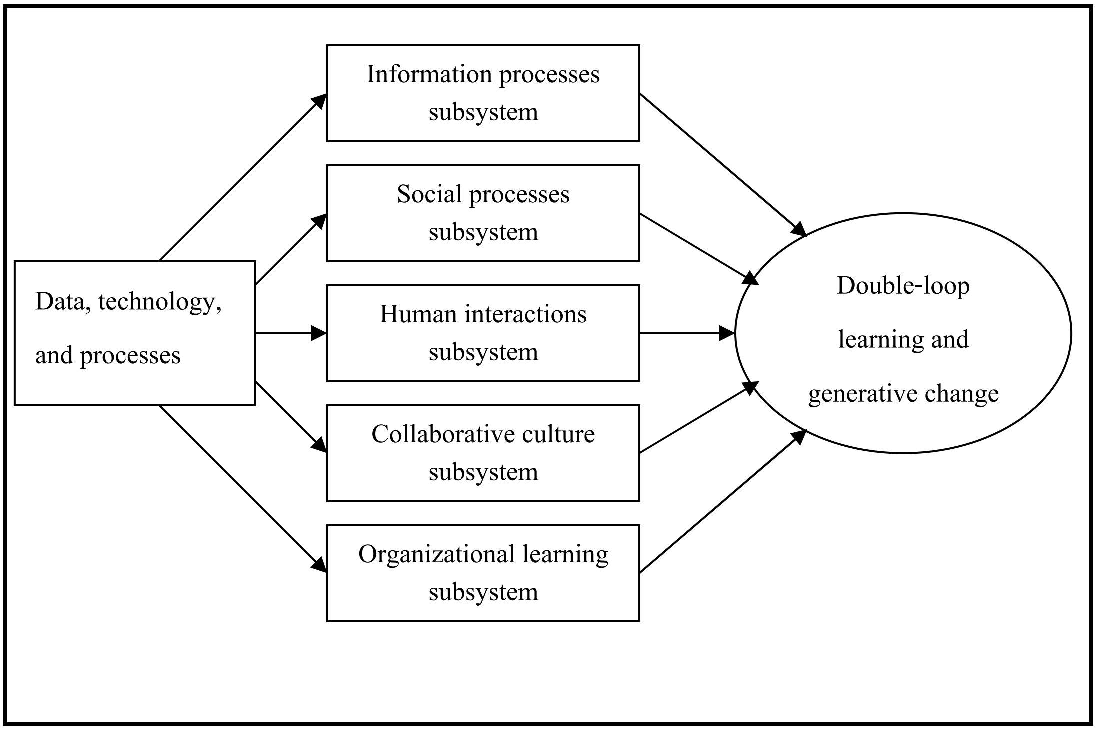


Figure 2.11 How KM subsystems interact to produce learning and generative change (Mcnabb, 2007)

2.4.3.2 A social processes subsystem

In this system, knowledge sharing and distribution are promoted. This subsystem is a product of investment in technology. The more important elements are the social processes that help put technology to work. It transfers and transforms information into knowledge through the four social processes (SECI) which are: socialization, internalization, combining, and externalizing as depicted in Figure 2.12 (Nonaka and Takeuchi, 1995). These ultimately result in formation of the informal, self-regulating communities of practice that form the heart of the human interactions subsystem. These components have evolved from earlier thinking on learning theory and the learning or knowledge cycle (Blessing and Wallance, 2000).

Information becomes knowledge when it is used by someone. The conversion of information into knowledge entails a vastly different process than converting data into information. Although IT tools may be used in the process, they are secondary to the rules of human interaction. Nonaka and Takeuchi (1995) explained it (Figure 2.12) as a process of converting tacit knowledge into more explicit knowledge, and vice versa. They identified four modes of knowledge conversion:

- Socialization: sharing and creating tacit knowledge through direct experience. It is in the form of self-learning by observation or copying to individual tacit knowledge.
- Externalizing: converting tacit knowledge into explicit knowledge by articulation through dialogue, group discussion and reflection.
- Combination: converting explicit knowledge into more explicit knowledge by creating or applying the knowledge and information system.
- Internalization: converting explicit knowledge into new tacit knowledge by learning and acquisition in practice.

Table 2.4 Comparison of Tacit and Explicit Knowledge (Tiwana, 2001)

Characteristic	Tacit knowledge	Explicit knowledge
Nature	Personal, context specific	May be codified, written
Formality	Hard to formalize, codify, record, code, or express	Is formalized through the process of explanation or interpretation of tacit knowledge
Location	In the minds of workers	Manuals, reports, drawings, databases, e-communications, charts, film, etc.
Conversion process	Conversion to explicit knowledge occurs in social processes, including externalization in stories, etc.	Converted back to tacit knowledge through personal understanding absorption, or remembering
IT influence	Difficult for IT to play a	Fully supportable by IT

	role in tacit knowledge; sharing is personal and takes place in social situations	and ICT
Medium	Needs a rich communications environment, a culture of sharing and trust	Can be transferred through normal communications media

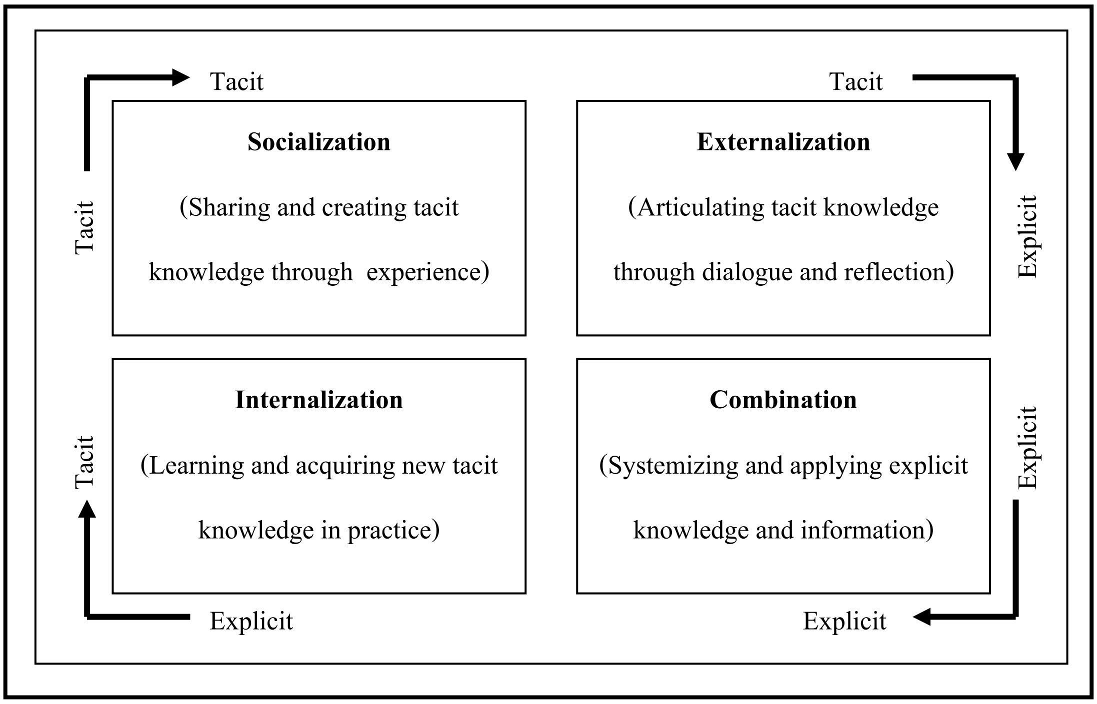


Figure 2.12 Knowledge formalization
(Udaeaja, Kamara, Carrillo, Anumba, Bouchlaghem and Tan, 2008)

2.4.3.3 A human interaction subsystem

This subsystem makes it possible to support and value knowledge creation, collection, and sharing using information and communication technology. Three key actions illustrate the types of mechanisms and processes that take place at this stage of a system: knowledge audits, communities of practice, and knowledge registries, among others, in order to begin the transition from a culture of knowledge hoarding to one of knowledge sharing.

2.4.3.4 A collaborative culture subsystem

This subsystem makes it the norm for all the experiences and knowledge of all members of a community of interest to be shared freely and employed when and where they are needed to carry out the mission of the agency.

2.4.3.5 An organizational learning subsystem

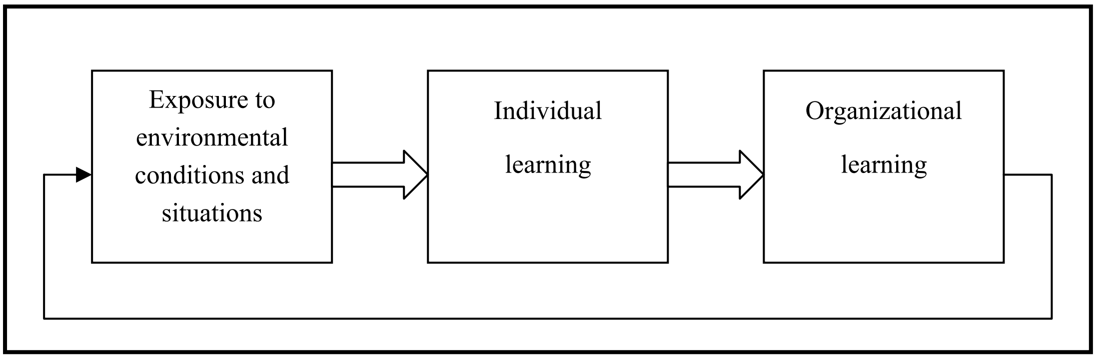


Figure 2.13 A Model of Single-Loop Learning (Mcnabb, 2007)

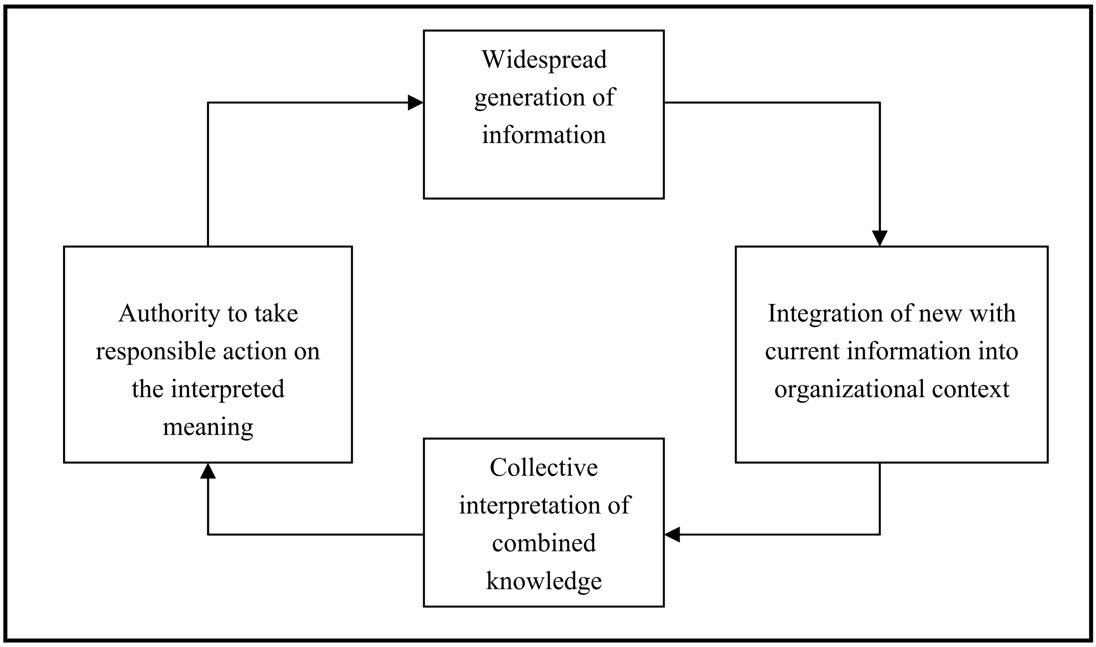


Figure 2.14 The APHIS (Department of Agriculture's Animal and Plant Health Inspection Service) Organizational learning Cycle (USDA, 2004)

The subsystem enables the transformation to an organizational focus solely on the essential single-loop adaptive change process to also value and implement the more rewarding processes of double-loop, generative learning.

2.4.4 The knowledge management process

Tiwana (2002) identified three basic processes of knowledge management: knowledge acquisition, knowledge sharing, and knowledge utilization. Acquisition is the process of developing and/or creating intellectual capital, including insights, skills, experiences, and relationships. Technology is used in a variety of ways and with a variety of objectives to capture data and develop databases. It uses such tools as key-word scanners, note capture tools, and electronic whiteboards in support of knowledge acquisition. Knowledge repositories are a way to categorize and store collected knowledge. Knowledge sharing is the dissemination and making available of the collected knowledge. Knowledge sharing is enabled through a social process made possible by an organizational culture that honors and rewards sharing activities. Many methods to distribute knowledge involve the application of information technology tools such as expert systems, Web portals and others. Knowledge utilization is the process of integrating knowledge into the agency. One increasingly important method to accomplish this task is by establishing and promoting greater use of communities of practice. Communities of practice are informal groups of individuals with a common interest in a topic or a program connected in electronic networks to share members' experience, knowledge and advice.

Alavi and Leidner (2001) concluded that there are five key processes extant in KM: knowledge creation, knowledge storage, knowledge retrieval, knowledge transfer, and knowledge application. Each of these processes is supported by one or more ICT (Information and Communication Technology) and each contributes to one or more knowledge application task. The processes and supporting technologies are displayed in Table 2.5.

Table 2.5 Knowledge management process and supporting ICT tools (Butler, 2003, and Alavi and Leidner, 2001)

Knowledge management process	Supporting information and communications technologies	What the information technologies enable	Example platform technologies	Knowledge management process
Knowledge creation	Data mining, e-learning tools	The creation and combination of new sources of knowledge; just-in-time learning	Knowledge "yellow pages", stories, dialogues, and discussions	Knowledge creation
Knowledge storage and retrieval	Electronic bulletin boards, knowledge repositories, and databases	Support of individual and organizational memory; inter-group knowledge access	Groupware and communication technologies	Knowledge storage and retrieval
Knowledge combination and transfer	Electronic bulletin boards, discussion forums,	More extensive internal networks and communication	Intranets; communities of practice	Knowledge combination and transfer

	knowledge directories	channels, and faster access to knowledge sources		
Knowledge application and reuse	Expert systems, workflow systems	Knowledge applied across time and space; faster application of new knowledge	Knowledge management system	Knowledge application and reuse

Knowledge management systems are the logical culmination of a management system that uses ICT to facilitate the capture, combination, and application processes of knowledge within the organization. It is important to recall however that no single technology constitutes a knowledge management system (Alavi and Leidner, 2001). Rather, three technology tools are found in most successful implementations. The first is a system for coding and sharing of best practice. The second is the creation and fastidious maintenance of an organizational knowledge directory. The third is the creation of formal and informal knowledge networks. In order to learn from others, knowledge workers must have free and open access to communication with others with a similar interest and focus in the practice.

Three trends are evident in the changing role of IT in supporting knowledge management: a diminishing role for ICT, a growing need for integration and collaboration, and acceleration in the use of wireless and mobile technology (Mcnabb, 2007).

2.4.5 Benefits of knowledge management (KM) and information technology (IT) integration

Researchers Karin Breu, David Grimshaw, and Andrew Myers (2000) at the UK Cranfield School of Management, have identified the knowledge-based benefits they received from IT and KM. The most important factors and their components are presented in Table 2.6.

The items are grouped into five composite benefit factors; innovation and growth, organizational responsiveness, customer focus, supplier network, and internal quality factor. Each factor is described below in more detail.

Innovation and Growth: This component describes the benefits to the organization that arise from a culture and philosophy that encourage new products and services, including approaches to the delivery of those services. It also values higher output from research and development efforts, seeking out and exploiting new business opportunities, and enhancing the creative and innovative capability of organization.

Organizational responsiveness: This component includes success at reducing or eliminating geographic barriers and achieving organizational integration and flexibility. In this way, the organizational culture is one in which the sharing of ideas and organizational learning is honored. A key metric often employed is improving the speed of decision making.

Table 2.6 Benefits of KM and IT integration and their components (Cranfield School of Management (UK) modified from Bahra, 2001)

Factors	Representative components
Innovation and growth	New products/services Research and development New [program] opportunities Developing new constituencies Capability to innovate
Organizational responsiveness	Organizational integration Organizational flexibility Sharing of ideas and knowledge Organizational learning Speed of decision making
Customer focus	Customer/client retention Customer service Meeting customer/client needs Product/service quality
Supplier network	Supply chain efficiency Integration of logistics Supplier relationships Sustaining existing markets Time to market of new products/service
Internal quality	Process innovation Capability for change Operational efficiency Project management Product/services management Staff morale Quality of decision making

Customer Focus: Achieving continuous improvements in such externally focused activities as customer retention, meeting customer needs, and maintaining product and service quality are important components of a system of performance measurements.

Supplier Network: These are the benefits an organization gains through common standards achieved through closer collaboration with other value chain organizations. Integrating logistics and improving supplier relationships are also included in this factor.

Internal Quality: These are the measurable benefits that occur as a result of process innovation, being open to change, enhancing organizational efficiency, and better management of projects. In addition, it includes the human resources benefits of better employee morale, improved retention, and higher-quality decision making.

2.4.6 Knowledge management systems (KMS) in the construction industry

Udaeaja, Kamara, Carrillo, Anumba, Bouchlaghem, and Tan (2008) developed a strategy for knowledge capture and reuse in the AEC sector (Architecture, Engineering and Construction) of the industry. They presented CAPRI.NET which is a web-based system whose objective was to establish a methodology for the live capture of reusable project knowledge (RPK) in the construction industry. The aim was to reflect both the organizational and human dimensions of knowledge capture and reuse and exploit the benefits of technology. The system (CAPRI.NET) is comprised of a project knowledge file developed as a database, and integrated workflow system developed as static and dynamic web pages. The potential benefits of CAPRI.NET for the AEC industry are as follows:

- Construction supply chains will benefit by the sharing of experiences that are captured as part of learning from key events (e.g. problems, breakthroughs, changed orders, etc.).The benefits to this group are both short and long-term. Short-term in the sense that project teams would be able to better manage the subsequent phases of a project through the capture and transfer of learning from previous phases. Long-term because it will increase their capacity to plan future projects more effectively as well as the ability to collaborate better with other organizations. Furthermore, learning from past projects can be used to train new employees and project managers.

- Other project teams can use the learning captured from previous/similar projects to deal with problems; reflection on previous learning can also trigger innovative thinking (to consider issues that might be relevant to their project).

- Client organizations will benefit from enriched knowledge about the development and construction of their assets. This will contribute to the effective management of facilities and the commissioning of other projects. In the longer term, clients will benefit from the increased certainty with which construction firms can predict project outcomes. These include:

- Improved supply chain management, as team members would work more collaboratively and share lessons on construction projects.

- Enhanced knowledge base as much learning that is presently not documented can be captured and reused.

- Facilitate the reuse of collective learning on a project by individual firms and teams involved in its delivery.

- Provide knowledge that can be utilized at the operational and maintenance stages of the asset's lifecycle.

- Involve members of the supply chain in a collaborative effort to capture learning in tandem with project implementation, irrespective of the contract type used to procure the project, for both ongoing and post-project evaluation.

- Maximize the value of reusing the knowledge captured through "live" capture and reuse. The true benefit of capturing knowledge comes only when the knowledge is being used, particularly if the knowledge is being reused during the implementation of a project.

- Enable the knowledge to be disseminated for reuse as soon as possible before the opportunities to reuse the knowledge diminish. This helps prevent knowledge loss due to time lapse after knowledge capture.

- Yin, Tserng and Tsai (2008) attempted to propose a novel and feasible KM framework and application model, a knowledge flow and work flow collaborative operation (KFWFCO) as shown in Figure 2.15, focused on construction industry characteristics. This model proposes a more systematic and flexible KM implementation than previous construction KM models. In Figure 2.16, knowledge guides actions and informs decisions, showing the difference between tacit and explicit knowledge for construction projects.

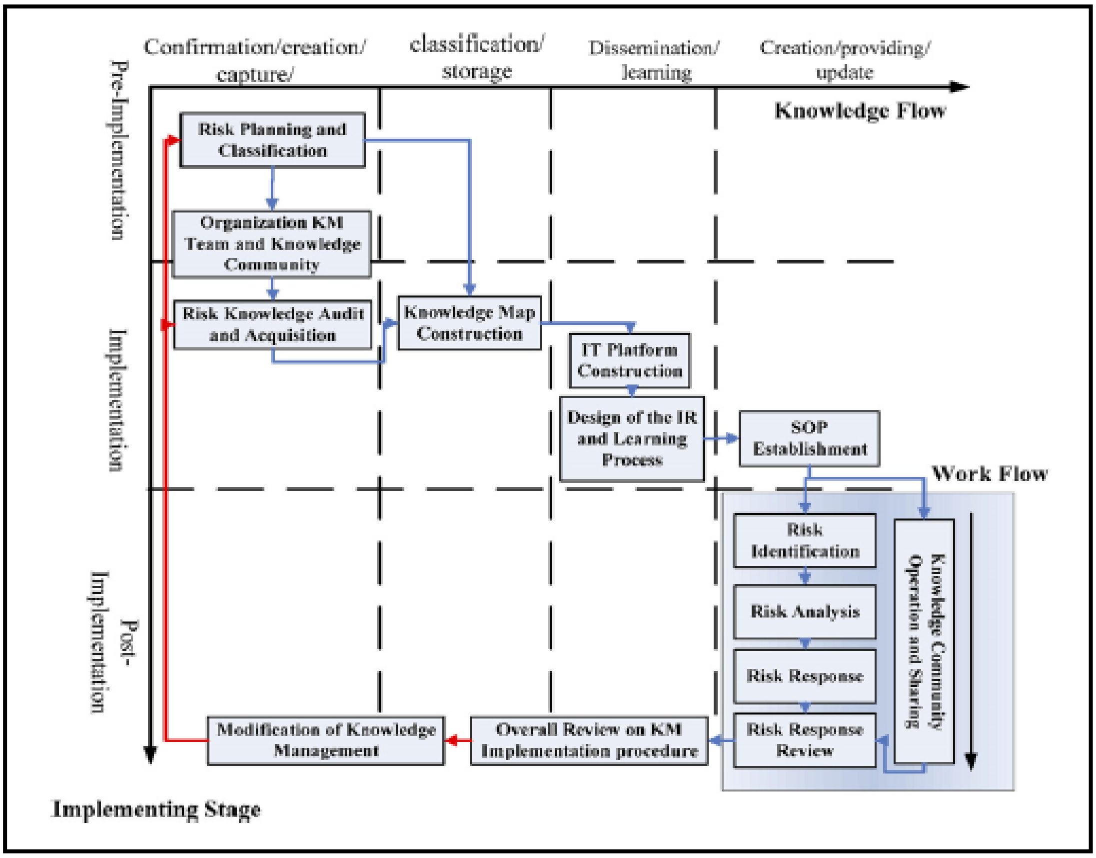


Figure 2.15 Implementation procedure for construction knowledge management (Yin, Tserng and Tsai, 2008)

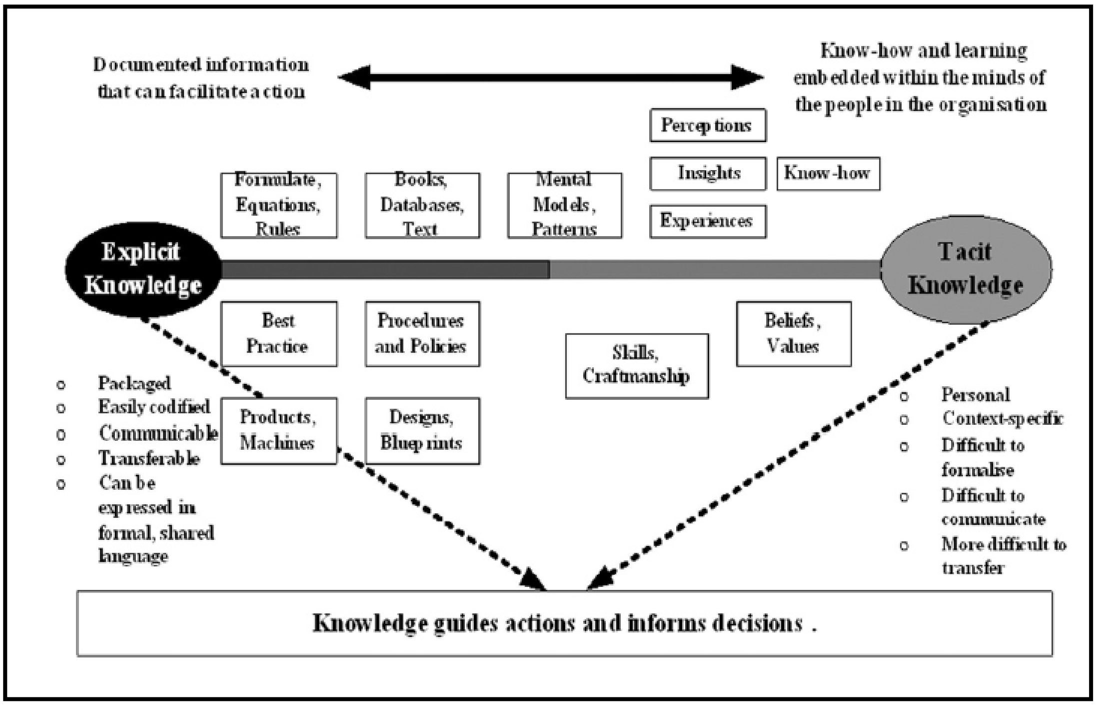


Figure 2.16 Tacit and Explicit Knowledge
(Udeaja, Kamara, Carrillo, Anumba, Bouchlaghen and Tan, 2008)

2.4.7 Knowledge Management System (KMS) in Construction Quality Management

The current study used the benefits of a knowledge management system (KMS) to increase accessibility to inspection knowledge because the proper use of a knowledge management system leads to success in decision making during problem solving. It can be applied to store field inspection data and information about quality inspection in the knowledge-base. Sunkpho, Garrett, Smailagic, Siewiorek and Liu (1998) and Sunkpho (2001) designed a computer-based system that includes field context and intelligent support for field data collection and decision making. It can help reduce the complexity of documents and knowledge. It also helps to overcome the limitations of a purely human inspection system because it can set the standard for quality criteria (Pesante-Santana, 1997). Moreover, the system can capture lessons learned from errors, problems and techniques of correction. As a result, the system can be used to integrate site-inspection knowledge for later retrieval and continuous improvement of quality control standards.

2.5 MATLAB

MATLAB (Matrix Laboratory) is a high-performance language for technical computing. It integrates computation, visualization, and programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. Typical uses include the following (Gonzalez, Woods and Eddins, 2004):

- Math and computation
- Algorithm development
- Data acquisition
- Modeling, simulation, and prototyping
- Data analysis, exploration, and visualization
- Scientific and engineering graphics
- Application development, including graphic user interface building

MATLAB is the standard computational tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the computational tool of choice for research, development, and analysis. MATLAB is complimented by a family of application specific solutions called toolboxes. The image processing toolbox is a collection of MATLAB functions (called M-functions or M-files) that extend the capability of the MATLAB environment to solve digital image processing problems. Other toolboxes that are used to complement IPT are the Signal Processing, Neural Network, Fuzzy Logic, and Wavelet Toolboxes.

We applied the image processing and fuzzy logic toolboxes in MATLAB to solve issues encountered in our research. MATLAB brings to digital image processing an extensive set of functions for processing multidimensional arrays of which images (two-dimensional numerical arrays) are a special case. The Image Processing Toolbox (IPT) is a collection of functions that extend the capability of the MATLAB numeric computing environment. These functions and the expressiveness of the MATLAB language, make many image-processing operations easy to write in a compact, clear manner, thus providing an ideal software prototyping environment for the solution of image processing problems. At the same time, fuzzy logic in the MATLAB Toolbox was applied to develop the structure of decision making to handle uncertainties and tolerate vagueness or ambiguity in many decision-making problems.

2.6 The art of the integrated system

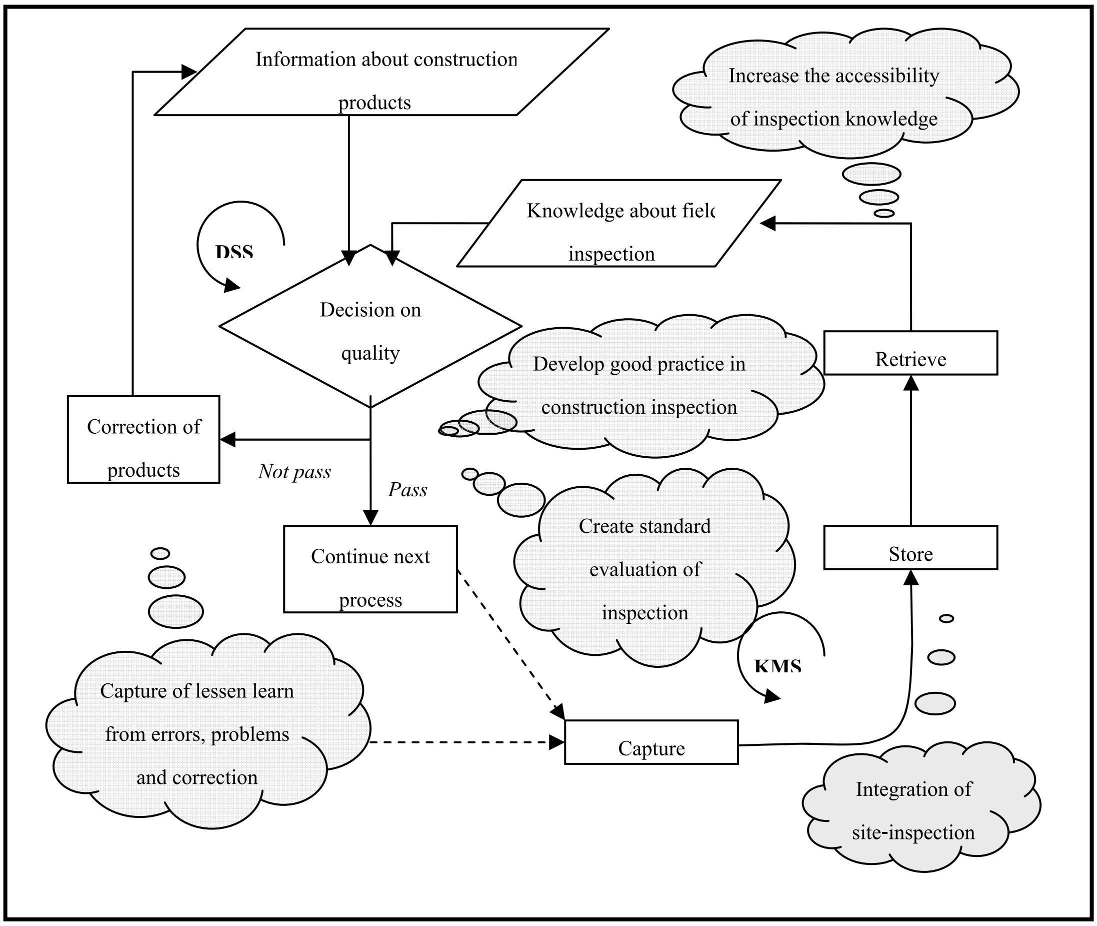


Figure 2.17 Framework for integration of the KMS and the DSS with field construction inspection

Figure 2.17 is an example of a framework for concept implementation. The KMS helps increase accessibility to inspection knowledge. A good knowledge base can be retrieved to support the decision making process of the DSS. It aids in the development of good construction practices in inspection and in the creation of the evaluation standards for quality inspection. As the information flow of our framework shows, the system can capture lessons learned from errors, problems and techniques of correction. It can also store the information on good practice and standards in construction inspection in the knowledge base. As a result, the system can be used to integrate site-inspection knowledge for continuous retrieval and improvement of quality control standards.

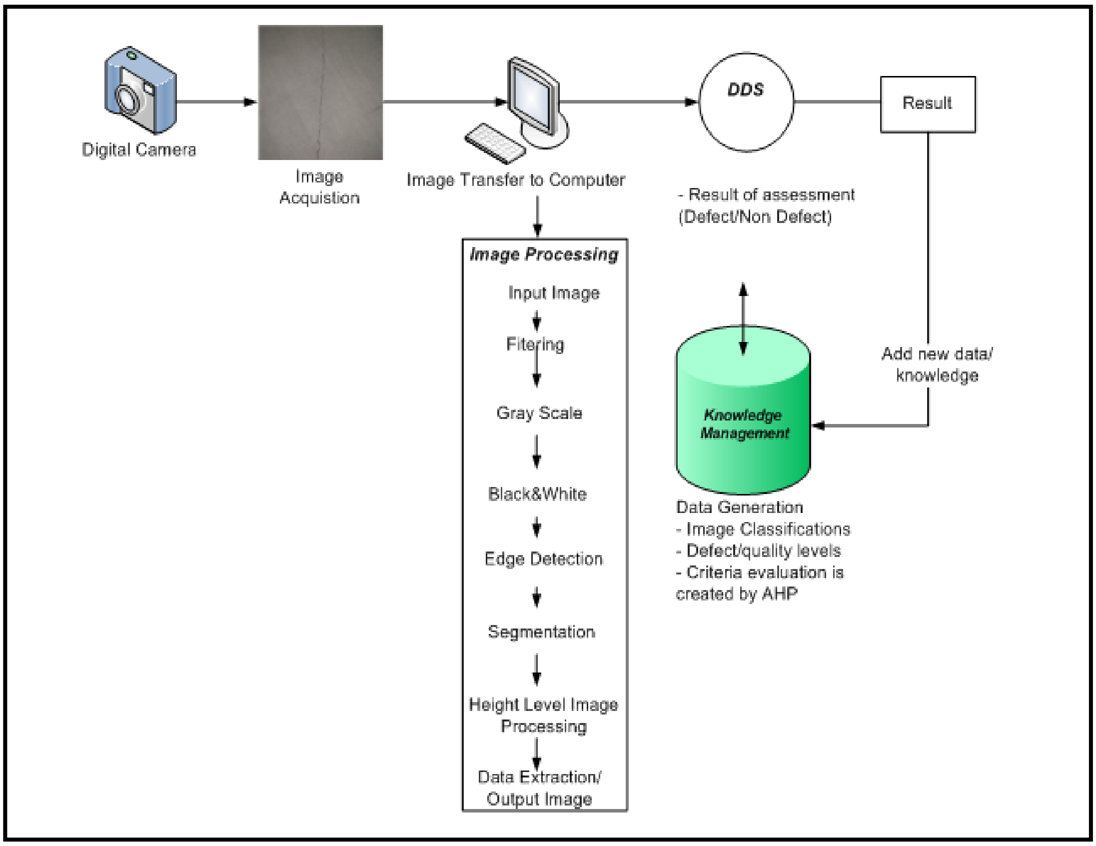


Figure 2.18 Concept of the information technology implementation

Figure 2.18 is an example of information and system work flow used to support inspection. In the first step, a digital camera is used to collect images of instances of damage found during the inspection. Next, image acquisition can be transferred to a computer and passed to image processing before being assessed by the DDS. The DSS then starts comparing the output image from image processing with image data stored in the knowledge-base. This step can help to identify the defects or non-defects in the work from visual inspection. Finally, the system can collect the visual inspection data and provide the results of inspection to be filed in the knowledge-base. This information can be reviewed and stored in the system where it can be used as inspection knowledge for continuous improvement of quality control standards.

CHAPTER III
RESEARCH METHODOLOGY

Our research methodology was conducted in five stages, as shown in Figure 3.1. The preliminary research began with a review of the literature and field observations. The research focused on case studies of tiling work. The initial studies can be considered as preliminary work that was used as a basis for constructing a conceptual framework. Then the conceptual framework was created by designing and developing a prototype of the system. MATLAB was used to develop the system, after which testing in the field was used to estimate the accuracy of the program and the feasibility of the concept. Finally, conclusions and recommendations based on the findings are presented in the last section. The stages of development are described in the next section.

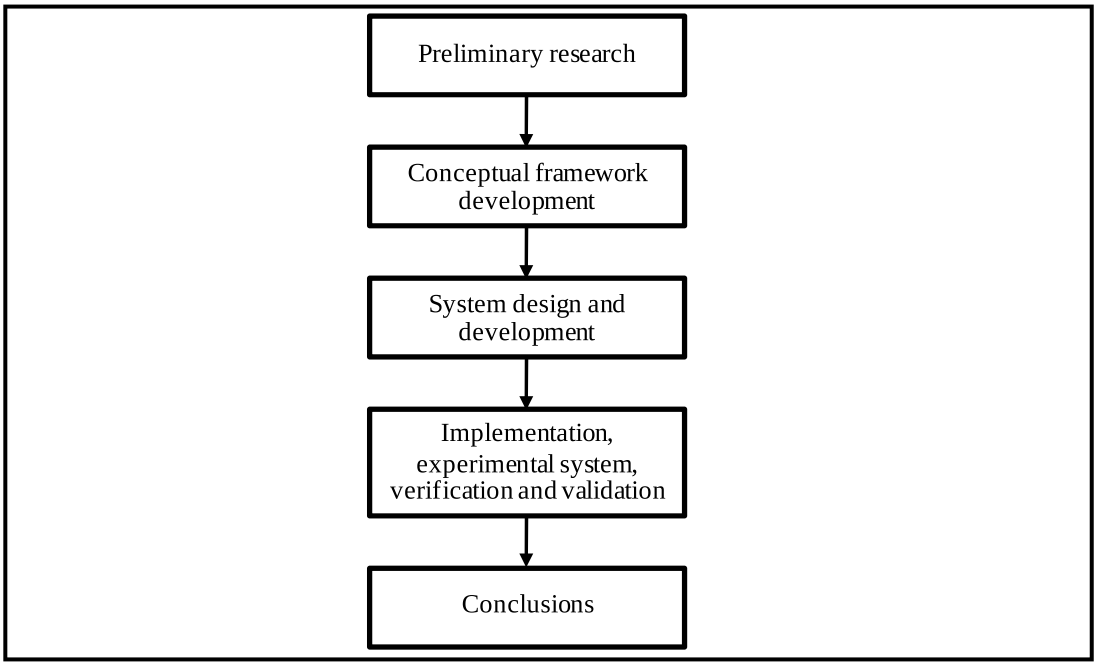


Figure 3.1 Research methodology

3.1 Preliminary research

This research started by reviewing literature and conducting field observations. These initial studies can be considered as preliminary work to be used as a basis in constructing a conceptual framework.

<u>3.1.1 Field Observation</u>

Field observation is conducted to complement the literature review. It presents a description of the current practice of visual quality inspection in the building construction stage. By doing field observation, an in-depth study about the problems of human subjective judgment in aesthetic issues can be more valid.

<u>3.1.2 Literature review</u>

Our literature review aimed to find ways to reduce subjective judgments and enhance the reliability of visual quality inspection in aesthetic issues during the building construction stage. Thus, the related literature is reviewed to present (1) an overview of quality inspection in construction projects by focusing on architectural work. We examine a case study of a housing project.; (2) a study of principles and definitions, basic concepts, benefits, implementation and integration of Digital Image Processing (DIP), Decision Support System (DSS) and Knowledge Management System (KMS) in construction quality management: (3) issues related to developed and integrated systems, study of the use of information technology tools and the programs of MATLAB (DIP and Fuzzy logic toolbox) for system development, and to provide recommendations on the advantages and limitations of these technologies.

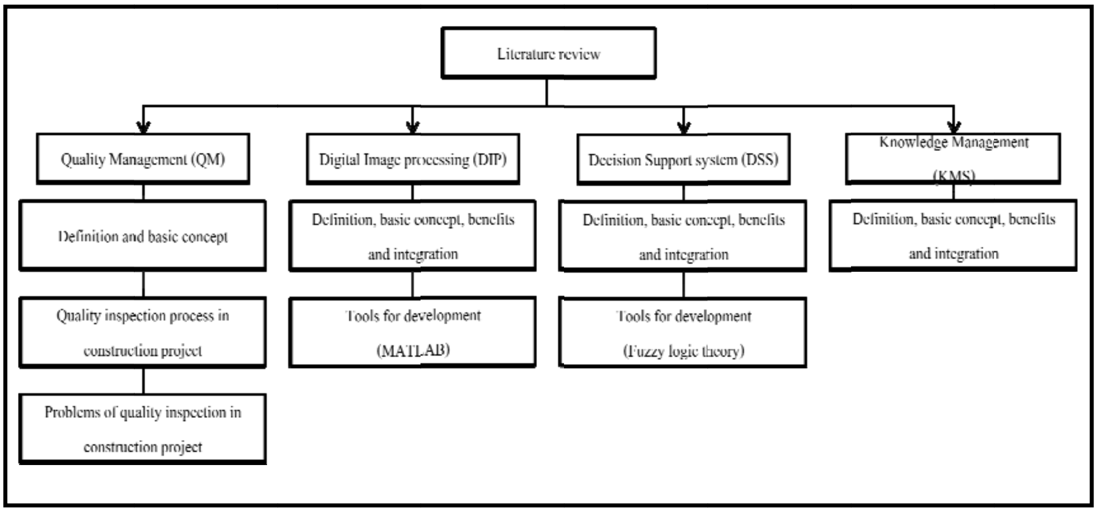


Figure 3.2 Literature review

Following the preliminary research, we direct our attention to ways to overcome the problem of the subjectivity of human judgment.

3.2 Conceptual framework development

The conceptual framework is derived from field observations and the literature review in chapter 2. We examine the capability of digital image processing techniques, fuzzy logic and principles of knowledge management to overcome the problems of subjective judgments. The proposed conceptual framework presents the possible application of these techniques to develop a defect evaluation system. This system will help to support the visual quality inspection process. The development of the conceptual framework is described the problems of visual quality inspection in current practice, approaches to solving the problems of subjectivity of judgment and presents the proposed conceptual framework of the defect evaluation system to support visual inspection in architectural work. Lastly, the expected benefits of the conceptual framework are presented at the end of the chapter.

3.3 System design and development

This section aims to present the design and development of the defect evaluation system to realize the proposed conceptual framework. There are several stages in designing and developing a defect evaluation system. The methodology used to develop a prototype of a defect evaluation system for inspecting tiling work will be explained in two parts: (1) the defect detection and quantification system, and (2) the defect level evaluation system. Each system is designed to show the related components for analysis in (1) input stage, (2) processing stage and (3) output stage in the form of the system framework. The system development uses MATLAB to develop the image processing technique in the defect detection and quantification system, and the Fuzzy logic tool box in MATLAB to develop a defect level evaluation system. After this, both systems are integrated to connect the data. Defect values from the defect detection and quantification system are used to determine the defect level in the defect level evaluation system. Finally, the proposed systems need to test the accuracy of algorithm in system before application on an actual construction site.

3.4 Implementation, experimental system, verification and validation

Implementation in an actual construction site is to verify the accuracy of system and to validate that the concept of this research is better than a human inspector using a purely visual rating method. The content describes the methodology of experimental system, verification and validation. The experimental system is to determine limitations of implementation on an actual construction site. The environments are controlled to ensure that the proposed system can accurately analyze before comparing with visual inspection by inspectors. After that the content describes how to verify the accuracy of proposed system, and to validate comparing with visual inspection by inspectors. Moreover, the results of experimental system, verification and validation are analyzed to identify the limitations and problems of system implementation in actual construction situations to provide suggestions for further study.

3.5 Conclusions

This stage aims to sum up the findings of each of the stages of the research. It originates in the motivation and objectives of the research. A brief description of the methodology in conducting this research is presented afterwards. Finally, the results of the research and recommendations are presented in the last section.

CHAPTER IV
CONCEPTUAL FRAMEWORK OF A DEFECT EVALUATION SYSTEM TO SUPPORT VISUAL QUALITY INSPECTION IN ARCHITECTURAL WORK

This chapter aims to present the conceptual framework of a possible application of digital image processing techniques, fuzzy logic, AHP and principles of knowledge management in a defect evaluation system. The system is designed to support visual quality inspection in architectural work. The content of this chapter describes the problems of visual quality inspection in current practice, approaches to solving the problems of subjectivity of judgment and presents the proposed conceptual framework of the defect evaluation system to support visual inspection in architectural work. Lastly, the expected benefits of the conceptual framework are presented at the end of the chapter.

4.1 Problems of visual quality inspection in current practice

The preliminary field observation, we interview the inspectors in housing projects about construction quality inspection process and quality control before delivers to customer, and problems in current practice. Usually, activities of inspection occur during the work-in-process and end-product stages. During the work-in-process, they check work preparation for each procedure to reduce the number of defects in the final product. Almost items relate with the structural work that are measurable attribute. It can be measured by using mechanical instruments and be compared the measurement value with tolerance value that specify as standard in specification, drawing, sampling in contract document. Inspection during the end-product stage, they check defects or construction errors that must be remedied to improve the quality of the final product before deliver to customer. Most items relate with the architectural work that use only visual inspection method to evaluate the aesthetic faults. A person’s ability to judge aesthetic faults is limited in that it cannot quantify the value of a given defect. The subjective visual inspection leads to subjective evaluation that depends on individual experience and differing perceptions which may not be based on a uniform standard and be unreliable. Therefore, the end-product stages always encounters conflicts regarding the judgment of acceptable defect levels between people involved in the construction inspection process such as inspectors, contractors, and the customer or owner. Both attributes of evaluation are summarized in Figure 1.1.

As above-mentioned, we need the method to solve the problems of subjective attributes. Idea of applying technique for solving the subjective attributes is presented in next section.

4.2 Idea of applying technique for solving the subjective attribute

From the review of related literature in Chapter 2, we have derived an understanding of the capability of digital image processing techniques, fuzzy logic theory, AHP and principle of knowledge management to overcome the problems of subjective judgment. Figure 4.1 describes the idea of application of techniques to solve the subjective attribute. These techniques are used to develop the defect evaluation system supporting the visual inspection in aesthetic faults of architectural work. The application is divided into two steps as follows.

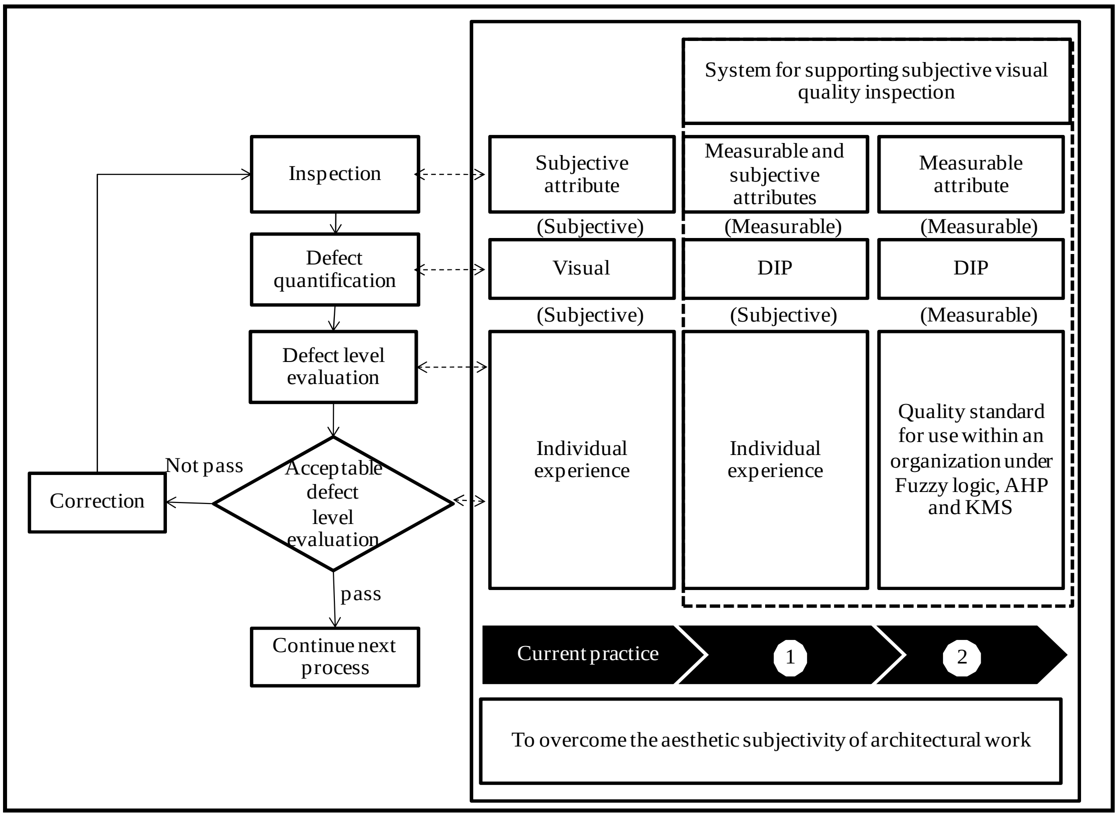


Figure 4.1 Idea of applying techniques for solving the subjective attribute

The first step of inspection process is the defect quantification. Limitations in human vision make it impossible to quantify defect value in the subjective attributes, especially aesthetic faults. Quality evaluation relies on subjective visual inspection which is unreliable. Previous research works have attempted overcome this limitation by using the digital image processing technologies. For examples, the damage inspection in several concrete structures by using digital image processing technique, Georgopoulos, Loizos and Flouda (1995), and Lee (2004) conducted studies to quantify defects and to classify crack types in road infrastructures. The results of these studies helped to optimize infrastructure maintenance strategies during the operation stage. Digital image processing (DIP) is a popular information technology in this field. In the same, Yu, Jang and Han (2007) studied to propose a system by using digital image processing technique for detecting and measuring cracks in a tunnel to provide objective crack data to be used in evaluating safety. Furuta, Namura, Nakatsu, Hattori, and Adachi (2009) studied to apply for evaluating damage level of bridge. Lee, Chang and Skibniewski (2006) studied the inspection of the deterioration of a steel bridge coating by quantifying the amount of rust on the steel surface. Moreover, the image processing can be applied to inspect the defect level in the architectural work. For example, Zhu and Brilakis (2008) studied to detect air pockets in architectural concrete for quality assessment. Mostly, the previous researches intended to apply image-processing technique to detect defect positions on materials in manufacturing such as wood defect classification, defects on tile (cracks, bumps, depressions, holes, dirt, drops, water drop, ondulations, colour and texture) (Boukouvalas, Kittler, Marik, Mirmehdi and Petrou, 1995; Srikanteswara, 1997; Ghazvini, Monadjemi, Movahhedinia and Jamshidi, 2009; Silvestre and Brito, 2009; Ruz, Estevez and Ramirez, 2009). Few researchers have focused on evaluating the intensive defect level of the subjective attributes of aesthetic issues during the construction stage. Therefore, we present the idea of applying the digital image processing technique (DIP) to increase reliability of subjective visual inspection in aesthetic faults of architectural work. The digital image processing technique can help detect the feature of defect from digital image and quantify the numerical value of defect.

The second step of inspection process is the defect level evaluation and the acceptable judgment of defect level. This step is a subjective evaluation depends on individual experience and different perceptions, without explicit standards. It leads to conflicts about judgments of acceptable defect levels. We attempt to reduce the subjective attributes in quality evaluation for improving the reliability of visual quality inspection. Especially, the quality evaluation in aesthetic issue likes fuzziness which is difficult for classifying defect level. In real, the classification in each defect level has the tolerate vagueness. From literature review, various cases of decision making problem in subjective attributes and ambiguity use fuzzy logic theory such as evaluation of customer satisfaction, concept of a comfortable temperature, and separating height value between short and tall (Zadeh, 1965; Zimmermann, 1991; Fasanghari and Roudsari, 2008). Therefore, fuzzy logic can be applied to overcome the ambiguity of defect level classification in aesthetic issue, and to be same standard for using within organization. The quality evaluation is more reliable. Moreover, AHP, and principle of knowledge management were used also to support the system development (Saaty, 1980; Huizingh and Virolijk, 1994; Sahoo, 1998; Tiwana, 2001; Alavi and Leidner, 2001; Bahra, 2001).

4.3 Proposed conceptual framework for the defect evaluation system

The above ideas lead to the proposal of the conceptual framework of the defect evaluation system to support visual quality inspection in architectural work. The defect evaluation system will help to reduce the subjectivity of human judgment in aesthetic issues that rely on the inspector's individual experience. It creates reliability by using digital image processing, fuzzy logic, AHP and knowledge management concepts.

The proposed conceptual framework for defect evaluation system is presented in Figure 4.2. It shows the steps in the methodology of the defect evaluation system that are sequentially linked. The system essentially consists of four main components base on the inspection process: (1) inspection method, (2) defect detection and quantification system, (3) defect level evaluation system and (4) acceptable judgment of defect level.

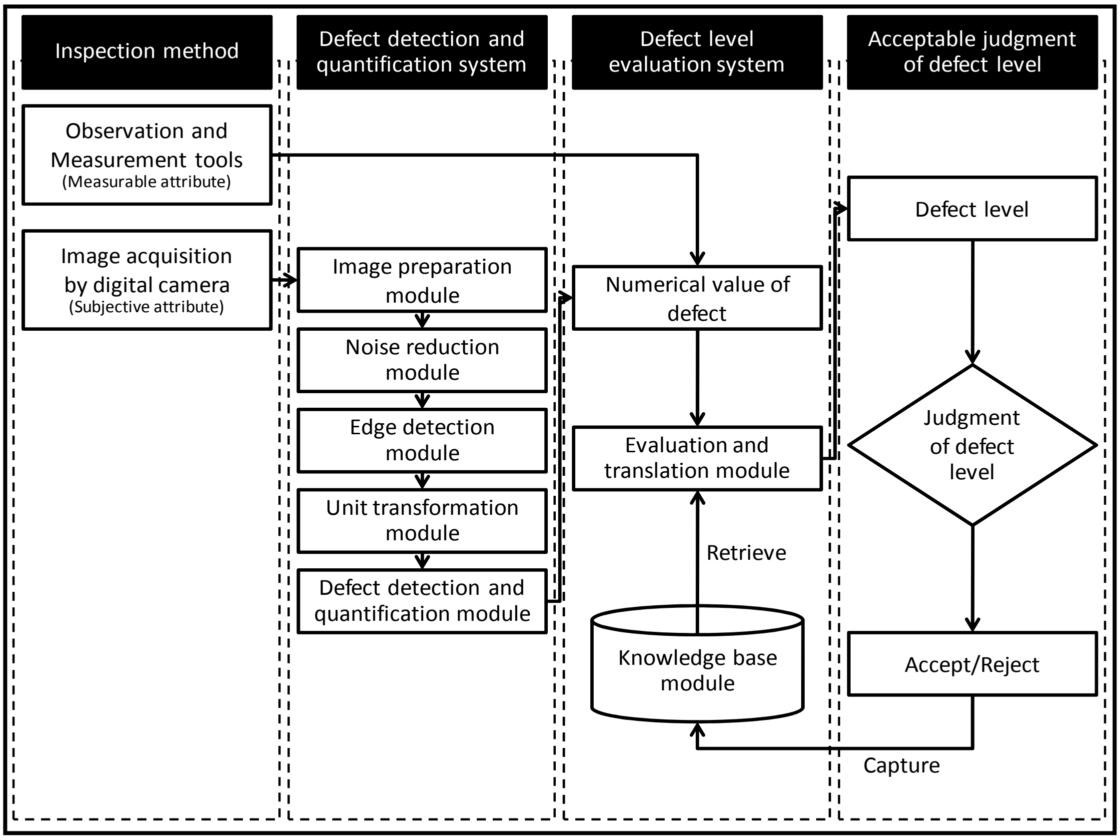


Figure 4.2 Proposed conceptual framework for the defect evaluation system

4.3.1 Inspection method

The first component shows the inspection methods for quantifying the numerical value of defect. We need to suitable select the inspection method with attribute of criteria item. The criteria items are measurable attributes by using the observation method and measurement tools. In criteria items are subjective attributes, the digital camera is used to take the digital images for analyzing the defect feature. However, the digital image processing technique can be not supported in all items. Some criteria item is subjective attributes and can be not overcome by digital image processing technique. We suggest convert the subjective attributes to measurable attributes by using the observation method to identify the defect positions. Although it is still semi-subjective attributes, it is more reliability than the old method.

4.3.2 Defect detection and quantification system

The second component presents the defect detection and quantification system. The system uses a digital image processing technique to detect defects and to quantify the defect value from a defect feature analysis on a digital image. Usually, the defect detection and quantification system is divided into five modules: (1) an image preparation module, (2) an image enhancement module, (3) an image feature analysis module, (4) a unit transformation module, and (5) a defect detection and quantification module.

First, the image preparation module is to adjust the distorted image from lens specification and perspective image from angle of taking photo. Second, the image enhancement module is the pre-processing that aims to improve the quality of digital image into suitable form for easier analysis by using the digital image processing method. The image enhancement module has several techniques. The application of each technique depends on the feature of interested object on image such as noise reduction, contrast enhancement, image sharpening and converting into binary image. Next, image feature analysis module used the principle of digital image processing to analyze image features such as regions, edges, scale, interest points and texture. These are used to calculate the defect value in the defect detection and quantification module. After that, the unit transformation module is used to transform the pixel unit from the image into a millimeter form of a real object. Usually, the image acquisition is characteristic of virtual image which is pixel value unit. Thus, this module helps to adjust the image unit according to scale ratio of virtual image per real object (pixel per mm.). The scale ratio depends on photography conditions such as camera specification, distance and angle camera. Finally, the defect detection and quantification module is used to specify the defect positions and to quantify the defect value by using the proposed algorithm to analyze the image features.

4.3.3 Defect level evaluation system

At present, there are several criteria items in the quality inspection of architectural work that still lacks the evaluation standard, especially in aesthetic faults. The evaluation is subjective attributes which depends on only the individual experience of inspectors. The subjective evaluation leads to conflict between the involved persons and to be unreliable. Moreover, the quality evaluation in construction stage of architectural work still lacks a method to capture the lessons learned from previous decisions, different scenarios and problems. These experiences can be developed as quality evaluation standards and stored in the knowledge base to support inspectors in the quality decision making process.

Therefore, the proposed conceptual framework of defect level evaluation system aims to present the evaluation mechanism and the developed knowledge base to be a standard to evaluate defect levels support inspectors for the acceptable judgment of defect level in aesthetic faults. The defect level evaluation system evaluates the defect level by comparing the results of defect value analysis from the previous component with defect level classification in the knowledge base. The knowledge base and evaluation mechanism are developed from the fuzzy logic and AHP concept of collecting knowledge from the experience of experts.

The defect level evaluation system includes two main modules: (1) the evaluation and translation module and (2) the knowledge base module, which is shown in Figure 4.2. The methodology of applying the fuzzy logic, AHP and knowledge base for defect level evaluation system can be explained as follows.

4.3.3.1 Evaluation and translation module

The evaluation and translation module is an evaluation mechanism to translate the numerical value of defect into a defect level by using the algorithm of logical and mathematical model, and using information of defect level classification from the knowledge base module. The evaluation in aesthetic faults is subjective attributes. Fuzzy inference system can handle ambiguity in some work items that can be not separated clearly. The proposed system attempts to mimic human inference processes in decision-making, but the system is more reliability because there is a systematic evaluation and the same standard using within organization. The evaluation mechanism of evaluation and translation module is designed corresponding with a hierarchical structure for evaluation. The evaluation consists of three stages; (1) stages of sub-criteria, (2) stage of criteria, and (3) stage of overall of work. First, the stage of sub-criteria is to evaluate the defect level in each sub-criterion by comparing defect value with defect level classification in knowledge base. Second, the stage of criteria is to evaluate the defect level in each criterion by considering overall of all sub-criteria. Last, evaluation in stage of overall defect level of work will consider from all criteria. Result of defect level evaluation from three stages can be used for comparing with defect level requirements for continuous quality improvement.

4.3.3.2 Knowledge base module

The knowledge base module aims to be contained the information for supporting the evaluation mechanism in evaluation and translation module. The knowledge base for supporting the fuzzy evaluation mechanism in the proposed conceptual framework consists of three main parts: (1) defect level classification or fuzzy sets (2) fuzzy rule bases and (3) the relative weight of criteria. The defect level classification or fuzzy sets and fuzzy rule bases are developed from a survey of experts bases on principle of fuzzy logic. The relative weight is developed by using the pairewise comparison method in AHP.

4.3.4 Acceptable judgment of defect level.

The final component, the human inspectors are acceptable judgment of defect level by using the information from the results of defect level evaluation. The proposed conceptual framework is to support the acceptable judgment of defect level in subjective visual inspection. However, the standard of acceptable judgment in defect level can be developed when there are more previous situation of acceptable judgment.

4.4 System and expected benefits

There are three main anticipated benefits of using this system.

First, it can increase the reliability of visual inspection on construction products by using the DIP to overcome the limitations of human vision. It can change subjective evaluations to measurable evaluations. It does not depend merely on the subjective judgment of each person. It can be used as a tool to evaluate defect levels and support the decision making process for problem resolution.

Second, it can be used to develop standards for evaluating quality in aesthetic issues in each construction project or organization. It is used to ensure that quality standards correspond to customer requirements.

Finally, it can reduce sources of conflict among project participants who are involved in evaluating tiling work defects.

4.5 Conclusions

The current construction inspection process encounters conflicts regarding acceptable levels of defect in aesthetic issues that arise in architectural work. This chapter has presented the conceptual framework of an innovative defect evaluation system to overcome such conflicts. The proposed framework adopts digital image processing technique to overcome the limitations of human visual inspection in the analysis of defect features as well as providing a method of quantification to identify the defect value to be evaluated for each defect level. Fuzzy logic, AHP and knowledge management are used to increase the reliability of visual quality inspection by developing evaluation standard using within organization or project. Then, to demonstrate the feasibility of the proposed conceptual framework, we chose tiling work inspection as a case study to design and develop a prototype of the defect detection and quantification system, and the defect level evaluation system. The stages of the design and development of the systems are described in chapter 5 and chapter 6 respectively.

CHAPTER V
THE DESIGN AND DEVELOPMENT OF A DEFECT DETECTION AND QUANTIFICATION SYSTEM PROTOTYPE

This chapter presents the design and development of the defect detection and quantification system to realize the proposed conceptual framework presented in Chapter 4. The design is used to support visual quality inspection in architectural work. The case study of tiling work is chosen to develop the prototype of system. The development of the defect detection and quantification system use MATLAB to formulate algorithms in the image processing facility in our system. We use the image processing technique to reduce noise and to detect edge. Moreover, the proposed algorithms are developed to detect the defect positions and quantify defect values.

5.1 System design

This section aims to design the prototype of defect detection and quantification system for case study of tiling inspection. The designed system needs to correspond with the proposed conceptual framework in Chapter 4. Before the beginning of the system design, the comparison of criteria and sub-criteria between the traditional and new inspection methods was reviewed in Table 5.1. This information is summarized from the results of interviewing inspectors in the field and reviewing the quality inspection standards of several organizations (Navon, 2000; CIS 7:2006, 2006). The traditional inspection methods use most frequently in the criteria items of F1, F2 and F3. These items are classified as the visual quality inspection method. The criteria F4 use the knock method as the measurement tool to identify the pieces of defective tile. In the same, all sub-criteria under criteria F1 and the sub-criterion f_{32} under criteria F3 can identify the pieces of defective tile or defect positions from observation method. While all sub-criteria under criteria F2 and the sub-criterion f_{31} under criteria F3 are subjective visual inspection that cannot quantify the defect value. Although the visual inspection of certain items can be supported by a caliper or alignment laser, these inspections cannot quantify the defect value, and the inspection uncovers all defect positions, especially in cases of mass products or large areas. It leads to subjective judgment that depends on individual perceptions without established standards.

Table 5.1 Summary of criteria and sub-criteria to evaluate the completion of tiling work in the traditional inspection methods (adapted from Navon (2000) and CIS 7:2006 (2006))

Criteria	Sub-criteria	Defect check list	Traditional inspection methods		New inspection methods	
			Inspection methods	Numerical value of defect for quality evaluation	Inspection methods	Numerical value of defect for quality evaluation
F1		Inspecting the completion of tile				
	f_{11}	Conformity of tile to specification	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
	f_{12}	Conformity of tile pattern to specification	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
	f_{13}	Number of tiles without nicks or gashes	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
F2		Inspecting distance between neighbouring tiles (gap)				
	f_{21}	Uniformity of gap size with the respect to standard	Visual inspection	Subjective judgment	Visual inspection DIP	Score rating Defect area (squ.m)/panel
	f_{22}	Uniformity of glue application over gap line	Visual inspection	Subjective judgment	Visual inspection DIP/Observation methods	Score rating Number of defect points/panel
F3		Tile alignment inspection				
	f_{31}	Straightness of tile alignment (parallel lines)	Visual inspection	Subjective judgment	Visual inspection DIP	Score rating Number of defect intersecting point/panel
	f_{32}	Uniformity of level of neighbouring tiles	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
F4		Inspection of adherence of tile to panel				
	f_{41}	The glue has to be spread uniformly back of the tile	Knock	Number of defect tiles/ panel	Knock	Number of defect tiles/ panel
	f_{42}	The tile must be pressed evenly against the panel	Knock	Number of defect tiles/ panel	Knock	Number of defect tiles/ panel

Therefore, this research attempts to overcome the subjective attributes by using digital image processing technique for developing the defect detection and quantification system supporting the subjective visual inspection. The proposed system was able to determine if the distance between the neighboring tiles was uniform and if it had a standard gap size (sub-criterion f_{21}). It also determined whether the tiles are set in straight parallel lines (sub-criterion f_{31}). For the sub-criterion f_{22}, our study still attempts to overcome the subjective attributes by applying digital image processing technique in future work because we envision its potential benefits. In this research, we suggest convert the subjective attributes to measurable attributes by using the observation method to identify the defect positions. Although this method uses the semi-subjective attribute to evaluation, it is more reliability than the old method. The new inspection methods are shown in Table 5.1.

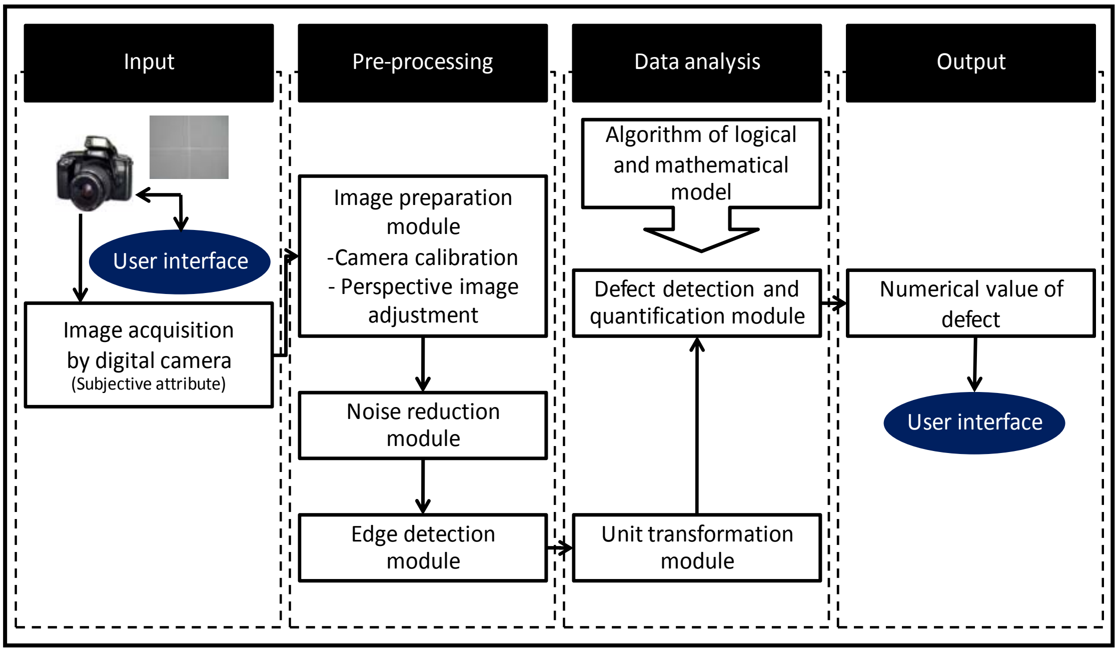


Figure 5.1 The process of defect detection and quantification system

The defect detection and quantification system was designed to support inspectors during a subjective visual inspection. The process of system was presented in Figure 5.1. It shows all of the methodological steps of system that are sequentially linked. The defect detection and quantification system includes four main processes; (1) input, (2) pre-processing, (3) data analysis, and (4) output. The image acquisition is in the input step. The five modules of digital image processing are in pre-processing step and data analysis step. In pre-processing step includes an image preparation module, a noise reduction module and an edge defection module. The data analysis step includes a unit transformation module and a defect detection and quantification module. First, the image preparation module is to adjust the distorted image and perspective image. Second, the noise reduction module pre-processes the digital image to reduce unnecessary background noise from the digital image. Next, the edge detection module uses a digital image processing technique to detect the edge of the object of interest in a digital image. After that, the unit transformation module is used to transform the pixel unit from the image into a millimeter form of a real object. Finally, the defect detection and quantification module is used to specify the defect positions and to quantify the defect value by using the proposed algorithm to analyze the image features. Finally, the output step is numerical value of defect. The details of development are explained in next section according to the framework of defect detection and quantification shown in Figure 5.2 and the user interface shown in Figure 5.3.

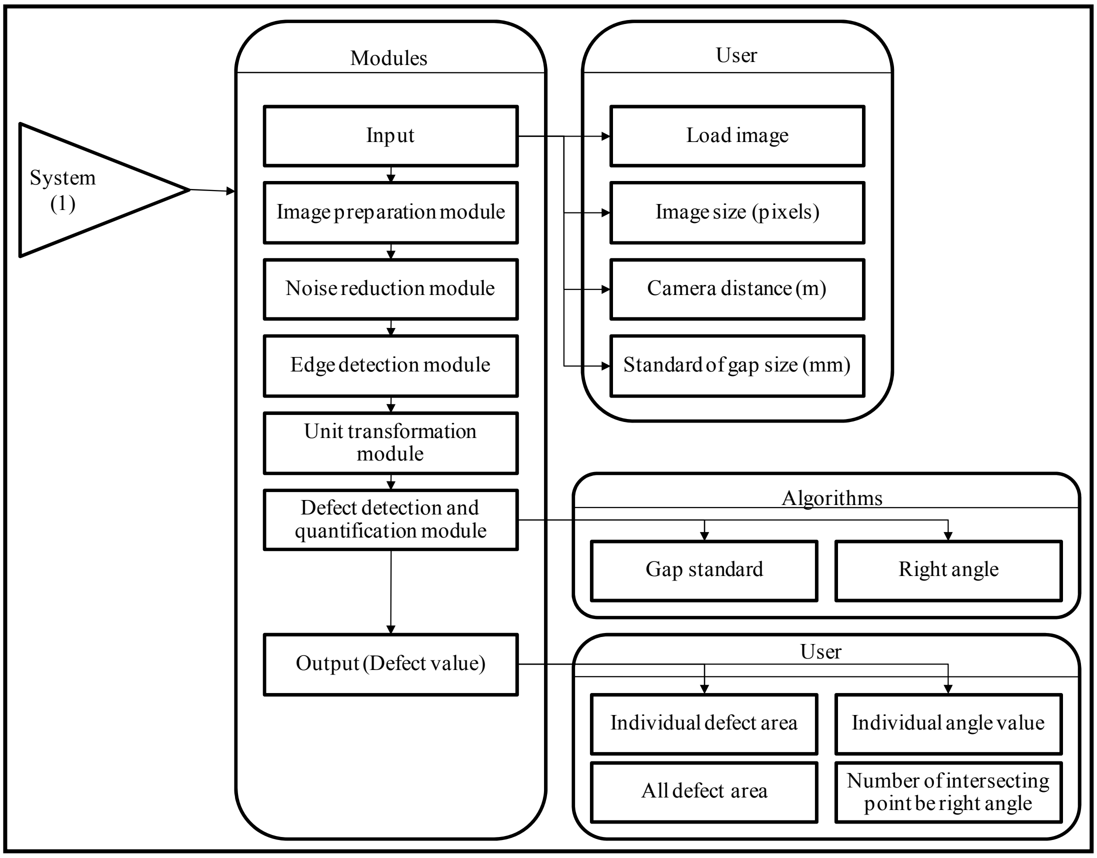


Figure 5.2 Framework for the defect detection and quantification system

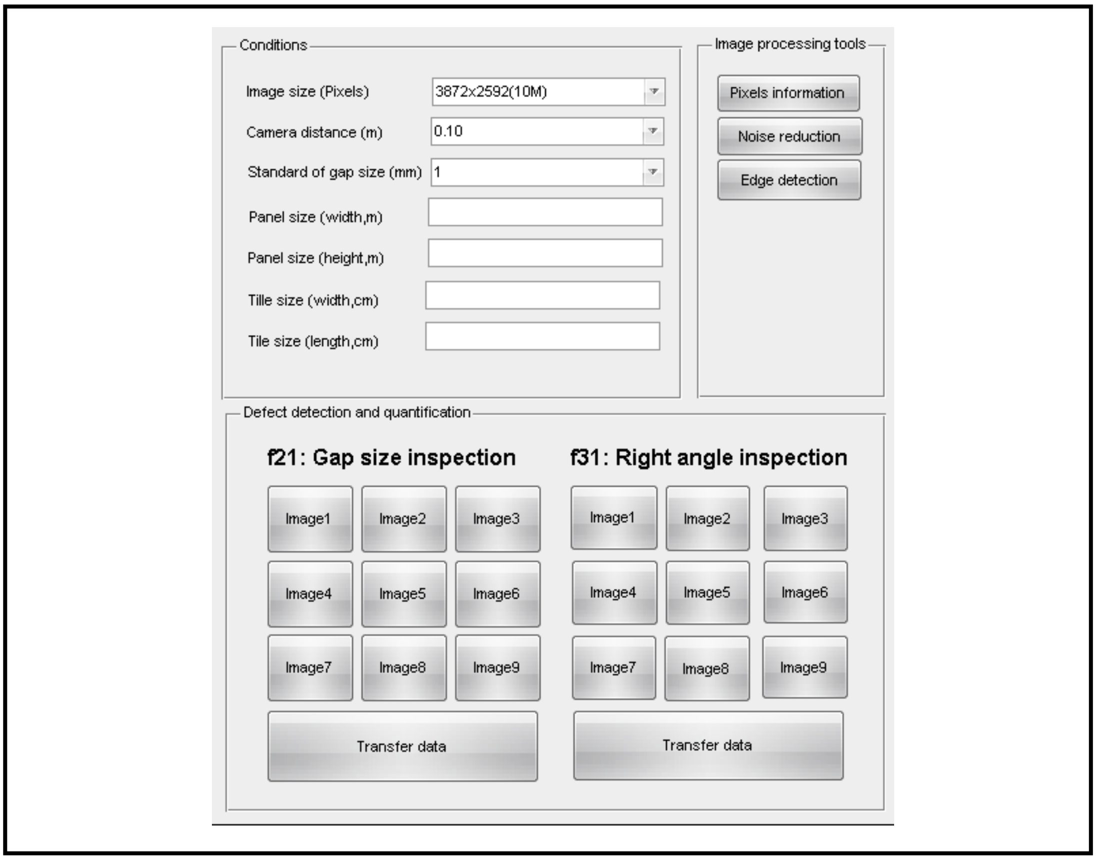


Figure 5.3 User interface of the defect detection and quantification system

5.2 System development

The detail development for the defect detection and quantification system of tiling work inspection is described in the following sections. The methodology can be divided into seven steps, as shown in Figure 5.2; (1) input, (2) an image preparation module, (3) a noise reduction module, (4) an edge defection module, (5) a unit transformation module, (6) a defect detection and quantification module and (7) output. We used the MATLAB program to develop the image processing in this system.

5.2.1 Input

The input data for the proposed system are acquired for data processing. Our method used a digital camera and a data link as the main tools for capturing and transferring images to the system. Moreover, the proposed system requires a user interface to manage the images as shown in Figure 5.3. Beside the system requires image data, the system also requires the information of image size (pixels), camera distance (m) and standards of gap size (mm) as conditions for defect feature analysis on digital images. Codes used image loading, are as follows:

```
%%%%%%%%%%%%%%%%%%Load image%%%%%%%%%%%%%%%
[fname,fpath] = uigetfile('*.jpg');
fname = strcat(fpath,fname);
d = imread(fname);
```

5.2.2 Image preparation module

Image preparation module includes with issues of the image distortion and the image perspective. Image distortion and image perspective are important issues that need to be adjusted before conducting image processing. Distorted images occur as a result of lens specifications. Image perspective occurs from the angle at which the photo was taken. These issues affect the accuracy of the visual inspection system. Although our system does not support these issues, we suggest basic principles for implementation as follows (Gonzalez and Woods, 1992; Gonzalez, Woods and et al., 2004).

(1) Camera calibration

Camera calibration is the process of determining the characteristics of a camera that affect the imaging process. Since the lens and other optical systems such as mirrors or prisms have defects which lead to blur, color changes, geometric distortion from the ideal ray, etc., we need to know the defect value of these parameters before the camera can be used. These parameters are used to improve accuracy without concern for the highest measurement.

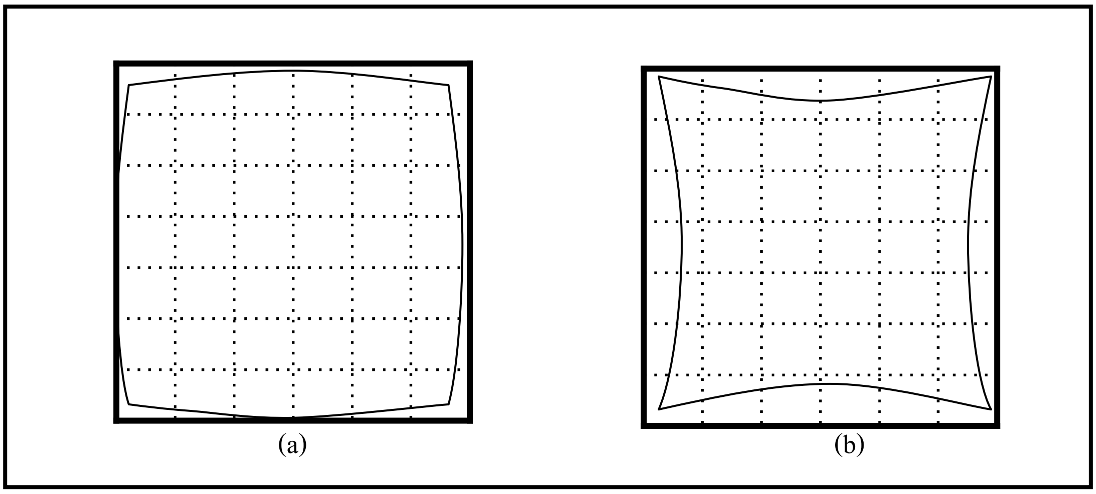


Figure 5.4 Radial distortion (a) Barrel distortion (b) Pincushion distortion (Gonzalez and Woods, 1992)

For example, geometric lens distortion refers to deformation of an image which causes a point's image on the imaging surface (film or ccd) to be shifted from its true position as if it had been imaged by an ideal pin-hole camera. If the object side is a flat grid consisting of squares then it is projected either as a barrel or pincushion, see Figure 5.4. In barrel distortion, magnification decreases with distance from the axis. In pincushion distortion, magnification increases with distance from the axis.

There are several software programs which can be used to correct these parameters such as PhotoModeler, Australis, SGAP (IGP-ETHZ) (Remondino and Fraser, 2006), Photoshop, the Matlab Toolbox and other softwares from several manufacturers. Image distortion can be corrected by using equations as follows (Sonka, Hlavac and Boyle, 2008):

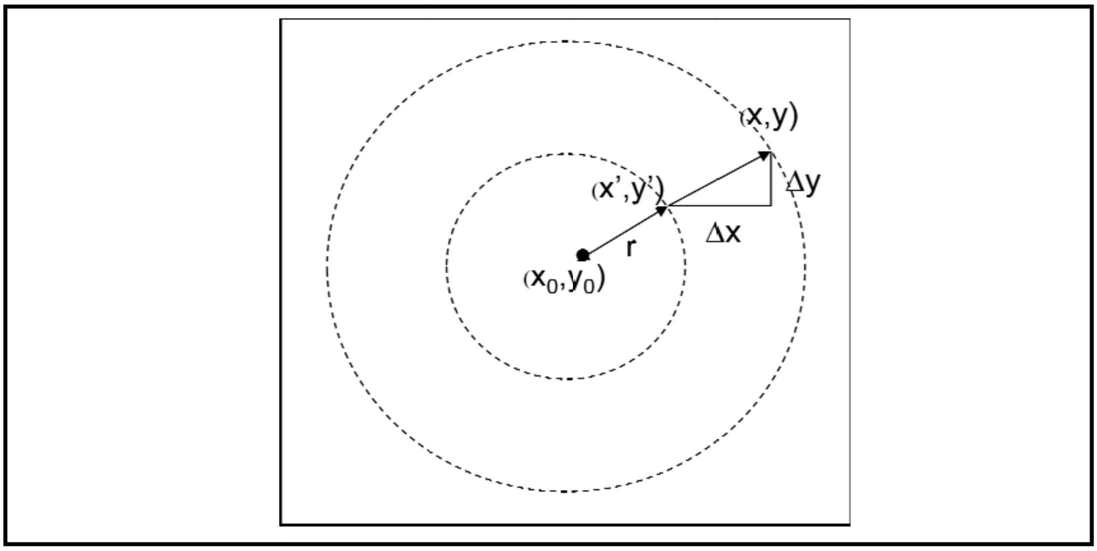


Figure 5.5 Distortion correction (Sonka, Hlavac and Boyle, 2008)

$$r = \sqrt{(x-x_0)^2+(y-y_0)^2} \tag{5.1}$$

$$\Delta x = (x'-x_0)(k_1r^2 + k_2r^4 + k_3r^6) \tag{5.2}$$

$$\Delta y = (y'-y_0)(k_1r^2 + k_2r^4 + k_3r^6) \tag{5.3}$$

$$x = x' + \Delta x \tag{5.4}$$

$$y = y' + \Delta y \tag{5.5}$$

Where, r = the distance between pixel (x_0,y_0) and (x',y')
(x,y) = pixel coordinates after correction
(x',y') = pixel coordinates measured in the image (uncorrected)
(x_0,y_0) = coordinates of the principal point
$(\Delta x, \Delta y)$ = components of the necessary correction

k_1, k_2, k_3 = coefficients from program (such as PhotoModeler program)

For this research, we used the AF Micro 60mm f/2.8D lens and Nikon D80 camera which creates few image distortions. These tools are used in our research to minimize the limitation of image distortion from the digital camera.

(2) Image perspective adjustment

This study refers to the adjustment of image perspective from the angle at which a photo is taken. Practically, it is too difficult to take a photo with a camera whose front is placed at right angles to the object without measurement. The image perspective can be corrected by Photoshop and other programs. Representative images in this research set the photo capture position by measuring the front of the camera to ensure it was at a right angle with the object to minimize this limitation.

Next, the prepared image is transferred to image processing to detect defect positions and quantify absolute defect value which can be explained as follows.

5.2.3 Noise reduction module

The noise reduction module is the first image processing of the system after the image is inputted into the system. This module supports the function of image adjustment to reduce unnecessary backgrounds or noise from a digital image by using the pre-processing of a digital image processing technique. There are many techniques in image processing (Gonzalez, Woods and Eddins, 2004) that can be used to reduce this background noise. However, we must select the technique most suitable for the objective of analysis.

When exploring representative images in tiling inspection, we found that non-uniform illumination caused by tile reflection is a major source of noise that must be reduced because it affects the step of edge detection module. The pixel value is variable, and it is difficult to choose the threshold value when converting image to a binary image (black = 0 and white = 1). Therefore, the morphological method is suggested to correct for non-uniform illumination. This method extracts unnecessary background noise from the image which is the pixel value of the tile reflection (Sonka, Hlavac and Boyle, 2008). The clarity of the gap lines in the image is improved by each step such that the differences between the histogram in Figure 5.6(b) and 5.6(c) are noticeable. Figure 5.6(b) shows sufficient contrast between the object and background, but it is very difficult to choose a threshold for edge detection in the next module. However, the data in the histogram in Figure 5.6(c) make it easier to choose the threshold value.

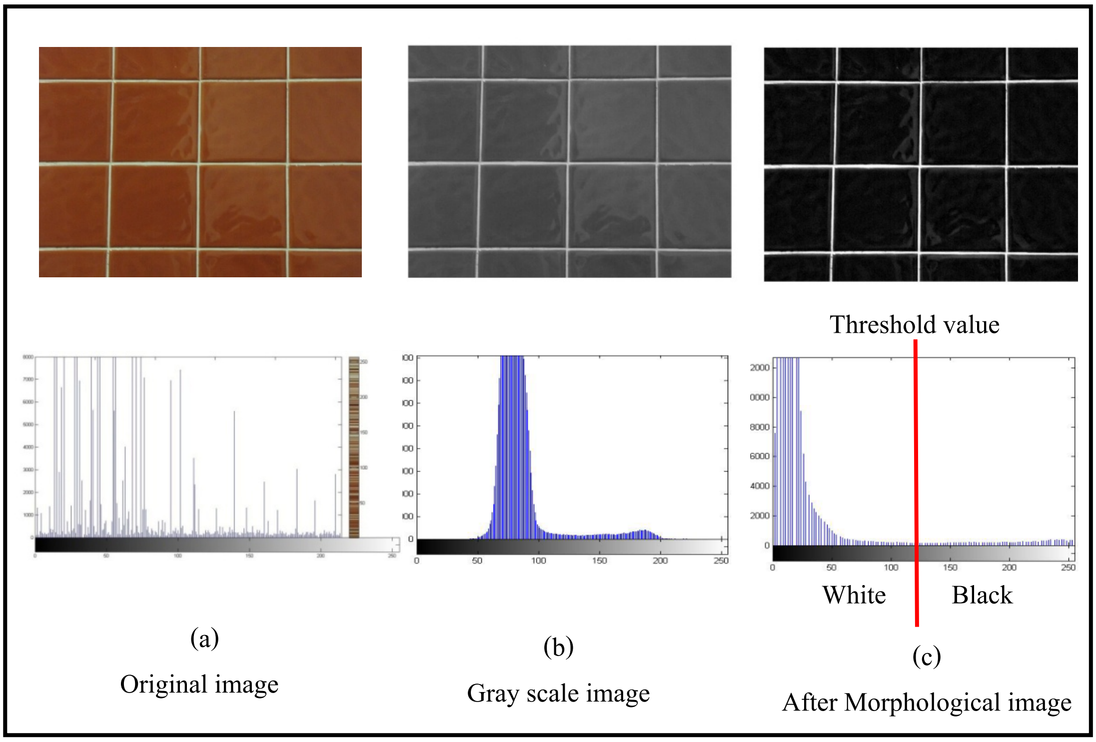


Figure 5.6 Histogram of each step of an image

Thus, we discuss morphological methods used to enhance image quality and automatic selection of threshold value, and we consider a method for varying the threshold according to the properties of local image neighborhoods. In this way, we can correct for non-uniform illumination (Image Processing ToolboxTM 7, User's Guide) as shown in the following five steps.

Step1: Read and display the color image

```
[fname,fpath] = uigetfile('*.jpg');
fname = strcat(fpath,fname);
RGB = imread(fname);
imshow(RGB);
```

Step2: Convert to grayscale image

```
I = rgb2gray(RGB);
```

Step3: Use a morphological opening operation

We use a morphological opening operation to estimate the background illumination. Morphological opening is an erosion followed by dilation, using the same structuring element for both operations. The 'imopen' is used to adjust the smooth of the image contour.

```
background = imopen(I,strel('disk',15));
```

The example shows the imopen function used to perform the morphological opening operation. The example commands the strel function to create a disk-shaped structuring element with a radius of 15.

Step4: Subtract the background image from the original image

To create a more uniform background, subtract the background image (background) from the original image (I).

```
I2 = I - background;
```

Step5: Increase image contrast

After subtraction, the image has a uniform background but is now a bit too dark. Use "imadjust" function to adjust the contrast of the image. The function increases the contrast of the image by saturating 1% of the data as both low and high intensities of I2 and by stretching the intensity value to fill the unit8 dynamic range (the unit8 class is scale range between 0 and 256).

```
I3 = imadjust(I2);
```

5.2.4 Edge detection module

Edge detection module in the proposed system supports the function of edge detection of interested object on the image for defect feature analysis. The edge of tile on image is interested object in case study of tiling inspection. The development of this module uses the digital image processing technique. Generally, edge detection shows the image location of discontinuities in the gray level of an image. There are various edge detection methods that are applied in different cases (Gonzalez and Woods, 1992; Gonzalez and Woods, 2004; Yodrayub, 2007; Sonka, Hlavac and Boyle, 2008). Our research tests three methods; (a) Canny, (b) Prewitt and (c) Sobel methods for selecting the suitable approach that can be applied in our system development. We tested these three methods with the 76 representative images in this study. We note that the edges in Figure 5.7 are the example of result of applying the (a) Canny, (b) Prewitt and (c) Sobel methods. The result of applying the

Canny method is shown in Figure 5.6(a). It has some lines that may not be the line segments of the tile edges in an image. Our research shows that the Canny method is not suitable for our case study because it shows all discontinuities of the gray-level, which includes the noise from tile patterns in all representative images. The Prewitt and Sobel methods show similar results. Both methods can be used to detect the tile edge in our system because the results have the least noise. The 50 images, or 73.68%, of all representative images can be used in the defect detection and quantification module because the lines of tile edge are clear.

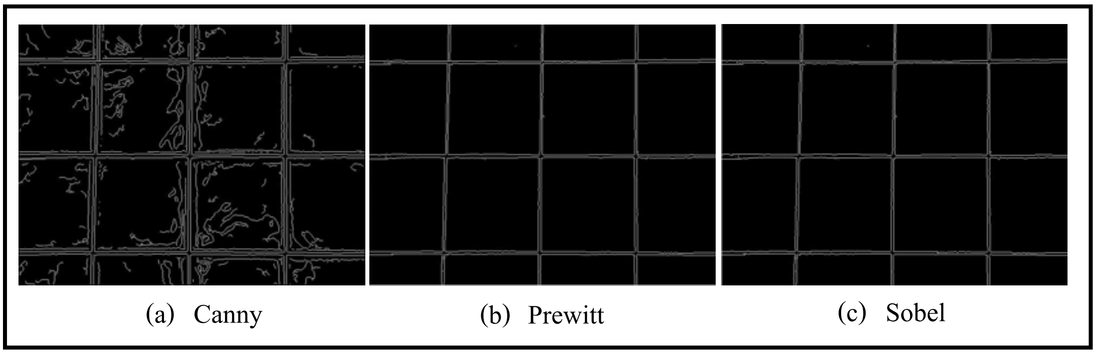


Figure 5.7 Edge detection

Therefore, we can choose the Prewitt or Sobel method to develop our system. Codes of edge detection are shown as follows:

```
%%%%%%#Edge detection stage, so result is a binary file.
        BW = edge(I3,'prewitt'); (or sobel)
        BW=im2double(BW);
```

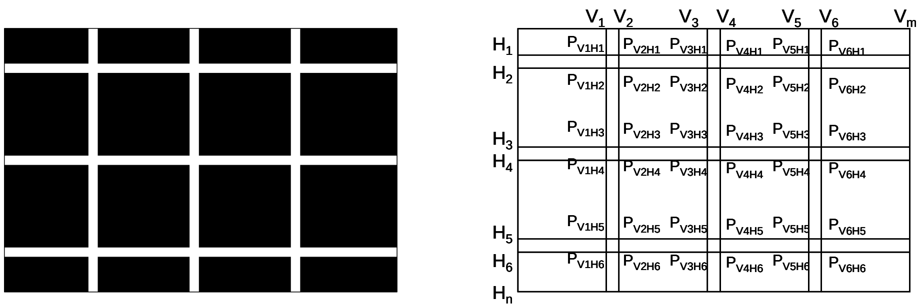


Figure 5.8 Image feature analysis

Next, the coordinates of each vertical line (V1,V2,..,Vm) and horizontal line (H1,H2,…Hn) (Figure 5.8) were used to analyze the defect positions and to calculate the defect value in the defect detection and quantification module.

<u>5.2.5 Unit transformation module</u>

The unit transformation module supports the function of transforming the pixel units into millimeters in the proposed system for comparing in the same unit of an actual object. The ratio of mm-per-pixel depends on the photographic conditions, such as the camera specifications, camera distance and pixel size. To determine the ratio of unit transformation, we used 45 representative images of letter sheet that were divided into 3 sets. The images in each set were taken at a camera distance interval of 0.10 m from 0.50 to 2.00 m. The camera position was set up as follows (modified from PhotoModeler manual).

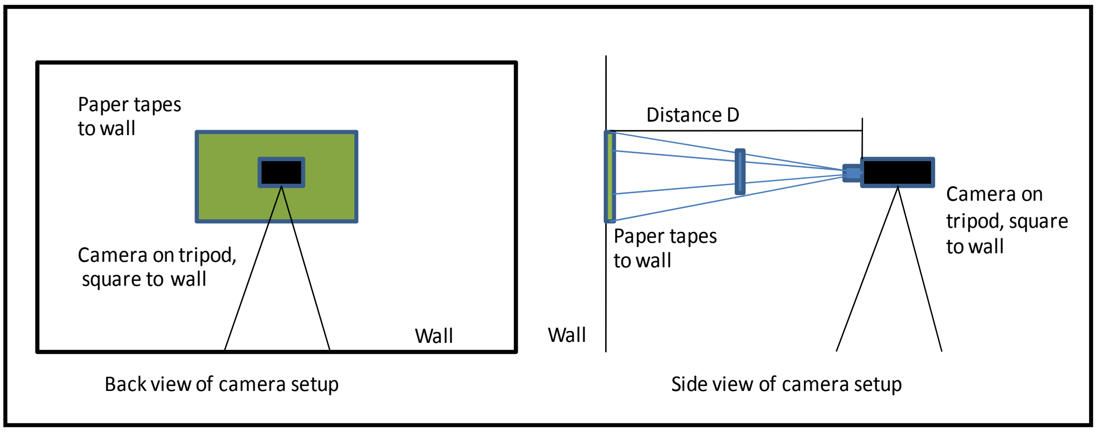


Figure 5.9 Camera position

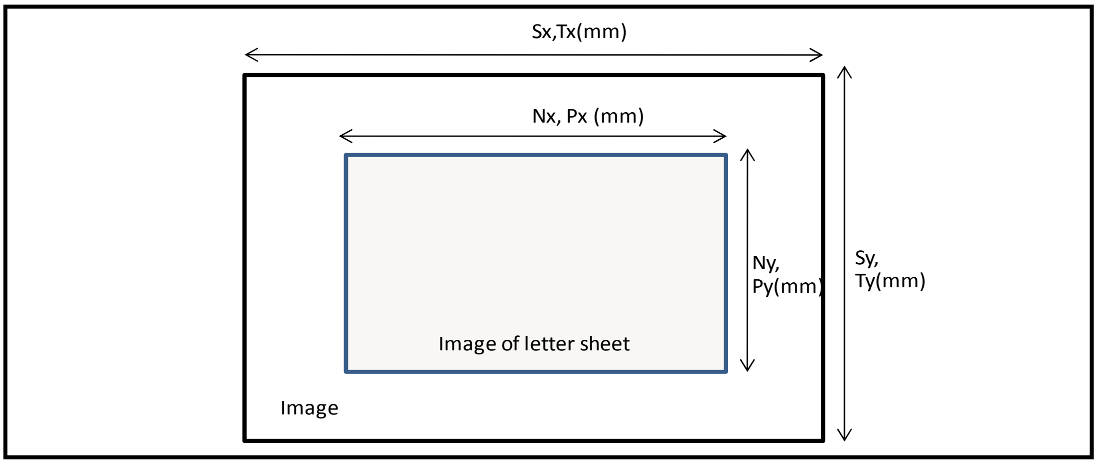


Figure 5.10 Image size measurements

Requirements:

- The digital camera
- A tripod (or camera support of some form)
- A sheet of paper (or A4 sheet)
- A measuring tape

Set up:

(1) Set the camera on top of the tripod. Make sure the camera is level and square to the wall.

(2) Tape a piece of paper to a wall at the height of the camera on the tripod as shown in Figure 5.9.

(3) Look through the camera viewfinder and center the paper in the viewfinder. Make sure the camera is in focus and the camera is still level and square to the wall.

(4) Take a picture of the paper.

(5) Measure the distance from the paper to the location of the focal node (usually half way through the lens) and record this distance as D.

(6) Find the focal length of the lens being used. Record this as f.

(7) Digitize the image of the paper and load onto your hard-disk.

(8) In an image processing program (such as the Distance measurement program in the MATLAB toolbox, PhotoShop or PhotoModeler) measure the number of pixels taken up by the paper in the image. See Figure 5.10. Record these values as Nx and Ny.

(9) Determine the number of pixels in the whole image. Record these values as Sx and Sy.

(10) Perform the calculations shown below to get an estimate of format size (fw and fh) to calculate scale ratio (Eqs. 5.6 to 5.7).

(11) The scale ratio for converting pixels to millimeters can be calculated from Eqs. 5.8 to 5.11 as follows:

$$fw(mm) = (Px/D) * (f/Nx) * Sx \tag{5.6}$$

$$fh(mm) = (Py/D) * (f/Ny) * Sy \tag{5.7}$$

$$Tx(mm) = fw * D/f \tag{5.8}$$

$$Ty(mm) = fh * D/f \tag{5.9}$$

Ave. scale ratio

$$(mm/pixel) = [(Tx(mm)/Sx(pixel)) + (Ty(mm)/Sy(pixel)) + (Px(mm)/Nx(pixel)) + (Py(mm)/Ny(pixel))] /4 \tag{5.10}$$

Ave. scale ratio

$$(pixel/mm) = [(Sx(pixel)/Tx(mm)) + (Sy(pixel)/Ty(mm)) + (Nx(pixel)/Px(mm)) + (Ny(pixel)/Py(mm))] /4 \tag{5.11}$$

The results of calculation to determine unit transformation are shown in Tables 5.2 and 5.3.

Table 5.2 Results of calculation to determine unit transformation

Camera distance (m)	0.5			0.6		
Case	1	2	3	1	2	3
Px(mm)	50	50	50	50	50	50
Nx(pixels)	1097	1088	1088	898	892	892
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	500	500	500	600	600	600
f	60	60	60	60	60	60
Py(mm)	40	40	40	40	40	40
Ny(pixels)	880	872	872	727	724	724
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	21.17775752	21.35294118	21.35294118	21.55902004	21.70403587	21.70403587
fh(mm)=(Py/D)*(f/Ny)*Sy	14.13818182	14.26788991	14.26788991	14.26134801	14.32044199	14.32044199
Tx(mm)= fw*D/f	176.4813127	177.9411765	177.9411765	215.5902004	217.0403587	217.0403587
Ty(mm)= fh*D/f	117.8181818	118.8990826	118.8990826	142.6134801	143.2044199	143.2044199
Tx(mm)/Sx(pixel)	0.045578851	0.045955882	0.045955882	0.055679287	0.056053812	0.056053812
Ty(mm)/Sy(pixel)	0.045454545	0.04587156	0.04587156	0.055020633	0.055248619	0.055248619
Px(mm)/Nx(pixel)	0.045578851	0.045955882	0.045955882	0.055679287	0.056053812	0.056053812
Py(mm)/Ny(pixel)	0.045454545	0.04587156	0.04587156	0.055020633	0.055248619	0.055248619
Ave	0.045516698	0.045913721	0.045913721	0.05534996	0.055651215	0.055651215
Total ave	0.04578138			0.055550797		
Sx(pixel)/Tx(mm)	21.94	21.76	21.76	17.96	17.84	17.84
Sy(pixel)/Ty(mm)	22.00	21.80	21.80	18.18	18.10	18.10
Nx(pixel)/Px(mm)	21.94	21.76	21.76	17.96	17.84	17.84
Ny(pixel)/Py(mm)	22.00	21.80	21.80	18.18	18.10	18.10
Ave	21.97	21.78	21.78	18.07	17.97	17.97
Total ave	21.84			18.00		
Img no.	5503	5522	5538	5502	5521	5537
Camera distance (m)	0.7			0.8		
Case	1	2	3	1	2	3
Px(mm)	50	50	50	100	100	100
Nx(pixels)	751	760	756	1319	1316	1316
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	700	700	700	800	800	800
f	60	60	60	60	60	60
Py(mm)	40	40	40	80	80	80
Ny(pixels)	603	608	604	1047	1048	1052
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.09625262	21.83458647	21.95011338	22.0166793	22.0668693	22.0668693
fh(mm)=(Py/D)*(f/Ny)*Sy	14.73773987	14.61654135	14.71333964	14.85386819	14.83969466	14.78326996
Tx(mm)= fw*D/f	257.7896138	254.7368421	256.0846561	293.555724	294.224924	294.224924
Ty(mm)= fh*D/f	171.9402985	170.5263158	171.6556291	198.0515759	197.8625954	197.1102662
Tx(mm)/Sx(pixel)	0.066577896	0.065789474	0.066137566	0.075815011	0.075987842	0.075987842
Ty(mm)/Sy(pixel)	0.066334992	0.065789474	0.066225166	0.076408787	0.076335878	0.076045627
Px(mm)/Nx(pixel)	0.066577896	0.065789474	0.066137566	0.075815011	0.075987842	0.075987842
Py(mm)/Ny(pixel)	0.066334992	0.065789474	0.066225166	0.076408787	0.076335878	0.076045627
Ave	0.066456444	0.065789474	0.066181366	0.076111899	0.07616186	0.076016735
Total ave	0.066142428			0.076096831		
Sx(pixel)/Tx(mm)	15.02	15.20	15.12	13.19	13.16	13.16
Sy(pixel)/Ty(mm)	15.08	15.20	15.10	13.09	13.10	13.15
Nx(pixel)/Px(mm)	15.02	15.20	15.12	13.19	13.16	13.16
Ny(pixel)/Py(mm)	15.08	15.20	15.10	13.09	13.10	13.15
Ave	15.05	15.20	15.11	13.14	13.13	13.16
Total ave	15.12			13.14		
Img no.	5501	5520	5536	5500	5519	5535

Table 5.2 Results of calculation to determine unit transformation (continued)

Camera distance (m)	0.9			1		
Case	1	2	3	1	2	3
Px(mm)	100	100	100	100	100	100
Nx(pixels)	1159	1156	1160	1035	1048	1032
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	900	900	900	1000	1000	1000
f	60	60	60	60	60	60
Py(mm)	80	80	80	80	80	80
Ny(pixels)	921	928	932	824	836	824
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.27207363	22.32987313	22.25287356	22.44637681	22.16793893	22.51162791
fh(mm)=(Py/D)*(f/Ny)*Sy	15.00977199	14.89655172	14.83261803	15.09902913	14.88229665	15.09902913
Tx(mm)= fw*D/f	334.0811044	334.9480969	333.7931034	374.1062802	369.4656489	375.1937984
Ty(mm)= fh*D/f	225.1465798	223.4482759	222.4892704	251.6504854	248.0382775	251.6504854
Tx(mm)/Sx(pixel)	0.086281277	0.08650519	0.086206897	0.096618357	0.095419847	0.096899225
Ty(mm)/Sy(pixel)	0.086862106	0.086206897	0.08583691	0.097087379	0.09569378	0.097087379
Px(mm)/Nx(pixel)	0.086281277	0.08650519	0.086206897	0.096618357	0.095419847	0.096899225
Py(mm)/Ny(pixel)	0.086862106	0.086206897	0.08583691	0.097087379	0.09569378	0.097087379
Ave	0.086571692	0.086356043	0.086021903	0.096852868	0.095556814	0.096993302
Total ave	0.086316546			0.096467661		
Sx(pixel)/Tx(mm)	11.59	11.56	11.60	10.35	10.48	10.32
Sy(pixel)/Ty(mm)	11.51	11.60	11.65	10.30	10.45	10.30
Nx(pixel)/Px(mm)	11.59	11.56	11.60	10.35	10.48	10.32
Ny(pixel)/Py(mm)	11.51	11.60	11.65	10.30	10.45	10.30
Ave	11.55	11.58	11.63	10.33	10.47	10.31
Total ave	11.59			10.37		
Img no.	5499	5518	5534	5498	5517	5533
Camera distance (m)	1.1			1.2		
Case	1	2	3	1	2	3
Px(mm)	100	100	100	297	297	297
Nx(pixels)	938	944	940	2553	2548	2520
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	1100	1100	1100	1200	1200	1200
f	60	60	60	60	60	60
Py(mm)	80	80	80	210	210	210
Ny(pixels)	762	764	752	1823	1812	1788
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.51599147	22.37288136	22.46808511	22.52220917	22.56640502	22.81714286
fh(mm)=(Py/D)*(f/Ny)*Sy	14.8432355	14.80437887	15.04061896	14.92923752	15.01986755	15.22147651
Tx(mm)= fw*D/f	412.793177	410.1694915	411.9148936	450.4441833	451.3281005	456.3428571
Ty(mm)= fh*D/f	272.1259843	271.4136126	275.7446809	298.5847504	300.397351	304.4295302
Tx(mm)/Sx(pixel)	0.106609808	0.105932203	0.106382979	0.116333725	0.116562009	0.117857143
Ty(mm)/Sy(pixel)	0.104986877	0.104712042	0.106382979	0.115194734	0.11589404	0.117449664
Px(mm)/Nx(pixel)	0.106609808	0.105932203	0.106382979	0.116333725	0.116562009	0.117857143
Py(mm)/Ny(pixel)	0.104986877	0.104712042	0.106382979	0.115194734	0.11589404	0.117449664
Ave	0.105798342	0.105322123	0.106382979	0.115764229	0.116228025	0.117653404
Total ave	0.105834481			0.116548553		
Sx(pixel)/Tx(mm)	9.38	9.44	9.40	8.60	8.58	8.48
Sy(pixel)/Ty(mm)	9.53	9.55	9.40	8.68	8.63	8.51
Nx(pixel)/Px(mm)	9.38	9.44	9.40	8.60	8.58	8.48
Ny(pixel)/Py(mm)	9.53	9.55	9.40	8.68	8.63	8.51
Ave	9.45	9.50	9.40	8.64	8.60	8.50
Total ave	9.45			8.58		
Img no.	5497	5516	5532	5496	5515	5531

Table 5.2 Results of calculation to determine unit transformation (continued)

Camera distance (m)	1.3			1.4		
Case	1	2	3	1	2	3
Px(mm)	297	297	297	297	297	297
Nx(pixels)	2359	2340	2336	2158	2160	2164
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	1300	1300	1300	1400	1400	1400
f	60	60	60	60	60	60
Py(mm)	210	210	210	210	210	210
Ny(pixels)	1663	1656	1656	1525	1536	1536
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.4994424	22.68213018	22.72096944	22.83828942	22.81714286	22.77496699
fh(mm)=(Py/D)*(f/Ny)*Sy	15.10671169	15.17056856	15.17056856	15.29704918	15.1875	15.1875
Tx(mm)= fw*D/f	487.4879186	491.4461538	492.2876712	532.8934198	532.4	531.4158965
Ty(mm)= fh*D/f	327.3120866	328.6956522	328.6956522	356.9311475	354.375	354.375
Tx(mm)/Sx(pixel)	0.125900805	0.126923077	0.127140411	0.137627433	0.1375	0.137245841
Ty(mm)/Sy(pixel)	0.126277811	0.126811594	0.126811594	0.137704918	0.13671875	0.13671875
Px(mm)/Nx(pixel)	0.125900805	0.126923077	0.127140411	0.137627433	0.1375	0.137245841
Py(mm)/Ny(pixel)	0.126277811	0.126811594	0.126811594	0.137704918	0.13671875	0.13671875
Ave	0.126089308	0.126867336	0.126976003	0.137666175	0.137109375	0.136982296
Total ave	0.126644215			0.137252615		
Sx(pixel)/Tx(mm)	7.94	7.88	7.87	7.27	7.27	7.29
Sy(pixel)/Ty(mm)	7.92	7.89	7.89	7.26	7.31	7.31
Nx(pixel)/Px(mm)	7.94	7.88	7.87	7.27	7.27	7.29
Ny(pixel)/Py(mm)	7.92	7.89	7.89	7.26	7.31	7.31
Ave	7.93	7.88	7.88	7.26	7.29	7.30
Total ave	7.90			7.29		
Img no.	5495	5514	5530	5494	5513	5529
Camera distance (m)	1.5			1.6		
Case	1	2	3	1	2	3
Px(mm)	297	297	297	297	297	297
Nx(pixels)	2012	2024	2012	1881	1880	1876
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	1500	1500	1500	1600	1600	1600
f	60	60	60	60	60	60
Py(mm)	210	210	210	210	210	210
Ny(pixels)	1427	1420	1420	1337	1324	1328
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.86250497	22.72695652	22.86250497	22.92631579	22.93851064	22.98742004
fh(mm)=(Py/D)*(f/Ny)*Sy	15.25774352	15.33295775	15.33295775	15.26701571	15.41691843	15.37048193
Tx(mm)= fw*D/f	571.5626243	568.173913	571.5626243	611.3684211	611.693617	612.9978678
Ty(mm)= fh*D/f	381.4435879	383.3239437	383.3239437	407.1204188	411.1178248	409.8795181
Tx(mm)/Sx(pixel)	0.147614314	0.14673913	0.147614314	0.157894737	0.157978723	0.158315565
Ty(mm)/Sy(pixel)	0.147161878	0.147887324	0.147887324	0.157068063	0.158610272	0.15813253
Px(mm)/Nx(pixel)	0.147614314	0.14673913	0.147614314	0.157894737	0.157978723	0.158315565
Py(mm)/Ny(pixel)	0.147161878	0.147887324	0.147887324	0.157068063	0.158610272	0.15813253
Ave	0.147388096	0.147313227	0.147750819	0.1574814	0.158294498	0.158224048
Total ave	0.147484047			0.157999982		
Sx(pixel)/Tx(mm)	6.77	6.81	6.77	6.33	6.33	6.32
Sy(pixel)/Ty(mm)	6.80	6.76	6.76	6.37	6.30	6.32
Nx(pixel)/Px(mm)	6.77	6.81	6.77	6.33	6.33	6.32
Ny(pixel)/Py(mm)	6.80	6.76	6.76	6.37	6.30	6.32
Ave	6.78	6.79	6.77	6.35	6.32	6.32
Total ave	6.78			6.33		
Img no.	5493	5512	5528	5492	5511	5527

Table 5.2 Results of calculation to determine unit transformation (continued)

Camera distance (m)	1.7			1.8		
Case	1	2	3	1	2	3
Px(mm)	297	297	297	297	297	297
Nx(pixels)	1777	1776	1772	1678	1668	1668
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	1700	1700	1700	1800	1800	1800
f	60	60	60	60	60	60
Py(mm)	210	210	210	210	210	210
Ny(pixels)	1254	1252	1248	1177	1188	1176
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.84055745	22.85341812	22.90500598	22.8443385	22.98129496	22.98129496
fh(mm)=(Py/D)*(f/Ny)*Sy	15.32001126	15.34448412	15.39366516	15.41546304	15.27272727	15.42857143
Tx(mm)= fw*D/f	647.1491277	647.5135135	648.9751693	685.3301549	689.4388489	689.4388489
Ty(mm)= fh*D/f	434.0669856	434.7603834	436.1538462	462.4638912	458.1818182	462.8571429
Tx(mm)/Sx(pixel)	0.167135622	0.16722973	0.167607223	0.176996424	0.178057554	0.178057554
Ty(mm)/Sy(pixel)	0.167464115	0.167731629	0.168269231	0.178419711	0.176767677	0.178571429
Px(mm)/Nx(pixel)	0.167135622	0.16722973	0.167607223	0.176996424	0.178057554	0.178057554
Py(mm)/Ny(pixel)	0.167464115	0.167731629	0.168269231	0.178419711	0.176767677	0.178571429
Ave	0.167299868	0.16748068	0.167938227	0.177708068	0.177412615	0.178314491
Total ave	0.167572925			0.177811725		
Sx(pixel)/Tx(mm)	5.98	5.98	5.97	5.65	5.62	5.62
Sy(pixel)/Ty(mm)	5.97	5.96	5.94	5.60	5.66	5.60
Nx(pixel)/Px(mm)	5.98	5.98	5.97	5.65	5.62	5.62
Ny(pixel)/Py(mm)	5.97	5.96	5.94	5.60	5.66	5.60
Ave	5.98	5.97	5.95	5.63	5.64	5.61
Total ave	5.97			5.62		
Img no.	5491	5510	5526	5490	5509	5525
Camera distance (m)	1.9			2		
Case	1	2	3	1	2	3
Px(mm)	297	297	297	297	297	297
Nx(pixels)	1590	1576	1584	1494	1499	1500
Sx(pixels)	3872	3872	3872	3872	3872	3872
D(mm)	1900	1900	1900	2000	2000	2000
f	60	60	60	60	60	60
Py(mm)	210	210	210	210	210	210
Ny(pixels)	1116	1120	1124	1053	1074	1064
Sy(pixels)	2592	2592	2592	2592	2592	2592
fw(mm)=(Px/D)*(f/Nx)*Sx	22.83980139	23.04269303	22.92631579	23.09204819	23.01502335	22.99968
fh(mm)=(Py/D)*(f/Ny)*Sy	15.40237691	15.34736842	15.29275145	15.50769231	15.20446927	15.34736842
Tx(mm)= fw*D/f	723.2603774	729.6852792	726	769.7349398	767.167445	766.656
Ty(mm)= fh*D/f	487.7419355	486	484.2704626	516.9230769	506.8156425	511.5789474
Tx(mm)/Sx(pixel)	0.186792453	0.188451777	0.1875	0.198795181	0.198132088	0.198
Ty(mm)/Sy(pixel)	0.188172043	0.1875	0.18683274	0.199430199	0.195530726	0.197368421
Px(mm)/Nx(pixel)	0.186792453	0.188451777	0.1875	0.198795181	0.198132088	0.198
Py(mm)/Ny(pixel)	0.188172043	0.1875	0.18683274	0.199430199	0.195530726	0.197368421
Ave	0.187482248	0.187975888	0.18716637	0.19911269	0.196831407	0.197684211
Total ave	0.187541502			0.197876103		
Sx(pixel)/Tx(mm)	5.35	5.31	5.33	5.03	5.05	5.05
Sy(pixel)/Ty(mm)	5.31	5.33	5.35	5.01	5.11	5.07
Nx(pixel)/Px(mm)	5.35	5.31	5.33	5.03	5.05	5.05
Ny(pixel)/Py(mm)	5.31	5.33	5.35	5.01	5.11	5.07
Ave	5.33	5.32	5.34	5.02	5.08	5.06
Total ave	5.33			5.05		
Img no.	5489	5508	5524	5488	5507	5523

Table 5.3 Results of calculation to determine unit transformation in each pixel size

factor	Camera distance (m)	mm/pixel							
		0.50	0.60	0.70	0.80	0.90	1.00	1.10	1.20
1	3872x2592/10.0M	0.0458	0.0556	0.0661	0.0761	0.0863	0.0965	0.1058	0.1165
1.33	2896x1944/5.6M	0.061	0.0741	0.0882	0.1015	0.1151	0.1286	0.1411	0.1554
2.00	1936x1296/2.5M	0.0916	0.1111	0.1323	0.1522	0.1726	0.1929	0.2117	0.2331
6.05	640x428	0.277	0.3361	0.4002	0.4604	0.5222	0.5836	0.6403	0.7051
factor	Camera distance (m)	mm/pixel							
		1.30	1.40	1.50	1.60	1.70	1.80	1.90	2.00
1	3872x2592/10.0M	0.1266	0.1373	0.1475	0.158	0.1676	0.1778	0.1875	0.1979
1.33	2896x1944/5.6M	0.1689	0.183	0.1966	0.2107	0.2234	0.2371	0.2501	0.2638
2.00	1936x1296/2.5M	0.2533	0.2745	0.295	0.316	0.3351	0.3556	0.3751	0.3958
6.05	640x428	0.7662	0.8304	0.8923	0.9559	1.0138	1.0758	1.1346	1.1972

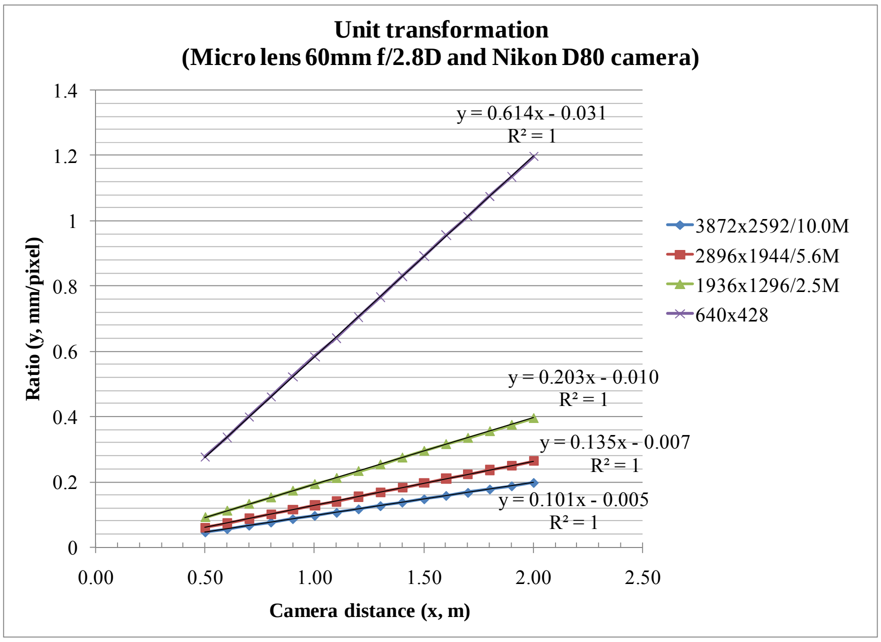


Figure 5.11 Unit transformation

Our experiment uses the representative images which pixel size is at 3872x2592/10.0M for determining ratio of mm per pixel. The result is shown in Table 5.3. Ratio of mm per pixel for other pixel sizes is calculated by crossing factor to adjust pixel size of image. The graph and equations in Figure 5.11 are created from the results of experiment in Table 5.3. These equations were used in the proposed system to transform the pixel units into millimeters to compare with the standard requirements.

5.2.5 Defect detection and quantification module

In the proposed system, the defect detection and quantification module supports the function of defect feature analysis. The module is designed to specify the defect positions and quantify the defect value by using the proposed algorithm analyzing the image features of a tile edge. We used two algorithms to verify the accuracy of the tiling. First, the algorithm that determines the distance between neighboring tiles (the gap) must be uniform ($\Delta X1=\Delta X2=\ldots=\Delta Xn=\Delta Y1=\Delta Y2=\ldots=\Delta Yn$). This is shown in Figure 5.12(a). Second, the algorithm for inspecting whether the angle of the intersecting straight lines produced a right angle is shown in Figure 5.12(b). Details of the analysis are as follows:

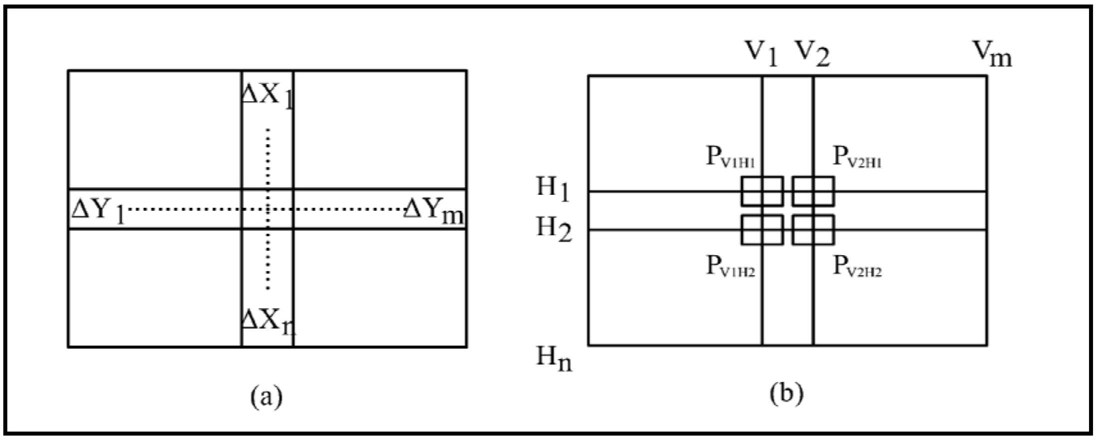


Figure 5.12 Algorithm used in tiling work inspection

(1) Algorithm for the distance between neighboring tiles (gap)

The defect value is determined by the difference between the distance between the parallel lines and the standard requirement (specification). The algorithm for the distance between neighboring tiles (gap) in both the vertical and horizontal scans is shown in Figure 5.13. The system plotted a green line when the distance between neighboring tiles (gap) deviated from the required standard (d) or when it was above the tolerance value for the gap size (T1). After that, the system counted the number of pixels on the painted area as shown in Figure 5.14 and showed the defect value in terms of the defect area (mm^2) by using the formula for converting pixel units into square millimeters units from the unit transformation module in section 5.2.5. The system showed all defect areas, of which some small defect areas were not significant. Therefore, we must define the tolerance value (T2) for a defect area. Therefore, the defect area was highlighted when the actual defect was greater than the tolerance value.

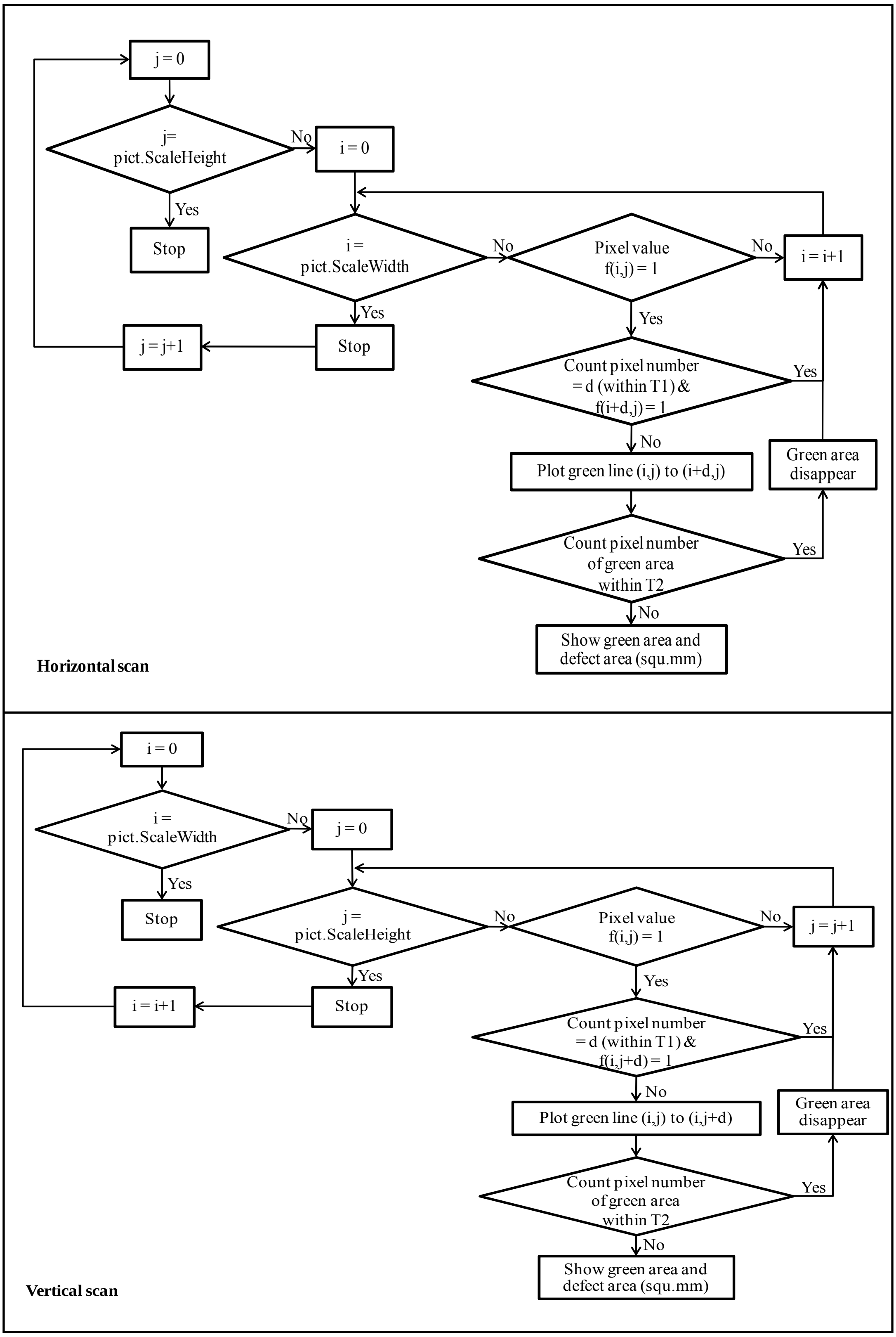


Figure 5.13 Algorithm for the inspection of the distance between neighboring tiles

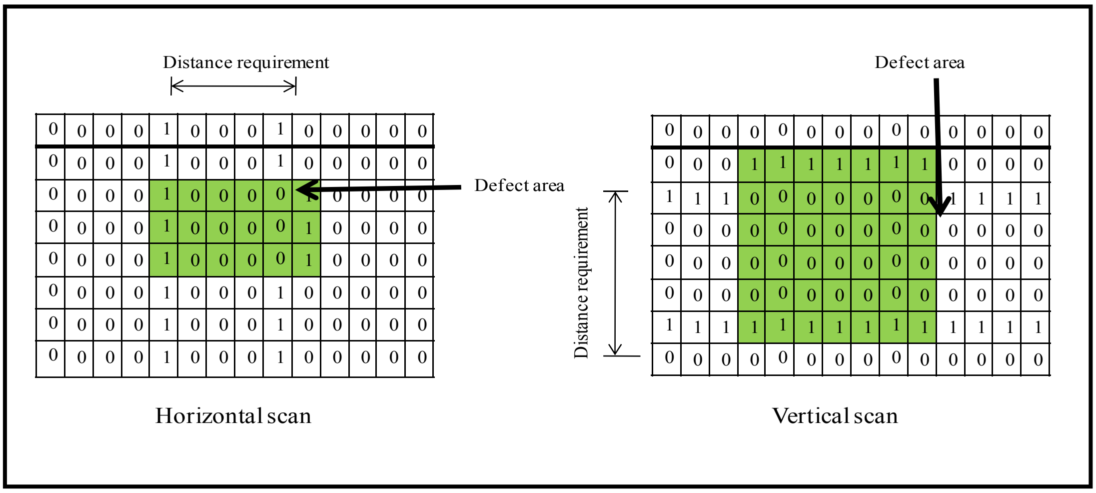


Figure 5.14 Display defect area in the inspection of the distance between neighboring tiles

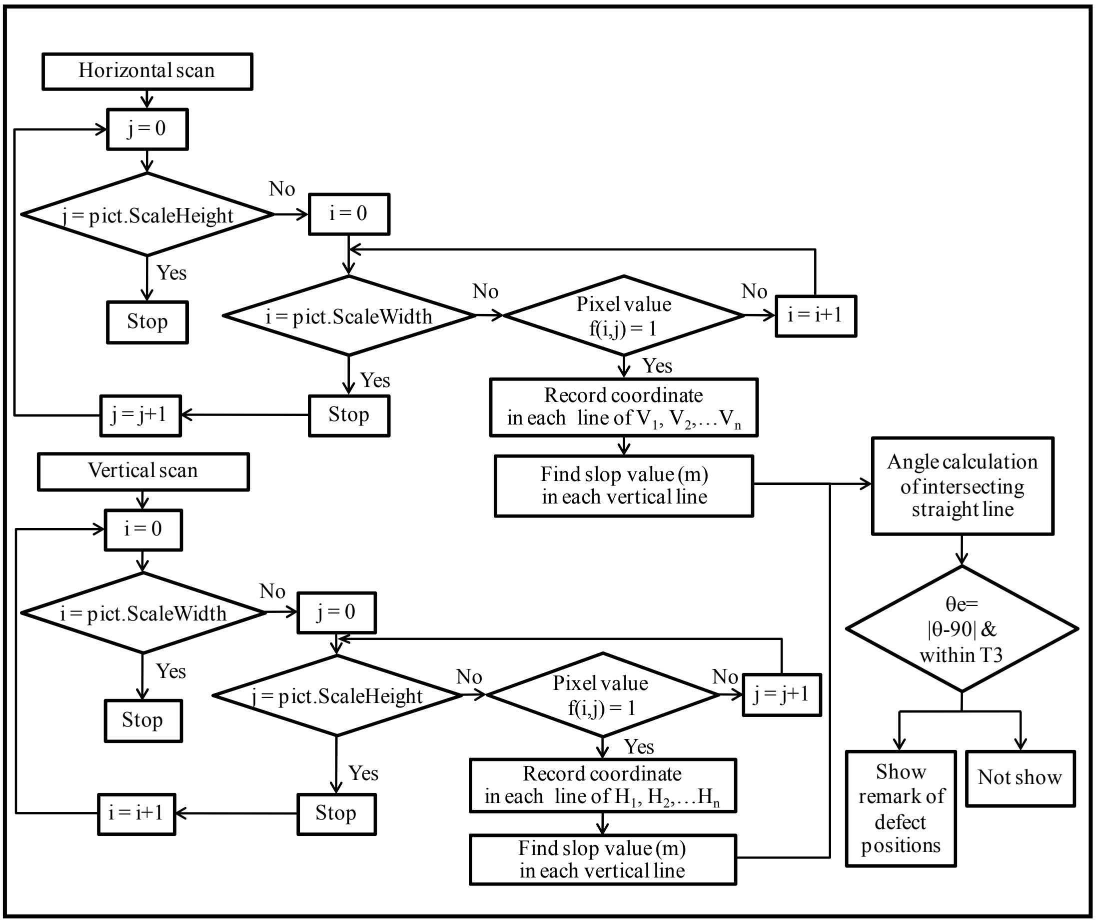


Figure 5.15 Algorithm for the inspection of the angle of intersecting straight lines

(2) Algorithm to inspect the angle of intersecting straight lines

This algorithm was used to inspect the right angle of intersecting straight lines as shown in Figure 5.15. The defect value is given in the form of the angle value which includes the deviation from a right angle (90°) using equations 5.12, 5.13, 5.14 and 5.15. We also specified a tolerance value (T3) that determines whether the defect was only slightly above the tolerance value or if it greatly exceeded the value.

The slope (m) for determining the angle of the intersecting straight line at each point (PV1H1, PV1H2, PV2H1, PV2H2,… PVmHn) was calculated using a linear regression equation (Eq. 5.12).

$$m = (n\sum xjyi - \sum xj\sum yi) / (n(\sum xj^2) - (\sum xj)^2) \quad (5.12)$$

Where m is the slope value, x and y are the coordinates of the image and n is the number of coordinates.

$$\theta = \tan^{-1} [(m2 - m1) / (1+m1m2)] \times (180/pi) \quad \text{or} \quad (5.13)$$

$$\gamma = \tan^{-1} [(m1 - m2) / (1+m1m2)] \times (180/pi) \quad (5.14)$$

$$\text{Defect value } (\theta e) = 90° - \theta = \gamma - 90° \quad (5.15)$$

Where m1 is the slope of a horizontal line, m2 is the slope of a vertical line, θ is the acute angle, γ is the obtuse angle, pi = 3.14 and θe is the error value of the right angle or how much the tile position deviates from a right angle

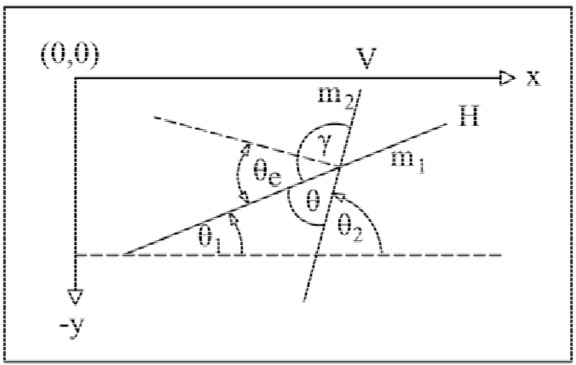
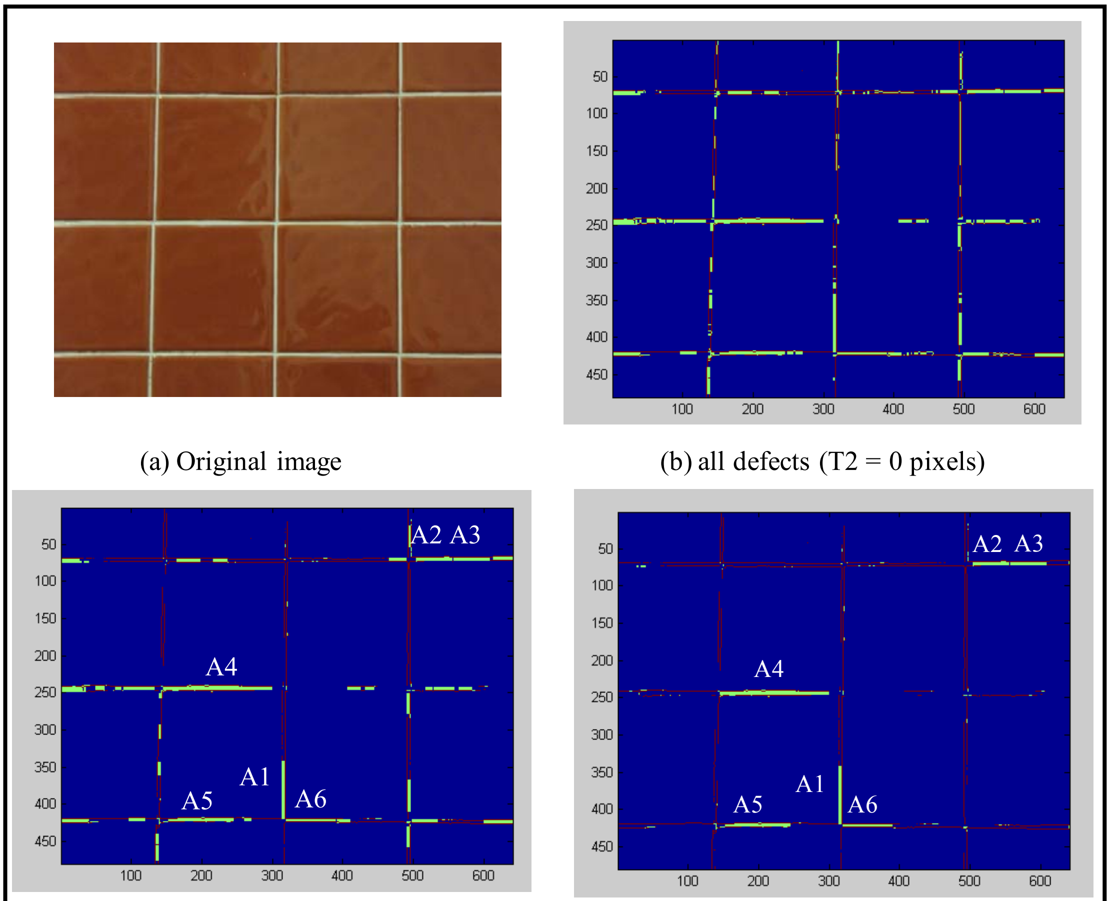


Figure 5.16 Inspection of the angle of intersecting straight lines

5.2.7 Output

The output section shows the results of the defect detection and quantification system. Both algorithms are shown in this section. For example, the images were taken at camera distance of 1.00 meter and pixels size of 640x428.

Figure 5.17 shows the results of the distance inspection between neighboring tiles (gap). Figure 5.17(a) shows original images. Next, the images in Figure 5.17(a) were transformed from binary to color images to show the defect color area. Figure 5.17(b) shows all defect positions that deviate from the standard requirements for gap size (d). Figures 5.17(c) and 5.17(d) show various tolerance values that detect whether the defect is only significant or very high. Last, Table 5.4 shows the results of defect areas in square millimeters (sq.mm).



(a) Original image

(b) all defects (T2 = 0 pixels)

(c) T2 = 10 pixels (5.83 square millimeters)

(d) T2 = 50 pixels (29.15 square millimeters)

Figure 5.17 Results of the inspection of tile gap which deviates from standard by the proposed system.

Table 5.4 Results of defect areas in square millimeters

Position	Defect area (sq.mm.)
A1	136.9026
A2	100.4545
A3	94.4537
A4	352.4797
A5	183.5739
A6	124.4569
sum	992.3213

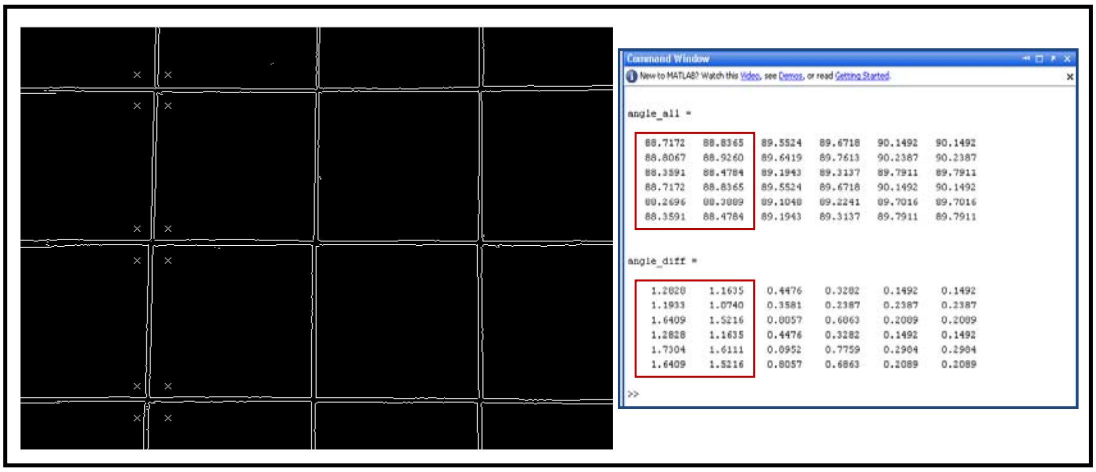


Figure 5.18 Results of inspection of the angle of intersecting straight lines

Figure 5.18 shows the inspection result of the angle of the intersecting straight line using the proposed system. The image of a tile wall with a size of 0.35 m x 0.30 m was used in this study. The result of the analysis shows the mark of defect position at the corner of each tile angle when the position of the tile diverged from a right angle at a level above the tolerance value. Our case study used ±1° degree as a tolerance value. It showed that there were 12 marks above that threshold that required correction.

5.3 Testing system

In order to test the accuracy of the proposed algorithms in the system, the detection of defect positions and calculation of defect values must be tested in several cases with image sampling as tile panel models in Photoshop. Since the images of the tile panel model in Photoshop are not affected by lighting and other environments, we can check the accuracy of calculation of the algorithms. These models identified the defect positions and calculated defect values to recheck the accuracy of algorithm calculation in the proposed system.

The defect detection and quantification system consists of two algorithms to (1) inspecting distances between neighbouring tiles (gap) and (2) inspectining angle of intersecting straight lines. The results of application of the testing system to several cases are as follows.

5.3.1 Algorithm of distance inspection between neighbouring tiles (gap)

This proposed algorithm needs to be tested for purposes of (1) detecting each gap size, (2) detecting multiple positions and (3) checking defect values.

Case 1: Detecting each gap size

The image in Figure 5.19 includes several gap size requirements at 4, 6, 7 and 9 pixels in the vertical and horizontal lines. We tested the proposed algorithm by detecting defect positions that do not conform to each gap size requirement. The results of detecting defect positions are shown in Figure 5.20.

The results in Figure 5.20 show that the proposed algorithm in the system is able to detect gap size accurately. Next, we need to check detection in several positions on an image and count the number of pixels in the defect area (green).

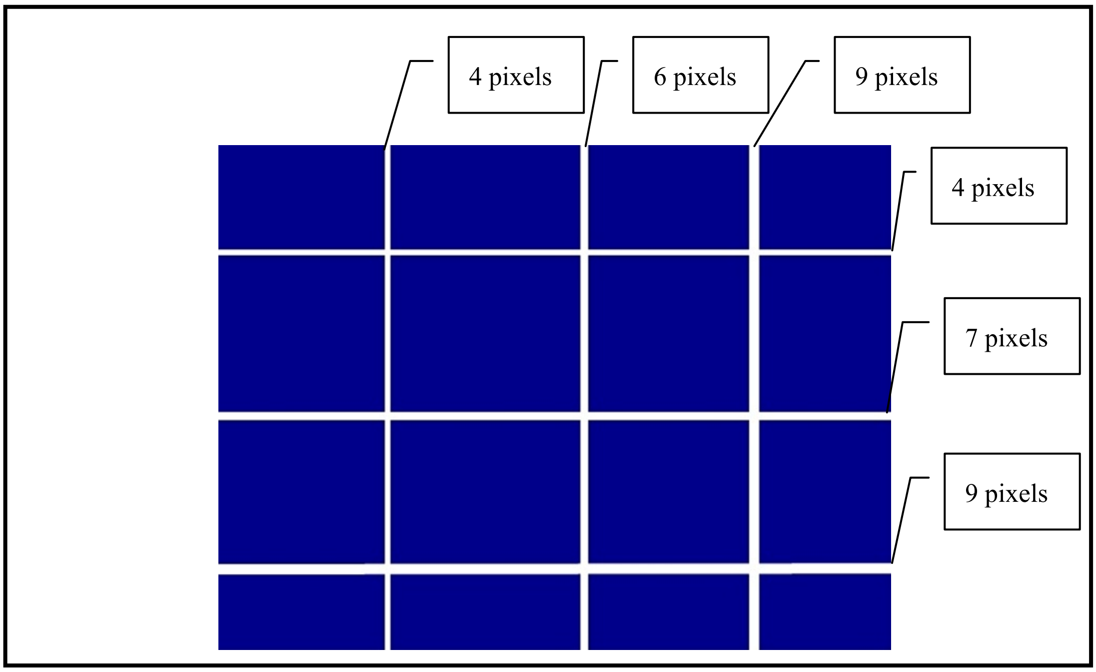


Figure 5.19 Image sampling

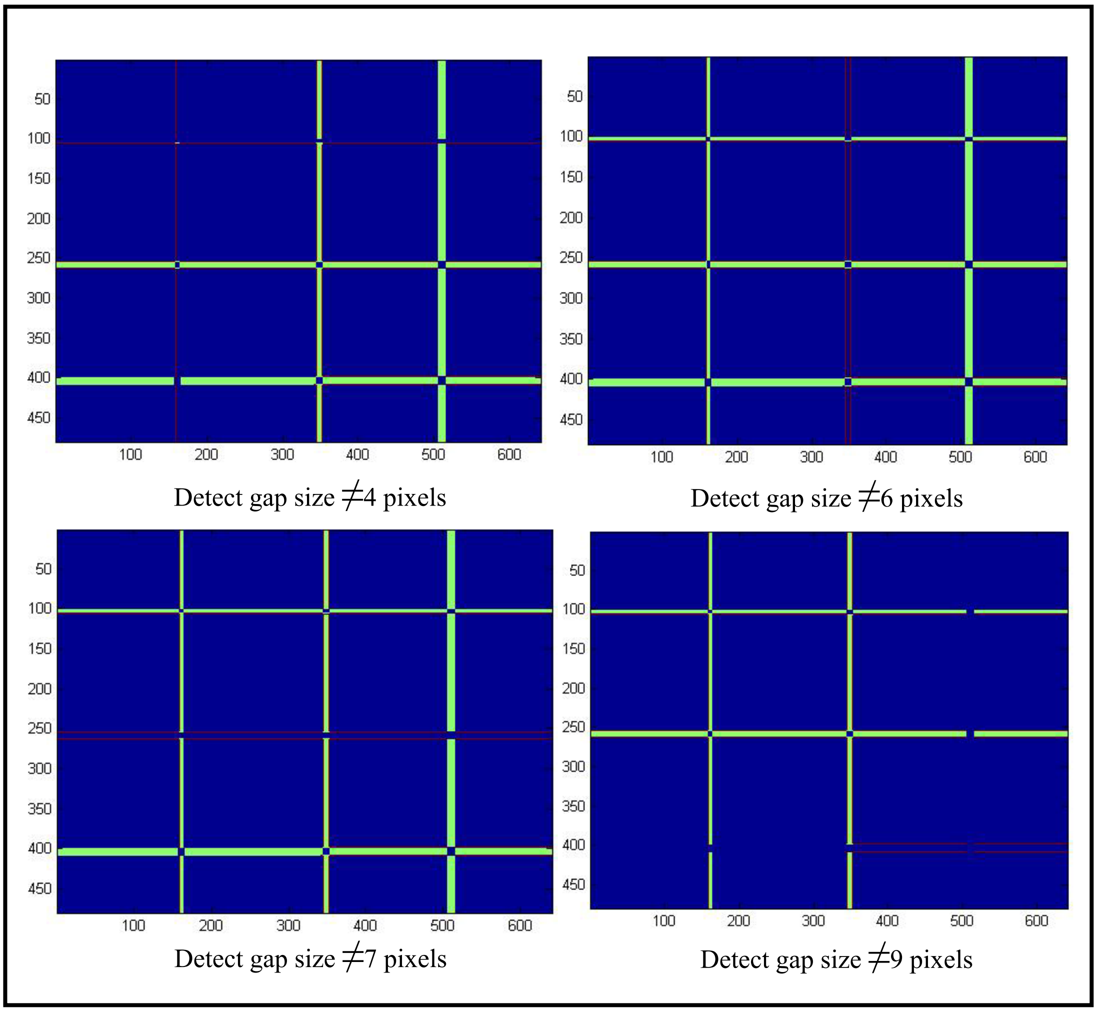


Figure 5.20 Results of detection in each gap size

Case 2: Detecting in several positions on an image

The original image in Figure 5.21 includes eight defect positions in line size at 4 pixels in both vertical and horizontal lines. We tested the proposed system by detecting defect positions that did not have a gap size of 4 pixels. The results of detecting defect positions are shown in Figure 5.22. The proposed system is able to detect all defect positions in line size at 4 pixels.

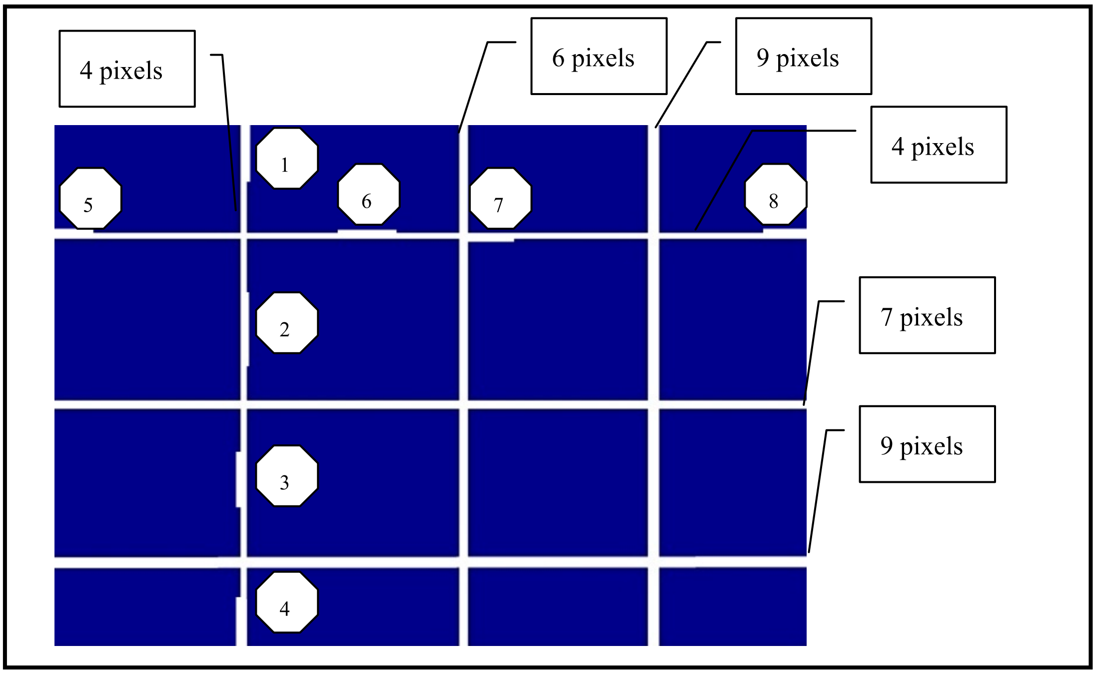


Figure 5.21 Image sampling

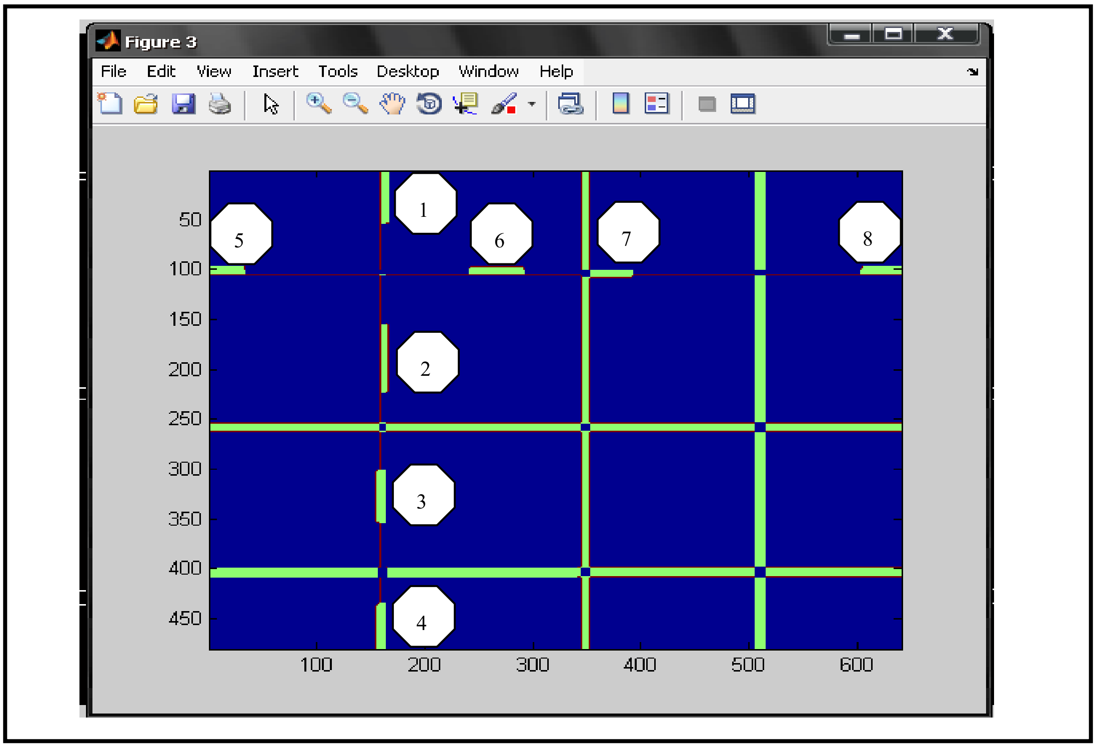


Figure 5.22 Results of detecting defect gap size (detect gap size ≠4 pixels)

Case 3: Calculation of defect value

Next, the results of calculating defect values (pixels) (Figure 5.22) are used to compare with manual calculation from coordinates shown in Figure 5.23. The results of the comparison given in Table 5.5, show that the level of errors in the proposed system did not exceed 2%.

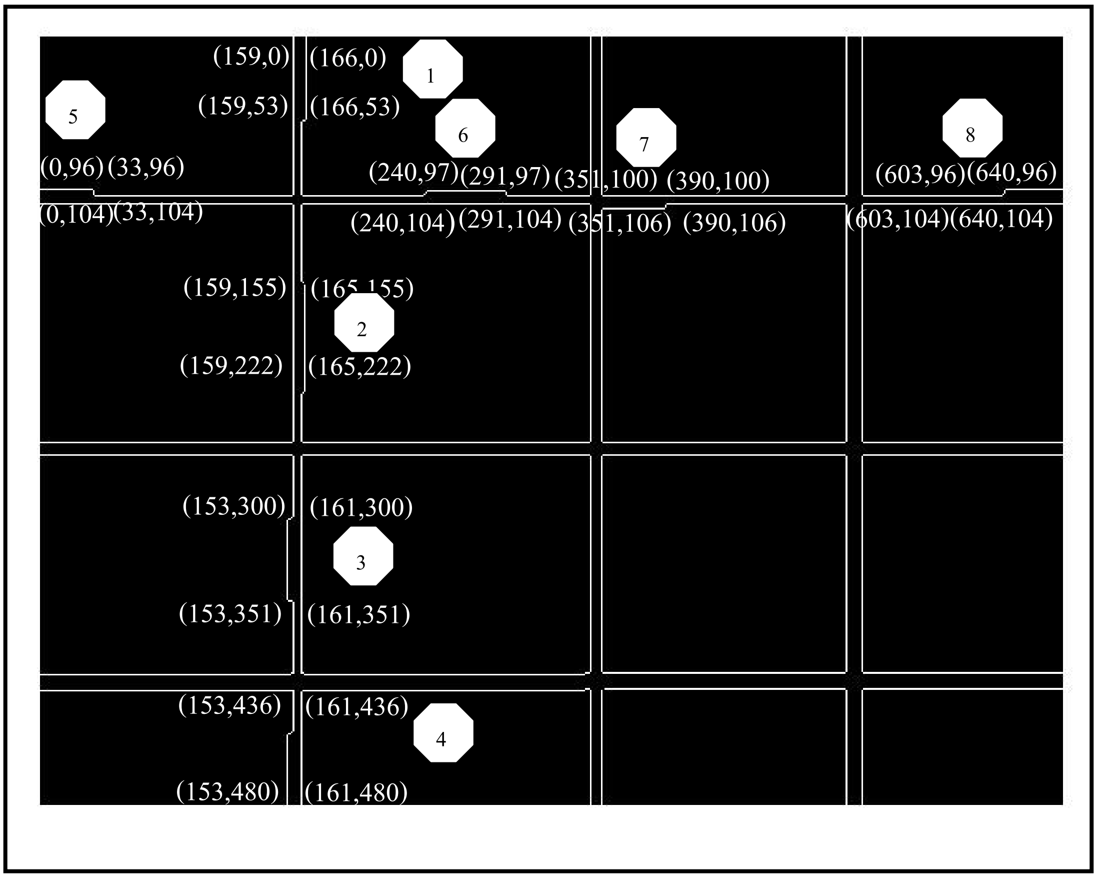


Figure 5.23 Coordinate value for manual calculation

Table 5.5 Comparison of defect value between manual calculation and the proposed system

Positions	Defect area by manual calculation (pixels)	Defect area by proposed system (pixels)	Error (pixels)	Error (%)
1	371	369	-2	0.54
2	402	407	+5	1.24
3	408	416	+8	1.96
4	352	355	+3	0.85
5	264	269	+5	1.89
6	357	359	+2	0.56
7	234	238	+4	1.71
8	296	291	-5	1.69

5.3.2 Algorithm for inspecting angles of intersecting straight lines

This section will check angle values and numbers of angles which are not right angles by comparing the proposed system with manual calculation when the coordinate value is known.

Case 1: Comparison of angle value

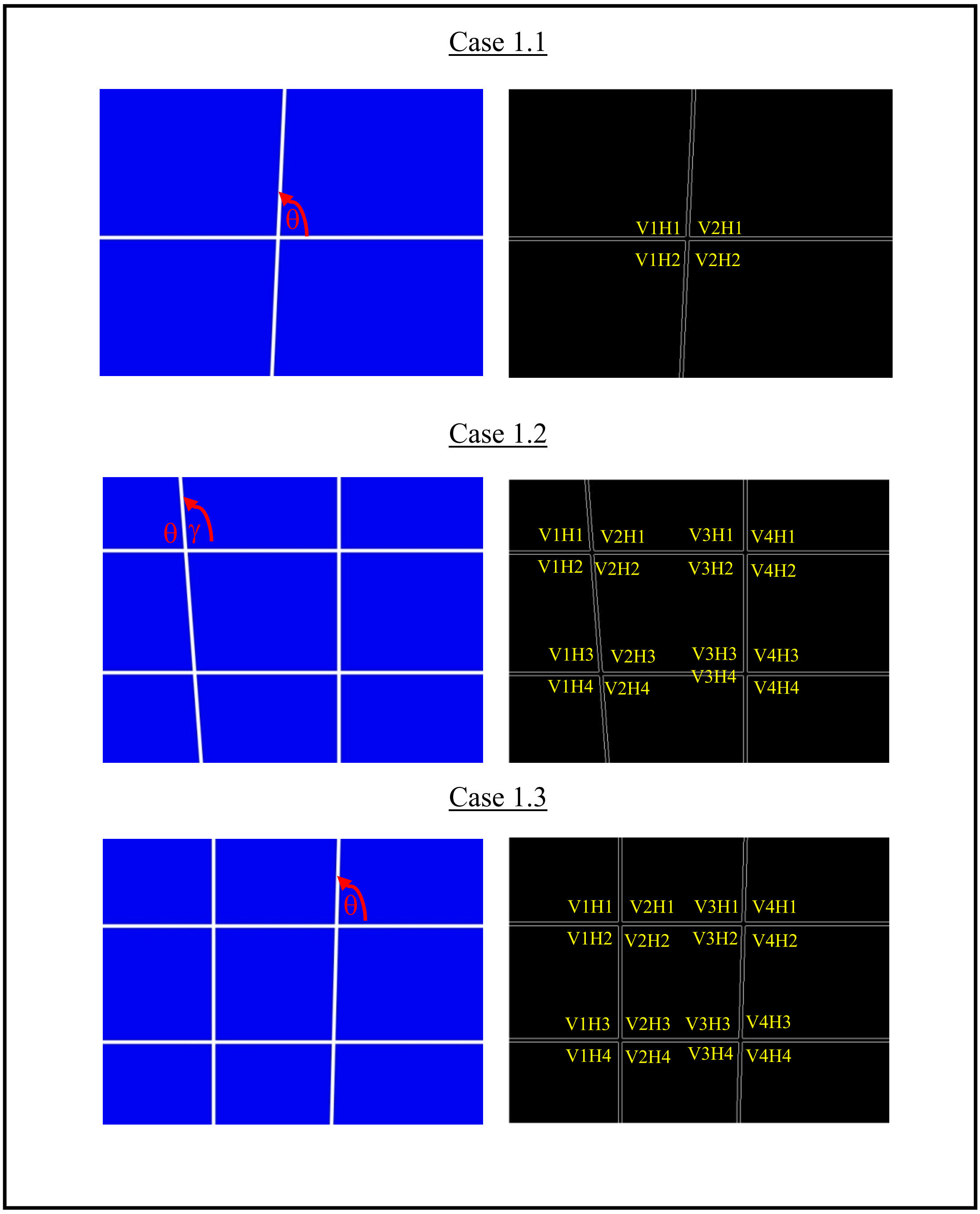
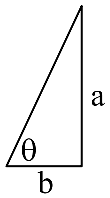


Figure 5.24 Checking angle value in the proposed system

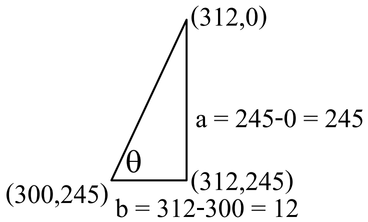
Example manual calculation



$$\theta = \text{tan-1 } [a / b] \text{ x } (180/\text{pi}) \tag{5.16}$$

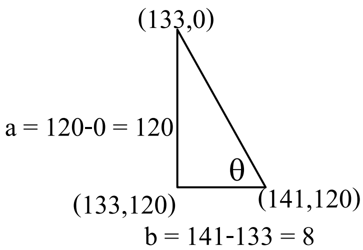
$$\gamma = 180 - \theta \tag{5.17}$$

Case 1.1:



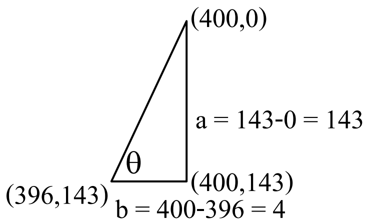
$$\theta = \text{tan-1 } [245/12] \text{ x } (180/\text{pi}) = 87.16083$$

Case 1.2:



$$\gamma = 180 - \text{tan-1 } [120/8] \text{ x } (180/\text{pi}) = 93.84875$$

Case 1.3:



$$\theta = \text{tan-1 } [143/4] \text{ x } (180/\text{pi}) = 88.36217$$

Table 5.6 Comparison of results of angle value calculation between a manual system and the proposed system

Case	Intersecting point	Manual calculation	Proposed system	Error (degree)	Error (%)
Case1.1	V1H1	87.16083	87.4949	+0.33407	0.38
	V2H1	87.16083	87.4949	+0.33407	0.38
	V1H2	87.16083	87.4949	+0.33407	0.38
	V2H2	87.16083	87.4949	+0.33407	0.38
Case1.2	V1H1	93.84875	94.1704	+0.32165	0.34
	V2H1	93.84875	94.1704	+0.32165	0.34
	V3H1	90	90	-	-
	V4H1	90	90	-	-
	V1H2	93.84875	94.1704	+0.32165	0.34
	V2H2	93.84875	94.1704	+0.32165	0.34
	V3H2	90	90	-	-
	V4H2	90	90	-	-
	V1H3	93.84875	94.1704	+0.32165	0.34
	V2H3	93.84875	94.1704	+0.32165	0.34
	V3H3	90	90	-	-
	V4H3	90	90	-	-
	V1H4	93.84875	94.1704	+0.32165	0.34
	V2H4	93.84875	94.1704	+0.32165	0.34
	V3H4	90	90	-	-
	V4H4	90	90	-	-
Case1.3	V1H1	90	90	-	-
	V2H1	90	90	-	-
	V3H1	88.36217	88.5679	+0.20573	0.23
	V4H1	88.36217	88.5679	+0.20573	0.23
	V1H2	90	90	-	-
	V2H2	90	90	-	-
	V3H2	88.36217	88.5679	+0.20573	0.23
	V4H2	88.36217	88.5679	+0.20573	0.23
	V1H3	90	90	-	-
	V2H3	90	90	-	-
	V3H3	88.36217	88.5679	+0.20573	0.23
	V4H3	88.36217	88.5679	+0.20573	0.23
	V1H4	90	90	-	-
	V2H4	90	90	-	-
	V3H4	88.36217	88.5679	+0.20573	0.23
	V4H4	88.36217	88.5679		0.23

The results of comparing angle values (Table 5.6) show that the level of errors in the proposed system did not exceed 0.38%.

Case 2: Counting numbers of angles

The proposed system is specified to mark and count the number of mark only positions whose angle error value deviate from a right angle over $\pm 1^{o}$.

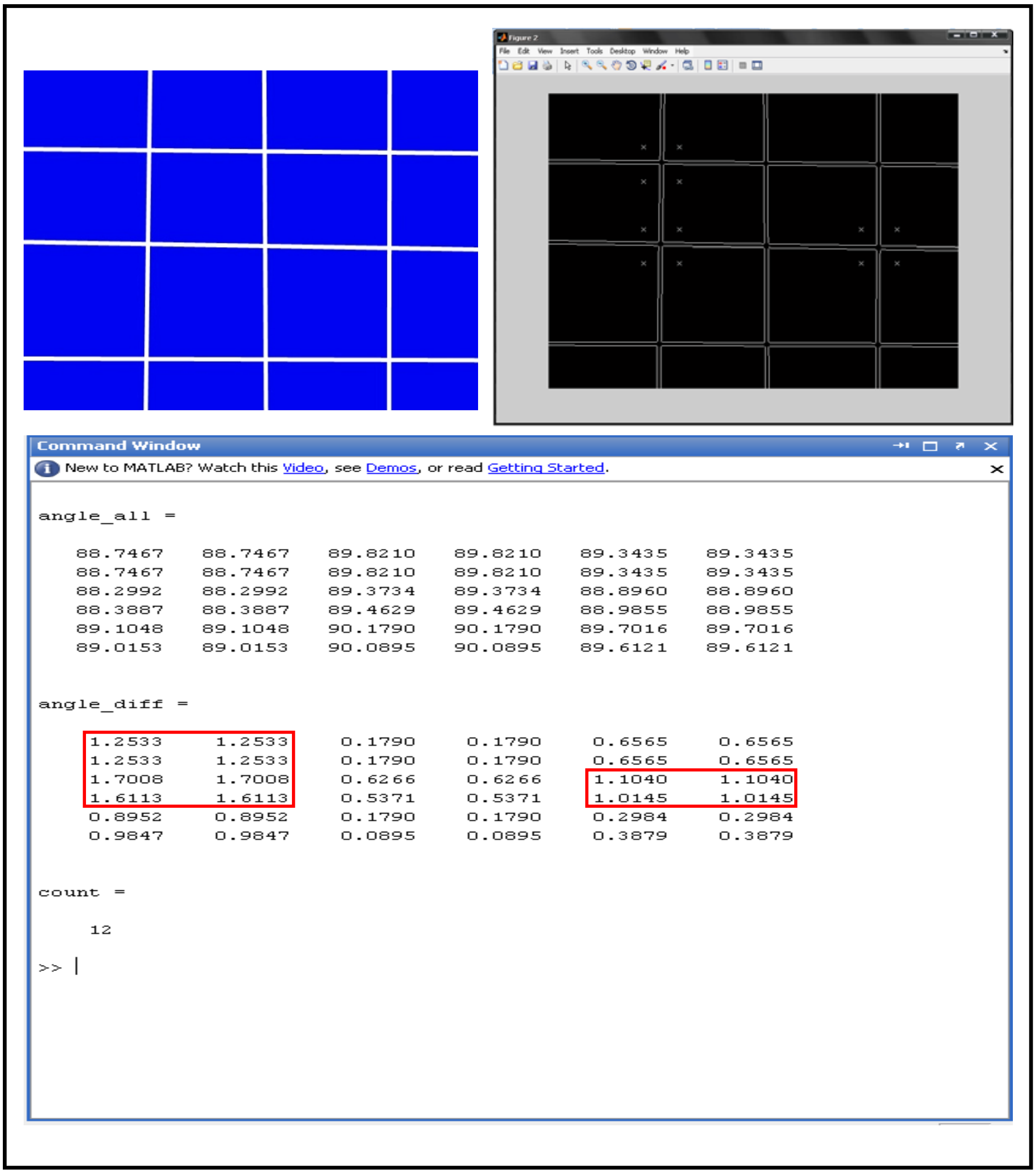


Figure 5.25 Number of positions whose angle error value from a right angle exceeded ±1°

As seen in Figure 5.25, the number of marks whose angle errors deviated from a right angle by over ±1° was 12. This conforms to the results of calculation.

5.4 Conclusions

The defect detection and quantification system for tiling work is design and developed according to image processing technique. The development uses MATLAB to formulate algorithms in the image processing facility in our system such as reduce noise, edge detection, and the proposed algorithms to detect the defect positions and quantify defect values. After that the proposed system is demonstrated the accuracy of algorithms within system before application on an actual construction site in Chapter 7. The representative images of the tile panel model are created from Photoshop program to be not affected from lighting and other environments. The results of testing the algorithm for gap inspection show that the calculation from the proposed algorithms is able to detect gap size defect positions accurately. Defect value errors from the proposed algorithm using manual calculation did not exceed 2%. Moreover, algorithm testing for angle inspection of intersecting straight lines is developed to check angle value and counts the number of angles which are not correct angles by comparing the proposed system with manual calculation known coordinate value. The results of comparison show that the proposed algorithm is able to determine the angle value with an error less than 0.38%. The count of the number of angles deviating from a right angle over tolerance value satisfied the results of calculation. Therefore, benefit of proposed system in this chapter is to reduce subjective attribute of visual quality inspection. Due to human cannot quantify defect value or it is not the same value especially in case of aesthetic faults. The proposed system can detect defect positions and quantify defect values. These defect values can be used to classify defect level for using as same evaluation standard within organization or project. It leads to improve quality continuously. The design and development of defect level evaluation system will be discussed in the next chapter.

CHAPTER VI
THE DESIGN AND DEVELOPMENT OF A DEFECT LEVEL EVALUATION SYSTEM PROTOTYPE

This chapter presents the design and development of a defect level evaluation system to realize the proposed conceptual framework described in Chapter 4. This chapter is extended the concept of defect detection and quantification system in Chapter 5. The defect level evaluation system is designed and developed to translate defect value (from Chapter 5 or other methods) into intensive level of defect. The proposed system is needed to use as same evaluation standard within organization or project supporting decision on quality of work. The quality evaluation is more reliable because it is not depend on only individual perception.

6.1 System design

The development of the defect level evaluation system can best be described by dividing it into two main modules: (1) an evaluation mechanism and translation module and (2) a knowledge base module. Both modules were developed from knowledge mining of experts' experience following the fuzzy logic and AHP concept. The designed framework of the defect level evaluation system is shown in Figure 6.1.

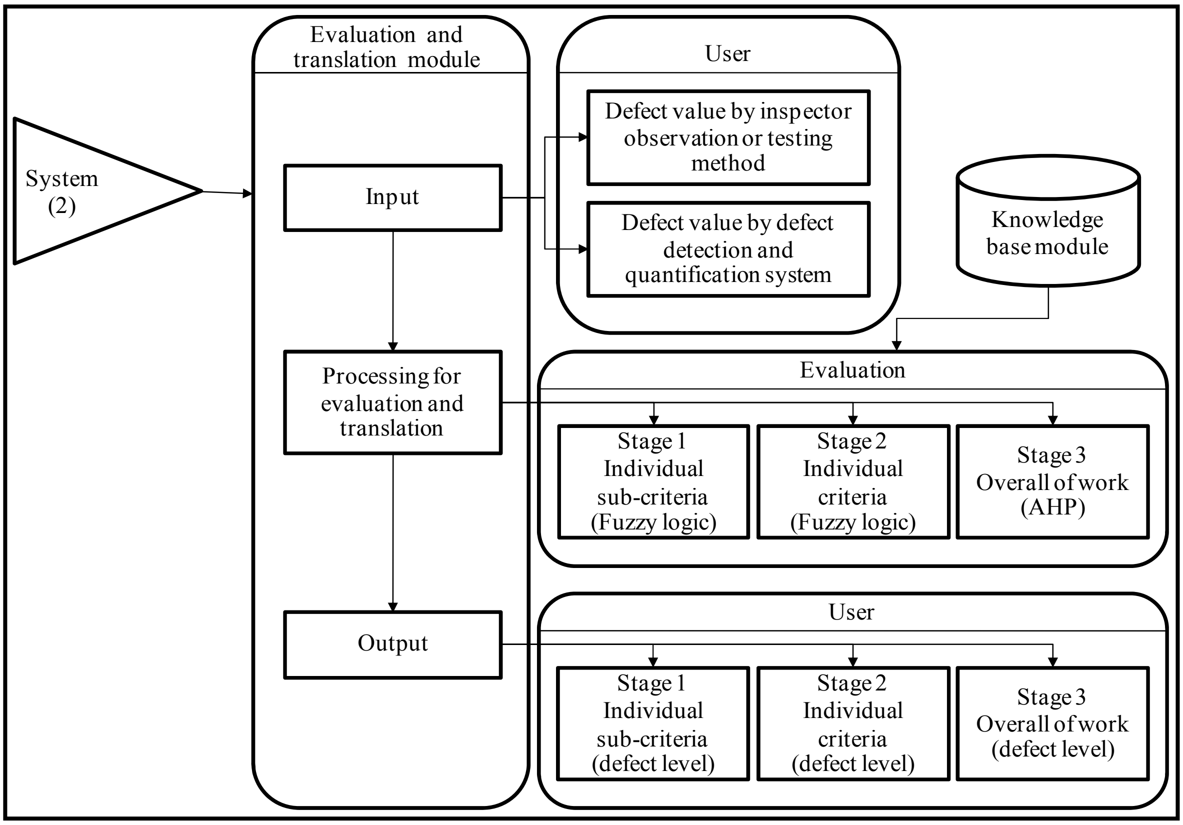


Figure 6.1 Framework of the defect level evaluation system

6.2 System development

In this section, the objective is to present the methodology of developing system for defect level evaluation. The defect level evaluation system is developed to decrease the human judgment on evaluation of aesthetic faults in architectural work. As the judgment of aesthetic faults of architectural work is relied on individual experience, the evaluation applies the fuzzy logic to reduce the individual judgment on evaluating defect level. The defect level evaluation system is designed from the concept of fuzzy logic and knowledge based system. The steps of methodology are shown in Figure 6.2. A cases study of tiling work inspection is presented to clarify the methodology of system development.

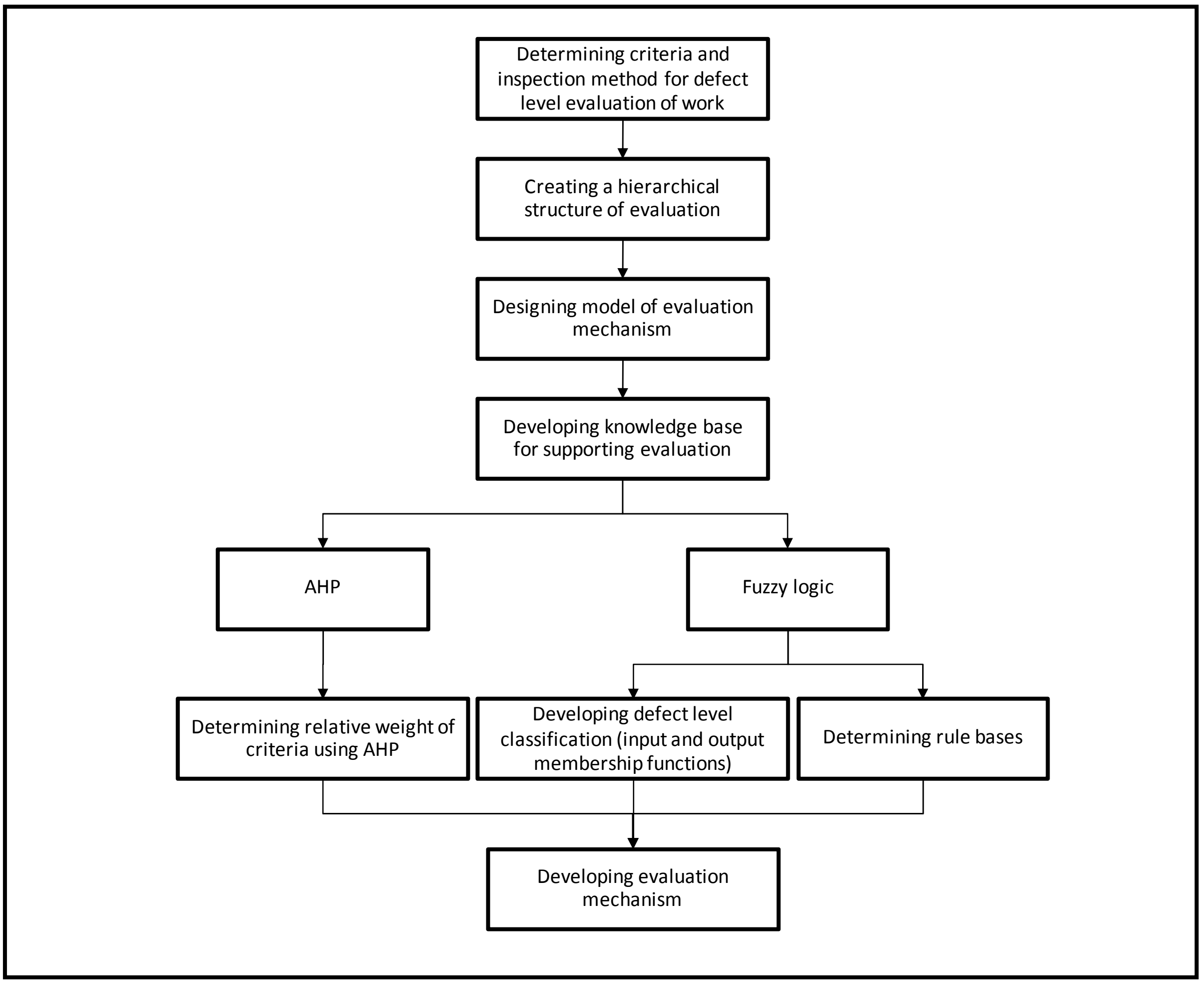


Figure 6.2 The methodology of developing system for defect level evaluation.

6.2.1 Determining criteria and inspection methods for evaluating defect level of work

First step, we must explore the specific evaluation criteria and inspection method in each criterion. The criteria and sub-criteria are used to create a hierarchical structure of evaluation in next step. The inspection method is applied to detect defect positions and quantify the numerical value of defect supporting the input stage of evaluation model. The criteria and sub-criteria for developing defect level evaluation, and the inspection methods can be derived from several channels such as collecting from previous researches, checklist documents for construction quality inspection that are included in the quality inspection manual from several organizations developed, or interviewing experts

The criteria and traditional inspection methods for evaluating defect levels in tiling work were adopted from Navon (2000), CIS 7:2006 (2006) and five expert interviews as shown in Table 6.1. The overall tiling work inspection is divided into four main components: (1) inspecting completion of tile, (2) inspection of distance between neighbouring tiles (gap), (3) inspection of tile alignment, and (4) inspection of adherence of tile to panel. There are various criteria for defect level evaluation e.g. F_i, i = 1, 2, 3, 4. The F_i criteria were classified as sub-criteria f_{ij}, i = 1, 2, 3, 4 and j = 1, 2, 3.

Based on the traditional inspection methods shown in Table 6.1, there are some sub-criteria of f_{21}, f_{22} and f_{31} which are difficult to quantify numerical value of defect because the human vision is limited. This preliminary research of our system was able to determine that the distance between the neighboring tiles should be uniform and that had a standard gap size (sub-criterion f_{21}). It also determined whether the tiles were set in straight parallel lines (sub-criterion f_{31}). For the sub-criterion f_{22}, we still attempt to overcome the subjective attributes by applying digital image processing technique in future work because we envision its potential benefits. Therefore, this preliminary research suggests the conversion of the subjective attributes to measurable attributes by using the observation method to identify the defect positions. Although it is still semi-subjective attribute, it is more reliability than the old method. The new inspection methods are shown in Table 6.1.

6.2.2 Creating a hierarchical structure of evaluation

The following step on creation of a hierarchical structure for developing defect level evaluation. The structure explains the relationship and hierarchy of each criteria and sub-criteria. The created hierarchical structure can help provide a more systematic evaluation for complex decision. Figure 6.3 is decomposed the defect level evaluation into a hierarchy at the top, criteria and sub-criteria at various levels, and decision alternatives of defect level at the bottom.

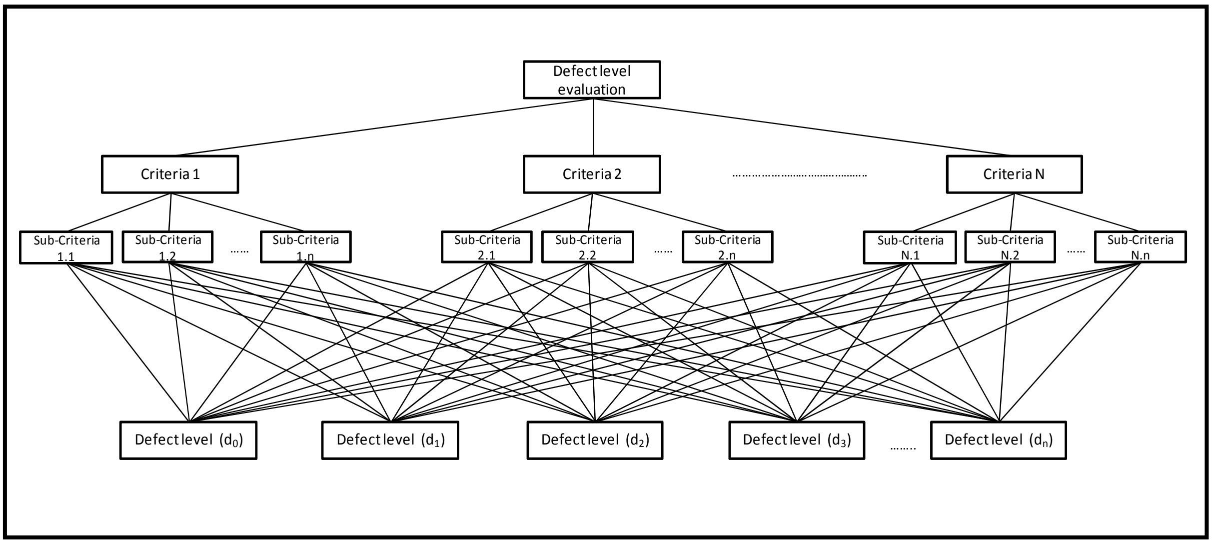


Figure 6.3 Hierarchical structure of defect level evaluation

Table 6.1 Criteria and inspection methods for defect level evaluation of tiling work

Criteria	Sub-criteria	Defect check list	Traditional inspection methods		New inspection methods	
			Inspection methods	Numerical value of defect for quality evaluation	Inspection methods	Numerical value of defect for quality evaluation
F1		Inspecting the completion of tile				
	f_{11}	Conformity of tile to specification	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
	f_{12}	Conformity of tile pattern to specification	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
	f_{13}	Number of tiles without nicks or gashes	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
F2		Inspecting distance between neighbouring tiles (gap)				
	f_{21}	Uniformity of gap size with the respect to standard	Visual inspection	Subjective judgment	Visual inspection DIP	Score rating Defect area (squ.m)/panel
	f_{22}	Uniformity of glue application over gap line	Visual inspection	Subjective judgment	Visual inspection DIP/Observation methods	Score rating Number of defect points/panel
F3		Tile alignment inspection				
	f_{31}	Straightness of tile alignment (parallel lines)	Visual inspection	Subjective judgment	Visual inspection DIP	Score rating Number of defect intersecting point/panel
	f_{32}	Uniformity of level of neighbouring tiles	Visual inspection	Number of defect tiles/ panel	Visual inspection	Number of defect tiles/ panel
F4		Inspection of adherence of tile to panel				
	f_{41}	The glue has to be spread uniformly back of the tile	Knock	Number of defect tiles/ panel	Knock	Number of defect tiles/ panel
	f_{42}	The tile must be pressed evenly against the panel	Knock	Number of defect tiles/ panel	Knock	Number of defect tiles/ panel

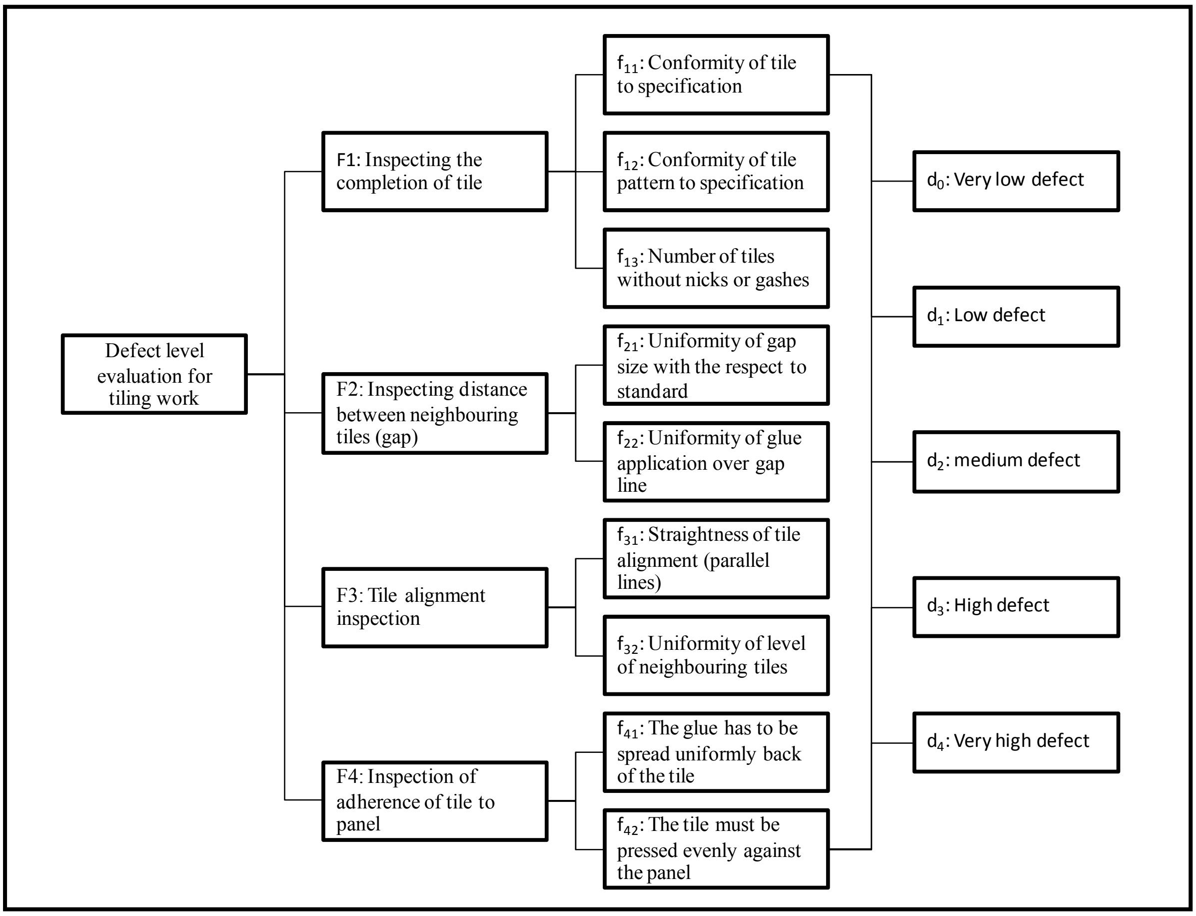


Figure 6.4 Hierarchical structure of defect level evaluation for tiling work

From criteria and sub-criteria in the first step, we can create a hierarchical structure of defect level evaluation for tiling work as shown in Figure 6.4. There are five degrees of defect level that define in Table 6.2.

Table 6.2 Defect level definitions

Defect level	**Linguistic Variable**
d_0	Very low defect
d_1	Low defect
d_2	Medium defect
d_3	High defect
d_4	Very high defect

6.2.3 Designing model of evaluation mechanism

This step aims to design the model of evaluation mechanism corresponding with the created hierarchical structure of defect level evaluation in previous step. The model includes the process of evaluation mechanism, and the information or knowledge to support the evaluation. The model development for supporting the defect level evaluation system in aesthetic faults of architectural work is based on the principle of fuzzy logic, AHP and knowledge base to handle ambiguity in some work items that can be not separated the intensive defect level clearly. The proposed model attempts mimics human inference processes in decision-making. The evaluation mechanism in model translates inputs (numerical value of defect in new inspection) into a defect level to support the acceptable judgment of work.

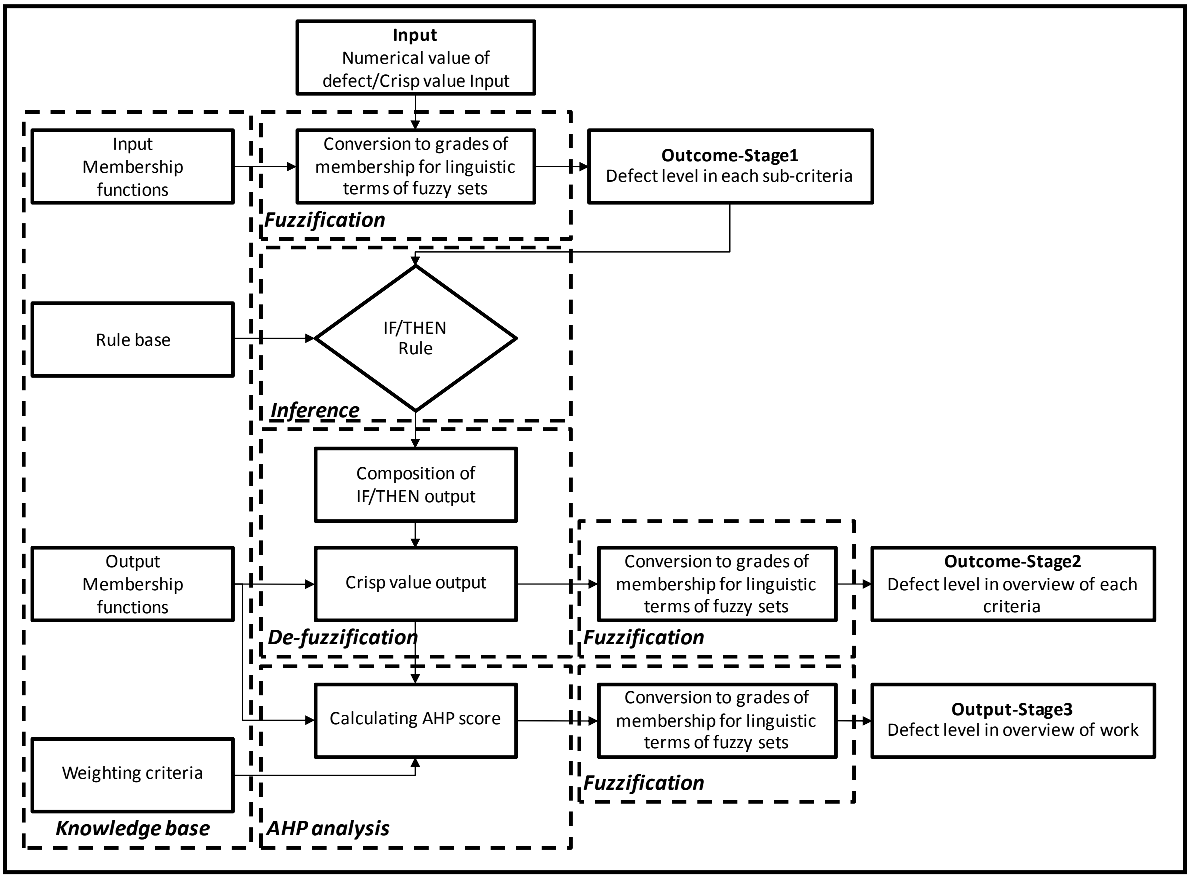


Figure 6.5 The designed model for defect level evaluation

The model of defect level evaluation is illustrated in Figure 6.5. There are three stages of outcome from defect evaluation. These stages are the results of defect level in each sub-criterion, defect level of each criterion and overall defect level of work. First, the stage of sub-criteria is to evaluate the defect level in each sub-criterion by comparing defect value with defect level classification in knowledge base. Second, the stage of criteria is to evaluate the defect level in each criterion by considering overall of all sub-criteria. Last, evaluation in stage of overall defect level of work will consider from all criteria. Result of defect level evaluation from three stages can be used for comparing with defect level requirements for continuous quality improvement. Moreover, the model also includes knowledge base for supporting the evaluation mechanism in each stage. The details will be explained in step of developing knowledge base. To obtain the outcome from defect evaluation, the detail methodology of each stage is described in the next section.

6.2.3.1 The methodology of defect level evaluation in first stage

Outcomes of the first stage are results of evaluating defect level from each sub-criterion. The fuzzification method in fuzzy logic theory is applied to converse the numerical value of defect (crisp input) to grades of membership for linguistic terms of fuzzy sets. For example, the input of f_{11} that equal to 36 can be medium degree category because it has a greater value than the low category. Such results lead to the determination of defect level, as in Figure 6.6.

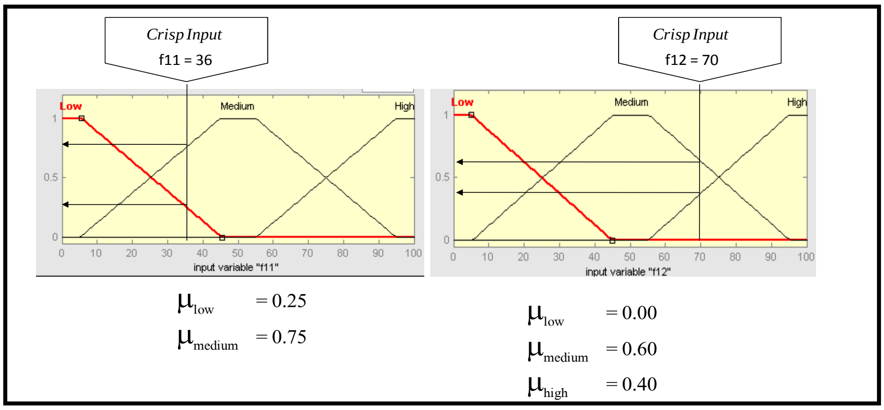


Figure 6.6 Fuzzification of input variables

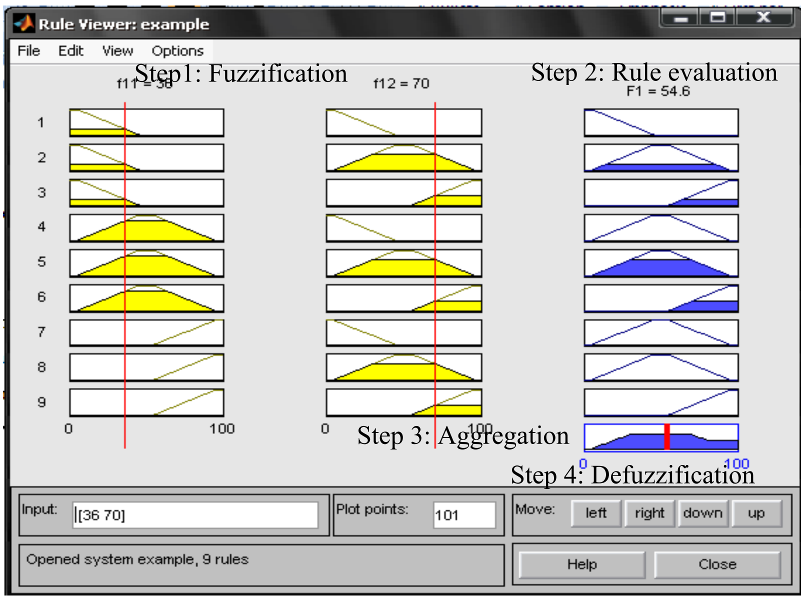


Figure 6.7 Mamdani's fuzzy reasoning method

6.2.3.2 The methodology of defect level evaluation in second stage

Outcomes of the second stage are results of evaluating defect level from each criterion. We use the fuzzy inference system from the Fuzzy Logic System Toolbox in MATLAB which contains the developed knowledge base of fuzzy sets (input and output membership functions) and the fuzzy rule base. We select the Mamdani-style inference (Mamdani, 1977) in fuzzy inference to evaluate and translate defect level scores. The four major steps to draw a conclusion using Mamdani's fuzzy reasoning are illustrated in Figure 6.7. Each step can be described as follows.

Step 1: Fuzzification

The fuzzification method is the conversion of the numerical value of defect (crisp input) to grades of membership for linguistic terms of fuzzy sets. This step is required the crisp inputs (f_{11} and f_{12}). The input value is used to determine the degree to which it belongs to each of the appropriate fuzzy sets. These results are derived from outcomes of the first stage. Example is shown as follows.

Crisp input $f_{11} = 36$

$\mu\ (f_{11} = \text{low}) = 0.25$

$\mu\ (f_{11} = \text{medium}) = 0.75$

$\mu\ (f_{11} = \text{high}) = 0.00$

Crisp input $f_{12} = 70$

$\mu\ (f_{12} = \text{low}) = 0.00$

$\mu\ (f_{12} = \text{medium}) = 0.60$

$\mu\ (f_{12} = \text{high}) = 0.40$

Step 2: Rule evaluation

Rule evaluation assists to take the fuzzified inputs ($\mu(f_{11} = \text{low}) = 0.25$, $\mu(f_{11} = \text{medium}) = 0.75$, $\mu(f_{11} = \text{high}) = 0.00$, $\mu(f_{12} = \text{low}) = 0.00$, $\mu(f_{12} = \text{medium}) = 0.60$, $\mu(f_{12} = \text{high}) = 0.40$) to the antecedents of the fuzzy rules. If a given fuzzy rule has multiple antecedents, the fuzzy operator (AND or OR) is used to obtain a single number that represents the result of the antecedent evaluation. This number (the truth value) is then applied to the consequent membership function. Our system applied the AND fuzzy operation intersection: $\mu A \cap B(x) = \min [\mu A(x), \mu B(x)]$. The consideration in each rule base will use the value of minimum membership function. This value will be contained in the output of defect level that is identified in rule base. The detail of rule base identification is explained in section 6.2.4.2. The number of rules depends on the number of inputs and linguistic variables in fuzzy sets. For example, there are 2 inputs (sub-criteria) of criterion F1 and 3 degrees of linguistic variables in fuzzy sets (low level, medium level and high level). Thus, the number of rules will be 3x3 = 9 rule bases that are shown in Table 6.3.

Table 6.3 Example of rule bases

Rule bases	Input (f_{11}) μA(x)	Input (f_{12}) μB(x)	Output (F1) μA∩B(x) = min [μA(x), μB(x)]
1	μ (f_{11} = low) = 0.25	μ (f_{12} = low) = 0.00	μ (F1 = low) = 0.00
2	μ (f_{11} = low) = 0.25	μ (f_{12} = medium) = 0.60	μ (F1 = medium) = 0.25
3	μ (f_{11} = low) = 0.25	μ (f_{12} = high) = 0.40	μ (F1 = high) = 0.25
4	μ (f_{11} = medium) = 0.75	μ (f_{12} = low) = 0.00	μ (F1 = medium) = 0.00
5	μ (f_{11} = medium) = 0.75	μ (f_{12} = medium) = 0.60	μ (F1 = medium) = 0.60
6	μ (f_{11} = medium) = 0.75	μ (f_{12} = high) = 0.40	μ (F1 = high) = 0.40
7	μ (f_{11} = high) = 0.00	μ (f_{12} = low) = 0.00	μ (F1 = medium) = 0.00
8	μ (f_{11} = high) = 0.00	μ (f_{12} = medium) = 0.60	μ (F1 = medium) = 0.00
9	μ (f_{11} = high) = 0.00	μ (f_{12} = high) = 0.40	μ (F1 = high) = 0.00

Step 3: Aggregation of rule output

Aggregation is the process of unification of the outputs of all rules. We take the membership functions of all rule consequents previously clipped or scaled value. Then, we combine them into a single fuzzy set. The final conclusion is aggregated by using the union of all output conclusions.

Step 4: Defuzzification

Defuzzification is a method to justifiably convert a fuzzy set into a precise value using a mathematical process. Our research uses the center of gravity (COG) method. The center of gravity method takes the center of the area under the curve of the membership function of a fuzzy set as the answer. Figure 6.7 demonstrates that the output for this example is 54.60. Center of gravity equation:

$$COG = \frac{\sum_{i=1}^{N} \alpha i w i}{\sum_{i=1}^{N} \alpha i} \tag{6.1}$$

Where COG = Center of gravity
N = Value from position 1 to i
αi = Fuzzy output at position i
wi = Area under the curve of the membership function of fuzzy set

After that the membership function of criterion F1 is taken to convert to the defect level in linguistic terms that can be determined from the fuzzification method likes first stage.

6.2.3.3 The methodology of defect level evaluation in third stage

In the third stage, the defect level scores of the four factors are used to calculate an overall defect level score for the tiling work by considering each factor's different priority (weight) as in Eq. (6.2).

$$\text{Defect level score of overall work (\%)} = \{[\text{Defect level score of F1 (\%)} \times w_{F1} (\%)] + [\text{Defect level score of F2 (\%)} \times w_{F2} (\%)] + [\text{Defect level score of F3 (\%)} \times w_{F3} (\%)] + [\text{Defect level score of F4 (\%)} \times w_{F4} (\%)]\} \times 100 \quad (6.2)$$

After that percentage of defect level score of overall work can be convert to the defect level in linguistic terms that can be determined from the fuzzification method likes first stage and second stage above.

The reasoning of our concept in conversion from quantitative data to qualitative data for outcome of all three stages is to increases clarity of defect level classification base on the same standard. As the quantitative data cannot indicate the intensive level of the defect clearly, the inspectors use the quantitative data to judge quality by different standards. It leads to unreliability of evaluation.

6.2.4 Developing knowledge base for supporting evaluation mechanism

The knowledge base for the quality evaluation standard is developed to support the evaluation mechanism according to the designed model in Figure 6.5. The methodology of knowledge base development uses the concepts of fuzzy logic and AHP. The knowledge for development obtains from experience of experts. The knowledge base of the quality evaluation standard consists of three main parts: (1) defect level classification (input and output membership functions), (2) fuzzy rule bases, and (3) the relative weight of criteria. The details of the development are as follows.

6.2.4.1 Developing defect level classification (input and output membership functions)

Our development of knowledge base of defect level classification is designed to obtain the information of fuzzy sets which include the input and output membership functions. The fuzzy sets are developed by interviewing experts. The interview aims to obtain the information about defect level classification in each defect value from each expert experience. These information are used to develop fuzzy sets as follows.

Our methodology starts from we use the definition of linguistic variables in Table 6.2 to be words with associated degrees of membership in the set, where the term set T(defect level) is defined as follows:

T (defect level from d_0 to d_4) = {d_0 = "Very low defect",
d_1 = "low defect",
d_2 = "medium defect",
d_3 = "high defect",
d_4 = "very high defect"}

Next, we adopt the horizontal scheme approach (Pedrycz and Gomide, 2007; Apolloni, Pedrycz, Bassis and Malchiodi, 2008) to estimate the value of membership function. We identify a collection of elements in the universe of discourse X and request that an expert answers the question: "Does x belong to set A?". The answers are expected to come in a binary ("yes"/ "no") format. Give m experts whose answers {xi} for a given point of X form a mix of "yes" or "no" replies, we count the number of "yes" answers and compute the ratio of the positive answers (xi = 1) versus the total number of replies m, that is Σxi/m. This ratio is treated as a membership degree of the set at the given point of the universe of discourse. When all experts accept that the element belongs to the set, then its membership degree is equal to 1.

In case of defect level evaluation in aesthetic faults, the set A defined in X could be any linguistic notion such as "very low defect level", "low defect level", "medium defect level", "high defect level" and "very high defect level". We consider the responses of five experts who came up with the following assessment of concept. For example, the tiling inspection in sub-criteria f_{42} (The tile must be pressed evenly against the panel) is based on an inspection of an area per sq.m. with a tile size of 20 sq.cm. (total tiles equal to 25 tiles per panel). The number of "yes" responses collected in the concept of "very low defect level", "low defect level", "medium defect level", "high defect level" and "very high defect level" respectively that are shown in Table 6.4. We do the same example with other sub-criteria (input membership function) and criteria (output membership function).

Before these results are used to develop the fuzzy sets, the number of defect tiles must be converted into percentage of defect tiles by using the formula in Table 6.5 because the proportion of defect value in form of percentage can be compared with other tile sizes and different panel area.

The fuzzy sets plotted in the form of trapezoid graphs, are piecewise linear function characterized by four parameter, a, m, n, and b, each of which defined one of the four linear parts of the membership function, as illustrated in Figure 6.8 and assume the following form (see Eq.6.3) (Pedrycz and Gomide, 2007):

$$A(x) = \begin{cases} 0, & \text{if } x < a \\ \dfrac{x-a}{m-a}, & \text{if } x \in [a,m) \\ 1, & \text{if } x \in [\mathrm{m},n) \\ \dfrac{b-x}{b-n}, & \text{if } x \in [n,b] \\ 0, & \text{if } x > b \end{cases} \qquad (6.3)$$

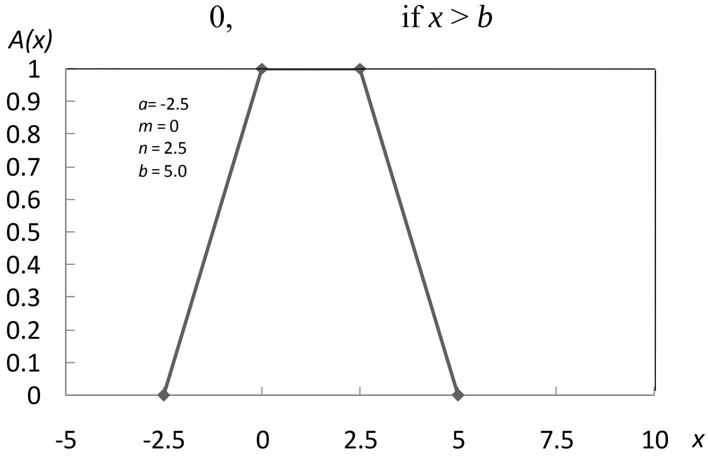


Figure 6.8 Trapezoidal membership functions (Pedrycz and Gomide, 2007)

Table 6.4 Number of “yes” responses for assessment from five experts

F1: Inspecting the completion of tile

Concept of "very low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Concept of "very high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

f_{11}: Conformity of tile to specification

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	3	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0.6	1	1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	3	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0.6	1	1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	3	5	5	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0.6	1	1	0.4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	3	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.6	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.4 Number of “yes” responses for assessment from five experts (continued)

f_{12}: Conformity of tile pattern to specification

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.4	1	1	1	1	1	1	1	1	1	1	1	1	1	1

f_{13}: Number of tiles without nicks or gashes

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	4	5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0.8	1	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	4	5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0.8	1	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	4	5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0.8	1	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.4 Number of “yes” responses for assessment from five experts (continued)

F2: Inspection of distance between neighbouring tiles (gap)

Concept of "very low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Concept of "very high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

f_{21}: Uniformity of gap size with the respect to standard

Concept of "very low defect level"																	
Defect area (sq.mm)/gap area (sq.mm.), x	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
No. of "yes" replies	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect area, x%	0.00	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	81.25	87.50	93.75	100.00
μ_A (x)	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																	
Defect area (sq.mm)/gap area (sq.mm.), x	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
No. of "yes" replies	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect area, x%	0.00	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	81.25	87.50	93.75	100.00
μ_A (x)	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																	
Defect area (sq.mm)/gap area (sq.mm.), x	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
No. of "yes" replies	0	0	0	0	0	2	5	5	3	0	0	0	0	0	0	0	0
Percentage of defect area, x%	0.00	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	81.25	87.50	93.75	100.00
μ_A (x)	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0
Concept of "high defect level"																	
Defect area (sq.mm)/gap area (sq.mm.), x	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
No. of "yes" replies	0	0	0	0	0	0	0	0	2	5	5	3	0	0	0	0	0
Percentage of defect area, x%	0.00	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	81.25	87.50	93.75	100.00
μ_A (x)	0	0	0	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0
Concept of "very high defect level"																	
Defect area (sq.mm)/gap area (sq.mm.), x	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000	9,000	10,000	11,000	12,000	13,000	14,000	15,000	16,000
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	2	5	5	5	5	5
Percentage of defect area, x%	0.00	6.25	12.50	18.75	25.00	31.25	37.50	43.75	50.00	56.25	62.50	68.75	75.00	81.25	87.50	93.75	100.00
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.4	1	1	1	1	1

Table 6.4 Number of “yes” responses for assessment from five experts (continued)

f_{22}: Uniformity of glue application over gap line

Concept of "very low defect level"																										
No. of defect points, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect points, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect points, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect points, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	2	5	5	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	0.4	1	1	0.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect points, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	2	5	5	5	5	5	5	5	5	5	5	5	5	5	5
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.4	1	1	1	1	1	1	1	1	1	1	1	1	1	1

F3: Tile alignment inspection

Concept of "very low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Concept of "very high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

Table 6.4 Number of “yes” responses for assessment from five experts (continued)

f_{31}: Straightness of tile alignment (parallel lines)

Concept of "very low defect level"																	
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of "yes" replies	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	6.25	12.5	18.8	25	31.3	37.5	43.8	50	56.3	62.5	68.8	75	81.3	87.5	93.8	100
μ_A (x)	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																	
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of "yes" replies	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	6.25	12.5	18.8	25	31.3	37.5	43.8	50	56.3	62.5	68.8	75	81.3	87.5	93.8	100
μ_A (x)	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																	
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of "yes" replies	0	0	0	0	0	1	5	5	4	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	6.25	12.5	18.8	25	31.3	37.5	43.8	50	56.3	62.5	68.8	75	81.3	87.5	93.8	100
μ_A (x)	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0
Concept of "high defect level"																	
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of "yes" replies	0	0	0	0	0	0	0	0	1	5	5	4	0	0	0	0	0
Percentage of defect tiles, x%	0	6.25	12.5	18.8	25	31.3	37.5	43.8	50	56.3	62.5	68.8	75	81.3	87.5	93.8	100
μ_A (x)	0	0	0	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0
Concept of "very high defect level"																	
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	1	5	5	5	5	5
Percentage of defect tiles, x%	0	6.25	12.5	18.8	25	31.3	37.5	43.8	50	56.3	62.5	68.8	75	81.3	87.5	93.8	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.2	1	1	1	1	1

f_{32}: Uniformity of level of neighbouring tiles

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.4 Number of "yes" responses for assessment from five experts (continued)

F4: Inspection of adherence of tile to panel

Concept of "very low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	0	0	0	0	0
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Concept of "very high defect level"																					
Defect score, x%	0	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5	5	5	5
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1

f_{41}: The glue has to be spread uniformly back of the tile

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	1	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0.2	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	1	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1

Table 6.4 Number of “yes” responses for assessment from five experts (continued)

f_{42}: The tile must be pressed evenly against the panel

Concept of "very low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "low defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	5	5	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	1	1	0.8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "medium defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	1	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0.2	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	5	5	5	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	1	1	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Concept of "very high defect level"																										
No. of defect tiles, x	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
No. of "yes" replies	0	0	0	0	0	0	0	0	0	0	0	4	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Percentage of defect tiles, x%	0	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	84	88	92	96	100
μ_A (x)	0	0	0	0	0	0	0	0	0	0	0	0.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1

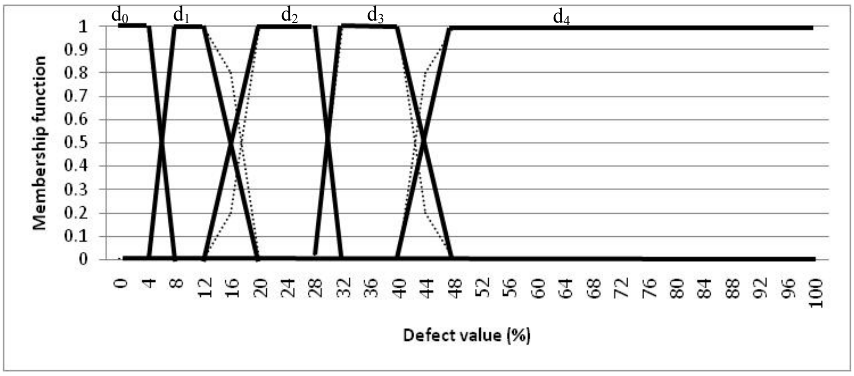


Figure 6.9 Example of fuzzy sets input (sub-criterion f_{42})

The dash lines plotted from the answered value that is changed to trapezoid graphs. Four parameters are extremely confident on the verdict of the experts (0 and 1) as illustrated in Figure 6.9. We use interpolation method at the location where is slope. Table 6.6 is the value of fuzzy set membership to plot the fuzzy set graphs as in Figure 6.10 to 6.13.

Table 6.5 Formulation to convert results from the expert questionnaire to fuzzy sets for comparison with other inspection cases

Factors	Criteria	Defect check list	Numerical value (Questionnnaire)	Numerical value (Fuzzy set)	Converting numerical value of input for comparing with Fuzzy set
F1		**Inspecting the completion of tile**	Defect level score (%)	Defect level score (%)	-
	f_{11}	Tile size meets specification	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 / panel area
	f_{12}	Tile pattern meets specification	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 / panel area
	f_{13}	The tile without nick or gash	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 / panel area
F2		**Inspecting distance between neighbouring tiles**	Defect level score (%)	Defect level score (%)	-
	f_{21}	Gap size uniforms and meets standard	Defect area (sq.mm.)/gap area (sq.mm.)	Percentage of defect area (sq.mm.) per gap area (sq.mm.)	= Defect area x 100 / [gap size x ((height of panel x ((width of panel / width of tile) - 1)) + (widtht of panel x ((height of panel / length of tile) - 1))]
	f_{22}	The glue has to be spread uniformly over gap line	Number of defect points/sq.m.	Number of defect point/sq.m.	= Number of defect point / panel area
F3		**Inspecting tile alignment**	Defect level score (%)	Defect level score (%)	-
	f_{31}	Tiles must be set in straight parallel lines	Number of defect intersecting points/sq.m.	Percentage of defect intersecting point per sq.m.	= Number of defect intersecting point (from proposed system) x 100 / (4 x (width of panel / width of tile) - 1) x ((height of panel / length of tile) - 1))
	f_{32}	Neighbouring tiles have to be on the same level	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 /panel area
F4		**Inspecting attachment between tile and panel**	Defect level score (%)	Defect level score (%)	-
	f_{41}	The glue has to be spread uniformly back of the tile	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 /panel area
	f_{42}	The tile must be pressed evenly against the panel	Number of defect tiles/sq.m.	Percentage of defect area per sq.m.	= Number of defect tile x width of tile x length of tile x 100 /panel area

Table 6.6 Fuzzy set membership

Factor			**F1**			**F2**		**F3**		**F4**
Defect level	F1,F2,F3 and F4	f_{11}	f_{12}	f_{13}	f_{21}	f_{22}	f_{31}	f_{32}	f_{41}	f_{42}
	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]	[a m n b]
d_0	[0 0 15 25]	[0 0 4 12]	[0 0 4 12]	[0 0 4 12]	[0 0 6.25 18.75]	[0 0 1 3]	[0 0 6.25 18.8]	[0 0 4 12]	[0 0 4 12]	[0 0 4 8]
d_1	[15 20 35 40]	[4 12 16 24]	[4 12 16 24]	[4 12 16 24]	[6.25 18.75 25 37.50]	[1 3 4 6]	[6.25 18.8 25 37.50]	[4 12 16 24]	[4 12 16 24]	[4 8 12 20]
d_2	[35 40 55 60]	[16 24 28 36]	[16 24 28 36]	[16 24 28 36]	[25 37.50 43.75 56.25]	[4 6 7 9]	[25 37.50 43.8 56.3]	[16 24 28 36]	[16 24 28 36]	[12 20 28 33]
d_3	[55 60 75 80]	[28 36 40 48]	[28 36 40 48]	[28 36 40 48]	[43.75 56.25 62.50 75]	[7 9 10 12]	[43.8 56.3 62.50 75]	[28 36 40 48]	[28 36 40 48]	[28 32 40 48]
d_4	[75 80 100 100]	[40 48 100 100]	[40 48 100 100]	[40 48 100 100]	[62.50 75 100 100]	[10 12 25 25]	[62.50 75 100 100]	[40 48 100 100]	[40 48 100 100]	[40 48 100 100]

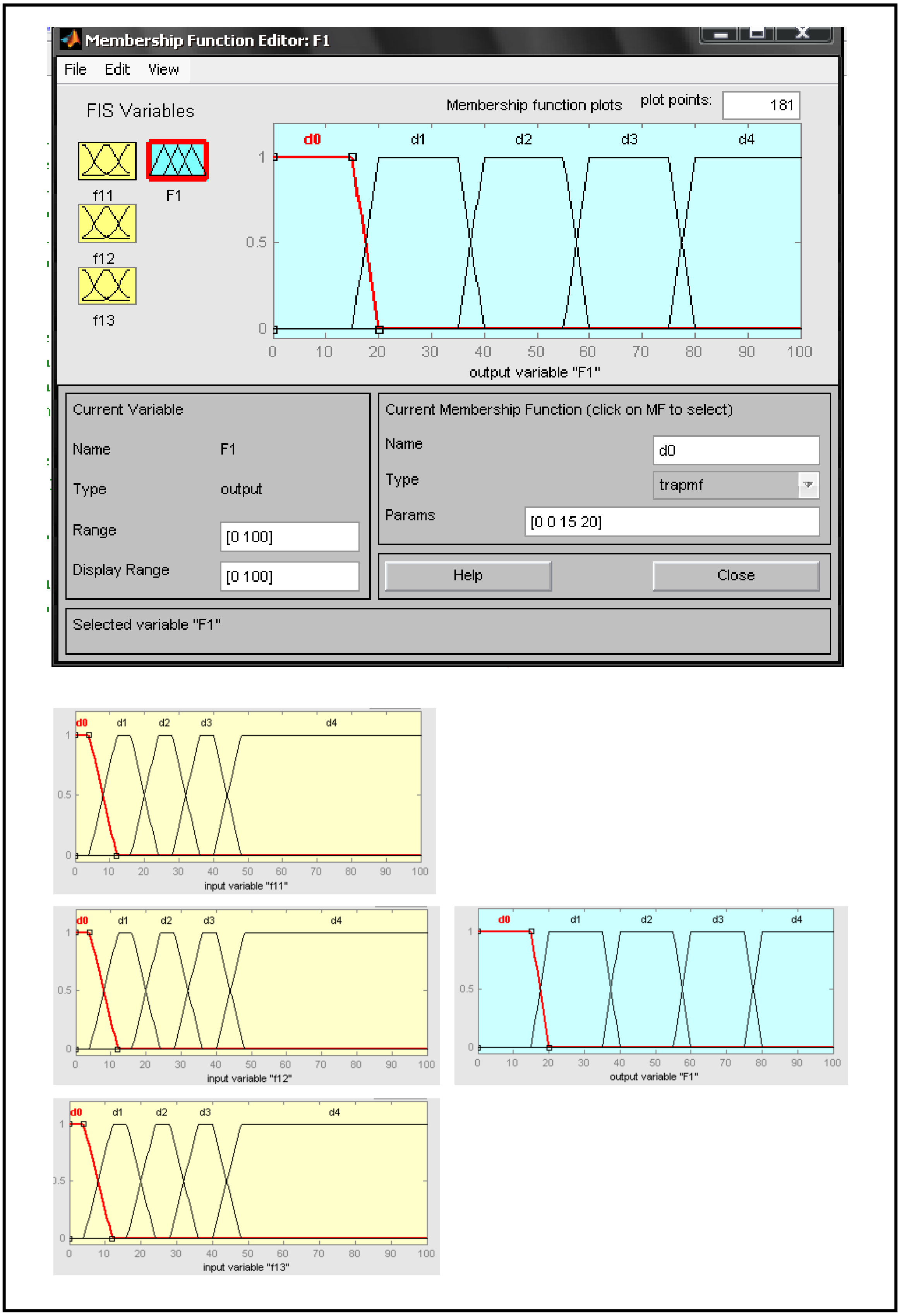


Figure 6.10 Fuzzy sets input (f_{11}, f_{12} and f_{13}) and output (F1)

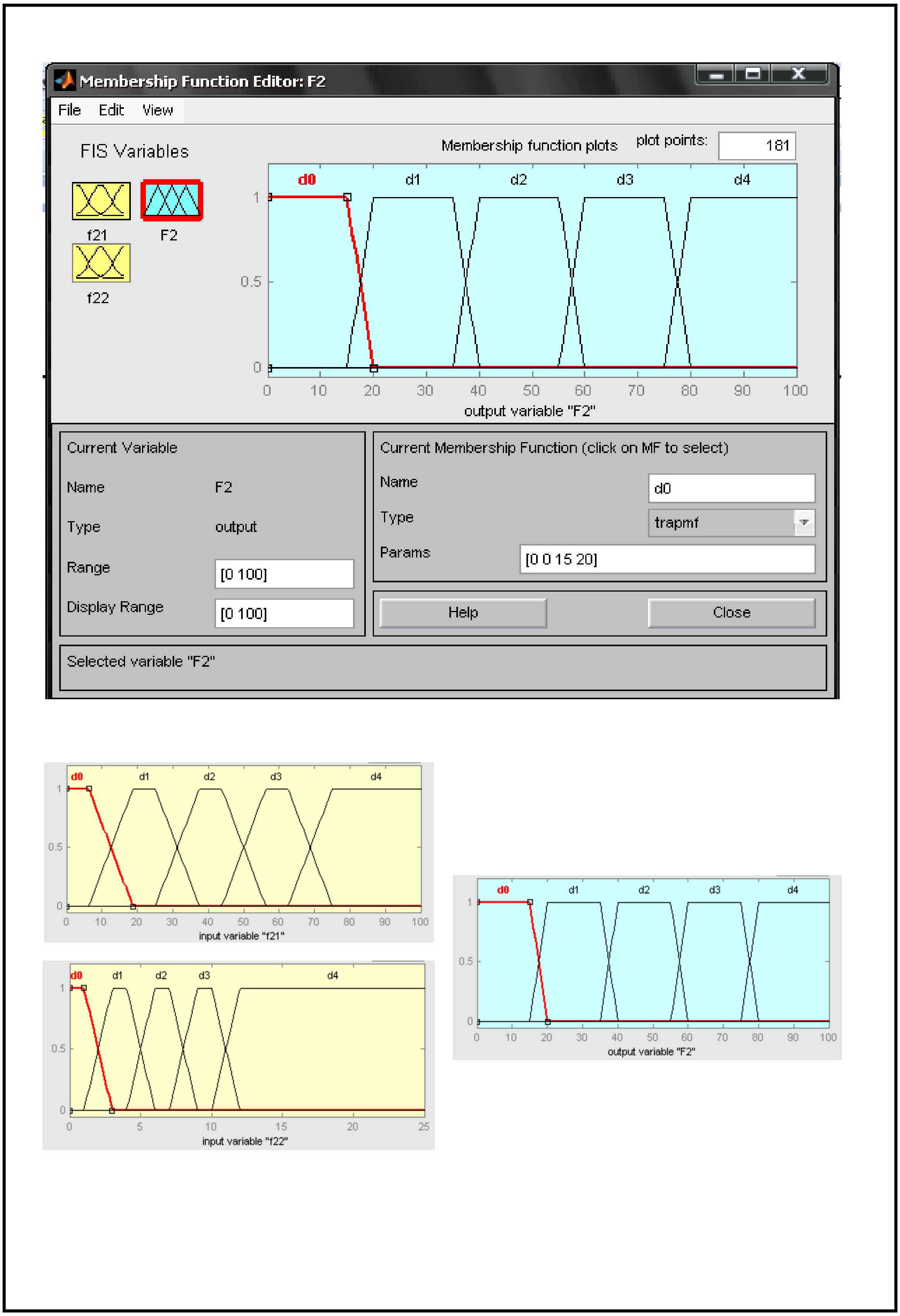


Figure 6.11 Fuzzy sets input ($f_{21}$and f_{22}) and output (F2)

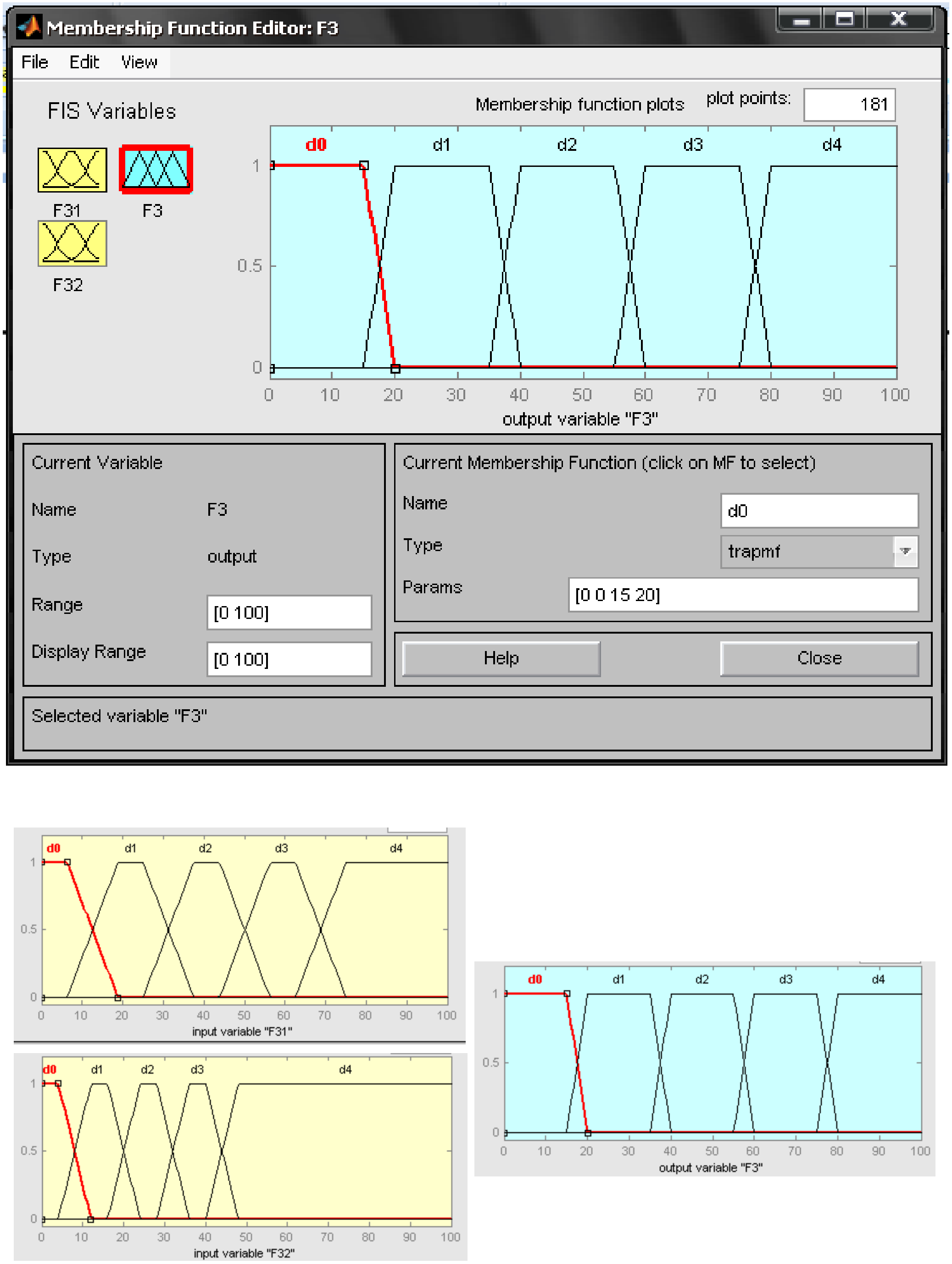


Figure 6.12 Fuzzy sets input ($f_{31}$and f_{32}) and output (F3)

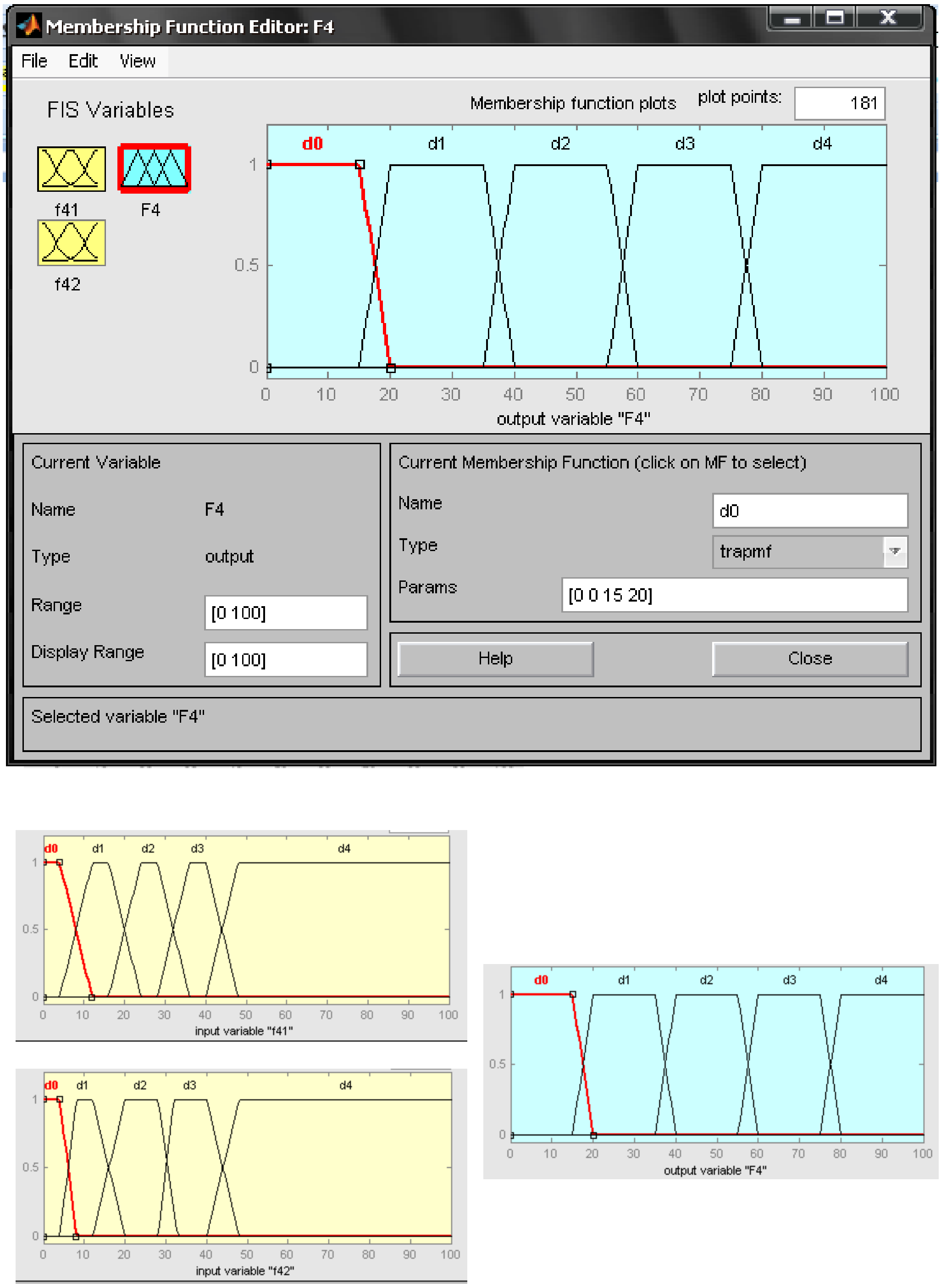


Figure 6.13 Fuzzy sets input ($f_{41}$and f_{42}) and output (F4)

6.2.4.2 Fuzzy rule base identification

Subjective perception-based reasoning is represented by "IF-THEN" fuzzy rules which can explain the logical evolution of unstructured decision-making process. This kind of fuzzy rule, which includes multiple antecedents and consequents, is exemplified in Figure 6.14. The number of rules depends on the number of inputs and linguistic variables in fuzzy sets. For example, there are 3 inputs (sub-criteria) in the first criteria of evaluation and 5 degrees of linguistic variables in fuzzy sets. Thus, the number of rules will be 5x5x5 = 125 rule bases. While the second and the third criteria, have 2 inputs, the number of rules will be 5x5 = 25 rule bases. The consequents of rule matrix in Table 6.7 were provided from the interview questionnaire of the experts and fed into the inference mechanism.

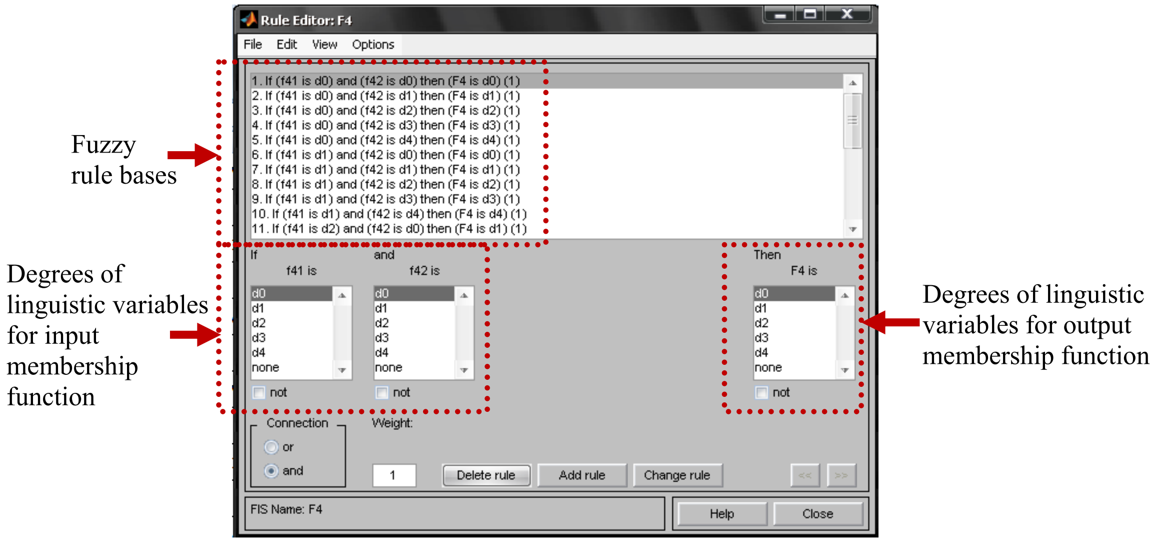


Figure 6.14 Method of rule base input in the fuzzy system

Table 6.7 Rule matrix

Criteria F1				f_{11}				
				Very low defect (d_0)	Low defect (d_1)	Medium defect (d_2)	High defect (d_3)	Very high defect (d_4)
f_{12}	Very low defect (d_0)	f_{13}	Very low defect (d_0)	Very low defect (d_0)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)
f_{12}	Very low defect (d_0)	f_{13}	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)
f_{12}	Very low defect (d_0)	f_{13}	Medium defect (d_2)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Very low defect (d_0)	f_{13}	High defect (d_3)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	High defect (d_3)	High defect (d_3)
f_{12}	Very low defect (d_0)	f_{13}	Very high defect (d_4)	High defect (d_3)	High defect (d_3)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)
f_{12}	Low defect (d_1)	f_{13}	Very low defect (d_0)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)
f_{12}	Low defect (d_1)	f_{13}	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)
f_{12}	Low defect (d_1)	f_{13}	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Low defect (d_1)	f_{13}	High defect (d_3)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	High defect (d_3)	High defect (d_3)
f_{12}	Low defect (d_1)	f_{13}	Very high defect (d_4)	High defect (d_3)	High defect (d_3)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)
f_{12}	Medium defect (d_2)	f_{13}	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)
f_{12}	Medium defect (d_2)	f_{13}	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Medium defect (d_2)	f_{13}	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Medium defect (d_2)	f_{13}	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)
f_{12}	Medium defect (d_2)	f_{13}	Very high defect (d_4)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)
f_{12}	High defect (d_3)	f_{13}	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)
f_{12}	High defect (d_3)	f_{13}	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	High defect (d_3)	f_{13}	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	High defect (d_3)	f_{13}	High defect (d_3)	Medium defect (d_2)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)
f_{12}	High defect (d_3)	f_{13}	Very high defect (d_4)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)
f_{12}	Very high defect (d_4)	f_{13}	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Very high defect (d_4)	f_{13}	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
f_{12}	Very high defect (d_4)	f_{13}	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	High defect (d_3)	High defect (d_3)	High defect (d_3)
f_{12}	Very high defect (d_4)	f_{13}	High defect (d_3)	High defect (d_3)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)
f_{12}	Very high defect (d_4)	f_{13}	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)

Table 6.7 Rule matrix (continued)

Criteria F2		f_{21}				
		Very low defect (d_0)	Low defect (d_1)	Medium defect (d_2)	High defect (d_3)	Very high defect (d_4)
f_{22}	Very low defect (d_0)	Very low defect (d_0)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)
	Low defect (d_1)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)
	Medium defect (d_2)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
	High defect (d_3)	Medium defect (d_2)	Medium defect (d_2)	High defect (d_3)	High defect (d_3)	High defect (d_3)
	Very high defect (d_4)	High defect (d_3)	High defect (d_3)	High defect (d_3)	Very high defect (d_4)	Very high defect (d_4)
Criteria F3		f_{31}				
		Very low defect (d_0)	Low defect (d_1)	Medium defect (d_2)	High defect (d_3)	Very high defect (d_4)
f_{32}	Very low defect (d_0)	Very low defect (d_0)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)
	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)
	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)
	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)
Criteria F4		f_{41}				
		Very low defect (d_0)	Low defect (d_1)	Medium defect (d_2)	High defect (d_3)	Very high defect (d_4)
f_{42}	Very low defect (d_0)	Very low defect (d_0)	Very low defect (d_0)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)
	Low defect (d_1)	Low defect (d_1)	Low defect (d_1)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)
	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	Medium defect (d_2)	High defect (d_3)
	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)	High defect (d_3)
	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)	Very high defect (d_4)

6.2.4.3 Determining relative weight of criteria using AHP

The concept of pair wise comparison (Saaty, 1980) in AHP is utilized to determine the priority weights for a decision-point. The comparison matrix, D, F_{kl}, is calculated by interviewing experts about the relative importance of a row element F_k when compared to a column element Fl, and ranking the answer on a-9 point scale (1-9) (Table 6.8). Next, F_{kl} and F_{lk} must be reciprocals of each other, and F_{kk} must be equal to 1 (k and l = 1 to n, n is the number of criteria). After that the summaries of each column are made to equal 1 by using Eq. (6.4) into the comparison matrix R. Finally, the relative weight can be determined by summarizing each row from matrix R.

$$D = \begin{pmatrix} f_{11} & f_{12} & \dots & f_{1n} \\ f_{21} & f_{22} & \dots & f_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ f_{n1} & f_{n2} & \dots & f_{nn} \end{pmatrix} \tag{6.4}$$

Table 6.8 Pair wise comparison scale (Saaty, 1980)

Qualitative scale	Quantitative scale
Equally preferred	1
Equally moderately	2
Moderately preferred	3
Moderately to strongly	4
Strongly preferred	5
Strongly to very strongly	6
Very strongly preferred	7
Very strongly to extremely	8
Extremely preferred	9

$$r_{nn} = \frac{f_{kl}}{\sum_{k=1}^{n} f_{kl}} \tag{6.5}$$

$$R = \begin{pmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ . & . & . & . \\ . & . & . & . \\ . & . & . & . \\ r_{n1} & r_{n2} & \dots & r_{nn} \end{pmatrix} \tag{6.6}$$

Next, AHP also calculated an inconsistency index to reflect the consistency of the decision maker's judgments during the evaluation phase (Huizingh and Virolijk, 1994; Sahoo, 1998). The consistency index can be calculated via Eq. (6.7) and (6.8). The consistency index should be lower than 0.10 for AHP results to be acceptable (CI<0.1). If this is not the case, the decision-maker should redo the assessments and comparisons.

$$CI = CR/RI \quad (6.7)$$

$$CR = \lambda max - n/ (n-1) \quad (6.8)$$

$$\lambda \max = \frac{1}{n}\sum_{i=1}^{n}(D.R/R) \quad (6.9)$$

Where, CI = Consistency index
CR = Consistency ratio
RI = Random inconsistency index (Table 6.9)
n = Square matrix size
λmax = Eigen value or average of consistency vector

Table 6.9 Random inconsistency index (RI) (Sahoo, 1998)

n	***RI***	***n***	***RI***	***n***	***RI***
1	0	6	1.24	11	1.51
2	0	7	1.32	12	1.48
3	0.58	8	1.41	13	1.56
4	0.90	9	1.46	14	1.57
5	1.12	10	1.49	15	1.59

The proposed model for defect level evaluation of tiling work uses the relative weights to determine the final computation of stage 3 in Figure 6.5. The evaluation of overall defect level of work is based on the outputs from four factors (F1, F2, F3 and F4) ranked according to relative priority (weight). The relative priority (weight) calculation can be seen in the results of answers from five experts in Tables 6.10 and the results of calculation in Table 6.11. Next, in checking the consistency value, in general, a consistency index of 0.1 or less is considered acceptable (Huizingh and Virolijk, 1994; Sahoo, 1998). The evaluation of five experts is considered an acceptable standard (CI<0.1) which is shown in Table 6.12.

Table 6.10 The relative weight calculation by pairwise comparison method

Experts	Criteria	Pairewise comparison matrix, D				Pairewise comparison matrix, R				Weight
		F1	F2	F3	F4	F1	F2	F3	F4	
1	F1	1	3	3	1/4	0.18	0.30	0.30	0.15	0.23
	F2	1/3	1	1	1/5	0.06	0.10	0.10	0.12	0.10
	F3	1/3	1	1	1/5	0.06	0.10	0.10	0.12	0.10
	F4	4	5	5	1	0.71	0.50	0.50	0.61	0.58
	sum	5.67	10	10	1.65	1.00	1.00	1.00	1.00	1.00
2	F1	1	2	2	1/3	0.20	0.25	0.25	0.18	0.22
	F2	1/2	1	1	1/4	0.10	0.13	0.13	0.14	0.12
	F3	1/2	1	1	1/4	0.10	0.13	0.13	0.14	0.12
	F4	3	4	4	1	0.60	0.50	0.50	0.55	0.54
	sum	5	8	8	1.83	1.00	1.00	1.00	1.00	1.00
3	F1	1	2	2	1/3	0.20	0.25	0.31	0.17	0.23
	F2	1/2	1	1/2	1/3	0.10	0.13	0.08	0.17	0.12
	F3	1/2	2	1	1/3	0.10	0.25	0.15	0.17	0.17
	F4	3	3	3	1	0.60	0.38	0.46	0.50	0.48
	sum	5	8	6.5	2	1.00	1.00	1.00	1.00	1.00
4	F1	1	2	2	1/3	0.20	0.20	0.27	0.19	0.21
	F2	1/2	1	1/2	1/5	0.10	0.10	0.07	0.11	0.09
	F3	1/2	2	1	1/4	0.10	0.20	0.13	0.14	0.14
	F4	3	5	4	1	0.60	0.50	0.53	0.56	0.55
	sum	5	10	7.5	1.78	1.00	1.00	1.00	1.00	1.00
5	F1	1	2	2	1/3	0.20	0.22	0.25	0.19	0.21
	F2	1/2	1	1	1/5	0.10	0.11	0.13	0.11	0.11
	F3	1/2	1	1	1/4	0.10	0.11	0.13	0.14	0.12
	F4	3	5	4	1	0.60	0.56	0.50	0.56	0.55
	sum	5	9	8	1.78	1.00	1.00	1.00	1.00	1.00

Table 6.11 Relative priority averages (weight)

Factor	Weight (%)					Weight (%) (average)
	Expert1	Expert2	Expert3	Expert4	Expert5	
F1	0.23	0.22	0.23	0.21	0.21	0.22
F2	0.10	0.12	0.12	0.09	0.11	0.11
F3	0.10	0.12	0.17	0.14	0.12	0.13
F4	0.58	0.54	0.48	0.55	0.55	0.54
Sum	1.00	1.00	1.00	1.00	1.00	1.00

Table 6.12 Checking consistency value

Expert	Evaluation of relative priority				Weight	Weight sum vector	Consistency vector	λ_{max}	CR	CI
1	1.00	3.00	3.00	0.25	0.23	0.95	4.08			
	0.33	1.00	1.00	0.20	0.10	0.38	4.03	4.10	0.03	0.04
	0.33	1.00	1.00	0.20	0.10	0.38	4.03			
	4.00	5.00	5.00	1.00	0.58	2.46	4.25			
2	1.00	2.00	2.00	0.33	0.22	0.89	4.02			
	0.50	1.00	1.00	0.25	0.12	0.49	4.01	4.02	0.01	0.01
	0.50	1.00	1.00	0.25	0.12	0.49	4.01			
	3.00	4.00	4.00	1.00	0.54	2.17	4.05			
3	1.00	2.00	2.00	0.33	0.23	0.96	4.16			
	0.50	1.00	0.50	0.33	0.12	0.48	4.08	4.12	0.04	0.05
	0.50	2.00	1.00	0.33	0.17	0.68	4.05			
	3.00	3.00	3.00	1.00	0.48	2.03	4.20			
4	1.00	2.00	2.00	0.33	0.21	0.87	4.09			
	0.50	1.00	0.50	0.20	0.09	0.38	4.04	4.06	0.02	0.02
	0.50	2.00	1.00	0.25	0.14	0.58	4.02			
	3.00	5.00	4.00	1.00	0.55	2.24	4.08			
5	1.00	2.00	2.00	0.33	0.21	0.86	4.01			
	0.50	1.00	1.00	0.20	0.11	0.45	4.01	4.02	0.01	0.01
	0.50	1.00	1.00	0.25	0.12	0.48	4.01			
	3.00	5.00	4.00	1.00	0.55	2.24	4.03			

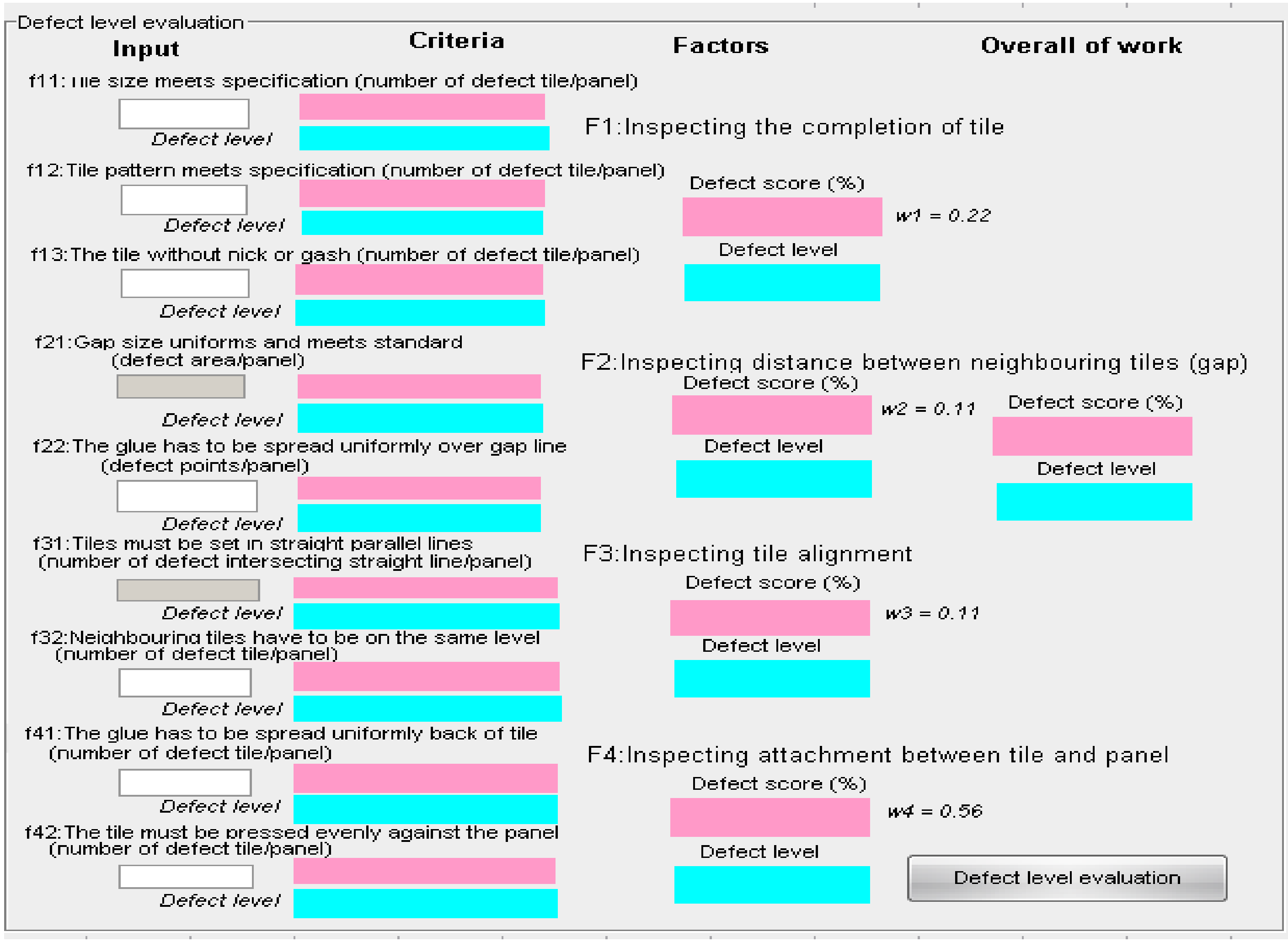


Figure 6.15 Defect level evaluation system

6.2.5 Developing evaluation mechanism

After the components of knowledge base are developed, this step aims to develop the evaluation mechanism. The evaluation mechanism is designed according to model of defect level evaluation in Figure 6.5. The development integrates the knowledge base to support in each stage of decision making. The user interface of defect level evaluation system can be seen in Figure 6.15.

6.3 Testing the system

The defect level evaluation system must be tested in order to verify the accuracy of the proposed system before implementing to validate with the decision making process of human inspectors in Chapter 7. Output of the defect level evaluation system must meet to conditions of rule base that are identified in the system. Our testing method, we assume a situation area of panel of sq.m. and a tile size of 20 sq.cm. The results of testing the proposed system are shown in Tables 6.13 to 6.16 which correspond to the identified rule base.

Table 6.13 Results of testing the proposed system (F1)

Identified fuzzy rule bases					**Numerical value input**			**Results of proposed system**			
Rule	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**	**f_{11}**	**f_{12}**	**f_{13}**	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**
1	Very low defect	Very low defect	Very low defect	Very low defect	0-1	0-1	0-1	Very low defect	Very low defect	Very low defect	Very low defect
2	Very low defect	Very low defect	Low defect	Low defect	0-1	0-1	2-4	Very low defect	Very low defect	Low defect	Low defect
3	Very low defect	Very low defect	Medium defect	Low defect	0-1	0-1	5-7	Very low defect	Very low defect	Medium defect	Low defect
4	Very low defect	Very low defect	High defect	Medium defect	0-1	0-1	8-10	Very low defect	Very low defect	High defect	Medium defect
5	Very low defect	Very low defect	Very high defect	High defect	0-1	0-1	11-25	Very low defect	Very low defect	Very high defect	High defect
6	Very low defect	Low defect	Very low defect	Very low defect	0-1	2-4	0-1	Very low defect	Low defect	Very low defect	Very low defect
7	Very low defect	Low defect	Low defect	Low defect	0-1	2-4	2-4	Very low defect	Low defect	Low defect	Low defect
8	Very low defect	Low defect	Medium defect	Medium defect	0-1	2-4	5-7	Very low defect	Low defect	Medium defect	Medium defect
9	Very low defect	Low defect	High defect	Medium defect	0-1	2-4	8-10	Very low defect	Low defect	High defect	Medium defect
10	Very low defect	Low defect	Very high defect	High defect	0-1	2-4	11-25	Very low defect	Low defect	Very high defect	High defect
11	Very low defect	Medium defect	Very low defect	Low defect	0-1	5-7	0-1	Very low defect	Medium defect	Very low defect	Low defect
12	Very low defect	Medium defect	Low defect	Low defect	0-1	5-7	2-4	Very low defect	Medium defect	Low defect	Low defect
13	Very low defect	Medium defect	Medium defect	Medium defect	0-1	5-7	5-7	Very low defect	Medium defect	Medium defect	Medium defect
14	Very low defect	Medium defect	High defect	High defect	0-1	5-7	8-10	Very low defect	Medium defect	High defect	High defect
15	Very low defect	Medium defect	Very high defect	High defect	0-1	5-7	11-25	Very low defect	Medium defect	Very high defect	High defect
16	Very low defect	High defect	Very low defect	Low defect	0-1	8-10	0-1	Very low defect	High defect	Very low defect	Low defect
17	Very low defect	High defect	Low defect	Medium defect	0-1	8-10	2-4	Very low defect	High defect	Low defect	Medium defect
18	Very low defect	High defect	Medium defect	Medium defect	0-1	8-10	5-7	Very low defect	High defect	Medium defect	Medium defect
19	Very low defect	High defect	High defect	Medium defect	0-1	8-10	8-10	Very low defect	High defect	High defect	Medium defect
20	Very low defect	High defect	Very high defect	High defect	0-1	8-10	11-25	Very low defect	High defect	Very high defect	High defect
21	Very low defect	Very high defect	Very low defect	Low defect	0-1	11-25	0-1	Very low defect	Very high defect	Very low defect	Low defect
22	Very low defect	Very high defect	Low defect	Medium defect	0-1	11-25	2-4	Very low defect	Very high defect	Low defect	Medium defect
23	Very low defect	Very high defect	Medium defect	Medium defect	0-1	11-25	5-7	Very low defect	Very high defect	Medium defect	Medium defect
24	Very low defect	Very high defect	High defect	High defect	0-1	11-25	8-10	Very low defect	Very high defect	High defect	High defect
25	Very low defect	Very high defect	Very high defect	Very high defect	0-1	11-25	11-25	Very low defect	Very high defect	Very high defect	Very high defect

Table 6.13 Results of testing the proposed system (F1) (continued)

Identified fuzzy rule bases					Numerical value input			Results of proposed system			
Rule	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**	**f_{11}**	**f_{12}**	**f_{13}**	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**
26	Low defect	Very low defect	Very low defect	Very low defect	2-4	0-1	0-1	Low defect	Very low defect	Very low defect	Very low defect
27	Low defect	Very low defect	Low defect	Low defect	2-4	0-1	2-4	Low defect	Very low defect	Low defect	Low defect
28	Low defect	Very low defect	Medium defect	Medium defect	2-4	0-1	5-7	Low defect	Very low defect	Medium defect	Medium defect
29	Low defect	Very low defect	High defect	Medium defect	2-4	0-1	8-10	Low defect	Very low defect	High defect	Medium defect
30	Low defect	Very low defect	Very high defect	High defect	2-4	0-1	11-25	Low defect	Very low defect	Very high defect	High defect
31	Low defect	Low defect	Very low defect	Low defect	2-4	2-4	0-1	Low defect	Low defect	Very low defect	Low defect
32	Low defect	Low defect	Low defect	Low defect	2-4	2-4	2-4	Low defect	Low defect	Low defect	Low defect
33	Low defect	Low defect	Medium defect	Medium defect	2-4	2-4	5-7	Low defect	Low defect	Medium defect	Medium defect
34	Low defect	Low defect	High defect	Medium defect	2-4	2-4	8-10	Low defect	Low defect	High defect	Medium defect
35	Low defect	Low defect	Very high defect	High defect	2-4	2-4	11-25	Low defect	Low defect	Very high defect	High defect
36	Low defect	Medium defect	Very low defect	Low defect	2-4	5-7	0-1	Low defect	Medium defect	Very low defect	Low defect
37	Low defect	Medium defect	Low defect	Low defect	2-4	5-7	2-4	Low defect	Medium defect	Low defect	Low defect
38	Low defect	Medium defect	Medium defect	Medium defect	2-4	5-7	5-7	Low defect	Medium defect	Medium defect	Medium defect
39	Low defect	Medium defect	High defect	High defect	2-4	5-7	8-10	Low defect	Medium defect	High defect	High defect
40	Low defect	Medium defect	Very high defect	Very high defect	2-4	5-7	11-25	Low defect	Medium defect	Very high defect	Very high defect
41	Low defect	High defect	Very low defect	Low defect	2-4	8-10	0-1	Low defect	High defect	Very low defect	Low defect
42	Low defect	High defect	Low defect	Medium defect	2-4	8-10	2-4	Low defect	High defect	Low defect	Medium defect
43	Low defect	High defect	Medium defect	Medium defect	2-4	8-10	5-7	Low defect	High defect	Medium defect	Medium defect
44	Low defect	High defect	High defect	High defect	2-4	8-10	8-10	Low defect	High defect	High defect	High defect
45	Low defect	High defect	Very high defect	Very high defect	2-4	8-10	11-25	Low defect	High defect	Very high defect	Very high defect
46	Low defect	Very high defect	Very low defect	Low defect	2-4	11-25	0-1	Low defect	Very high defect	Very low defect	Low defect
47	Low defect	Very high defect	Low defect	Medium defect	2-4	11-25	2-4	Low defect	Very high defect	Low defect	Medium defect
48	Low defect	Very high defect	Medium defect	Medium defect	2-4	11-25	5-7	Low defect	Very high defect	Medium defect	Medium defect
49	Low defect	Very high defect	High defect	High defect	2-4	11-25	8-10	Low defect	Very high defect	High defect	High defect
50	Low defect	Very high defect	Very high defect	Very high defect	2-4	11-25	11-25	Low defect	Very high defect	Very high defect	Very high defect

Table 6.13 Results of testing the proposed system (F1) (continued)

Identified fuzzy rule bases					Numerical value input			Results of proposed system			
Rule	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**	**f_{11}**	**f_{12}**	**f_{13}**	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**
51	Medium defect	Very low defect	Very low defect	Low defect	5-7	0-1	0-1	Medium defect	Very low defect	Very low defect	Low defect
52	Medium defect	Very low defect	Low defect	Low defect	5-7	0-1	2-4	Medium defect	Very low defect	Low defect	Low defect
53	Medium defect	Very low defect	Medium defect	Medium defect	5-7	0-1	5-7	Medium defect	Very low defect	Medium defect	Medium defect
54	Medium defect	Very low defect	High defect	Medium defect	5-7	0-1	8-10	Medium defect	Very low defect	High defect	Medium defect
55	Medium defect	Very low defect	Very high defect	High defect	5-7	0-1	11-25	Medium defect	Very low defect	Very high defect	High defect
56	Medium defect	Low defect	Very low defect	Low defect	5-7	2-4	0-1	Medium defect	Low defect	Very low defect	Low defect
57	Medium defect	Low defect	Low defect	Low defect	5-7	2-4	2-4	Medium defect	Low defect	Low defect	Low defect
58	Medium defect	Low defect	Medium defect	Medium defect	5-7	2-4	5-7	Medium defect	Low defect	Medium defect	Medium defect
59	Medium defect	Low defect	High defect	Medium defect	5-7	2-4	8-10	Medium defect	Low defect	High defect	Medium defect
60	Medium defect	Low defect	Very high defect	High defect	5-7	2-4	11-25	Medium defect	Low defect	Very high defect	High defect
61	Medium defect	Medium defect	Very low defect	Low defect	5-7	5-7	0-1	Medium defect	Medium defect	Very low defect	Low defect
62	Medium defect	Medium defect	Low defect	Medium defect	5-7	5-7	2-4	Medium defect	Medium defect	Low defect	Medium defect
63	Medium defect	Medium defect	Medium defect	Medium defect	5-7	5-7	5-7	Medium defect	Medium defect	Medium defect	Medium defect
64	Medium defect	Medium defect	High defect	High defect	5-7	5-7	8-10	Medium defect	Medium defect	High defect	High defect
65	Medium defect	Medium defect	Very high defect	Very high defect	5-7	5-7	11-25	Medium defect	Medium defect	Very high defect	Very high defect
66	Medium defect	High defect	Very low defect	Low defect	5-7	8-10	0-1	Medium defect	High defect	Very low defect	Low defect
67	Medium defect	High defect	Low defect	Medium defect	5-7	8-10	2-4	Medium defect	High defect	Low defect	Medium defect
68	Medium defect	High defect	Medium defect	Medium defect	5-7	8-10	5-7	Medium defect	High defect	Medium defect	Medium defect
69	Medium defect	High defect	High defect	High defect	5-7	8-10	8-10	Medium defect	High defect	High defect	High defect
70	Medium defect	High defect	Very high defect	Very high defect	5-7	8-10	11-25	Medium defect	High defect	Very high defect	Very high defect
71	Medium defect	Very high defect	Very low defect	Medium defect	5-7	11-25	0-1	Medium defect	Very high defect	Very low defect	Medium defect
72	Medium defect	Very high defect	Low defect	Medium defect	5-7	11-25	2-4	Medium defect	Very high defect	Low defect	Medium defect
73	Medium defect	Very high defect	Medium defect	High defect	5-7	11-25	5-7	Medium defect	Very high defect	Medium defect	High defect
74	Medium defect	Very high defect	High defect	Very high defect	5-7	11-25	8-10	Medium defect	Very high defect	High defect	Very high defect
75	Medium defect	Very high defect	Very high defect	Very high defect	5-7	11-25	11-25	Medium defect	Very high defect	Very high defect	Very high defect

Table 6.13 Results of testing the proposed system (F1) (continued)

Identified fuzzy rule bases					**Numerical value input**			**Results of proposed system**			
Rule	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**	**f_{11}**	**f_{12}**	**f_{13}**	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**
76	High defect	Very low defect	Very low defect	Low defect	8-10	0-1	0-1	High defect	Very low defect	Very low defect	Low defect
77	High defect	Very low defect	Low defect	Low defect	8-10	0-1	2-4	High defect	Very low defect	Low defect	Low defect
78	High defect	Very low defect	Medium defect	Medium defect	8-10	0-1	5-7	High defect	Very low defect	Medium defect	Medium defect
79	High defect	Very low defect	High defect	High defect	8-10	0-1	8-10	High defect	Very low defect	High defect	High defect
80	High defect	Very low defect	Very high defect	Very high defect	8-10	0-1	11-25	High defect	Very low defect	Very high defect	Very high defect
81	High defect	Low defect	Very low defect	Low defect	8-10	2-4	0-1	High defect	Low defect	Very low defect	Low defect
82	High defect	Low defect	Low defect	Low defect	8-10	2-4	2-4	High defect	Low defect	Low defect	Low defect
83	High defect	Low defect	Medium defect	Medium defect	8-10	2-4	5-7	High defect	Low defect	Medium defect	Medium defect
84	High defect	Low defect	High defect	High defect	8-10	2-4	8-10	High defect	Low defect	High defect	High defect
85	High defect	Low defect	Very high defect	Very high defect	8-10	2-4	11-25	High defect	Low defect	Very high defect	Very high defect
86	High defect	Medium defect	Very low defect	Low defect	8-10	5-7	0-1	High defect	Medium defect	Very low defect	Low defect
87	High defect	Medium defect	Low defect	Medium defect	8-10	5-7	2-4	High defect	Medium defect	Low defect	Medium defect
88	High defect	Medium defect	Medium defect	Medium defect	8-10	5-7	5-7	High defect	Medium defect	Medium defect	Medium defect
89	High defect	Medium defect	High defect	High defect	8-10	5-7	8-10	High defect	Medium defect	High defect	High defect
90	High defect	Medium defect	Very high defect	Very high defect	8-10	5-7	11-25	High defect	Medium defect	Very high defect	Very high defect
91	High defect	High defect	Very low defect	Low defect	8-10	8-10	0-1	High defect	High defect	Very low defect	Low defect
92	High defect	High defect	Low defect	Medium defect	8-10	8-10	2-4	High defect	High defect	Low defect	Medium defect
93	High defect	High defect	Medium defect	Medium defect	8-10	8-10	5-7	High defect	High defect	Medium defect	Medium defect
94	High defect	High defect	High defect	High defect	8-10	8-10	8-10	High defect	High defect	High defect	High defect
95	High defect	High defect	Very high defect	Very high defect	8-10	8-10	11-25	High defect	High defect	Very high defect	Very high defect
96	High defect	Very high defect	Very low defect	Medium defect	8-10	11-25	0-1	High defect	Very high defect	Very low defect	Medium defect
97	High defect	Very high defect	Low defect	Medium defect	8-10	11-25	2-4	High defect	Very high defect	Low defect	Medium defect
98	High defect	Very high defect	Medium defect	High defect	8-10	11-25	5-7	High defect	Very high defect	Medium defect	High defect
99	High defect	Very high defect	High defect	High defect	8-10	11-25	8-10	High defect	Very high defect	High defect	High defect
100	High defect	Very high defect	Very high defect	Very high defect	8-10	11-25	11-25	High defect	Very high defect	Very high defect	Very high defect

Table 6.13 Results of testing the proposed system (F1) (continued)

Identified fuzzy rule bases					Numerical value input			Results of proposed system			
Rule	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**	**f_{11}**	**f_{12}**	**f_{13}**	**IF f_{11} is**	**AND f_{12} is**	**AND f_{13} is**	**THEN F1 is**
101	Very high defect	Very low defect	Very low defect	Low defect	11-25	0-1	0-1	Very high defect	Very low defect	Very low defect	Low defect
102	Very high defect	Very low defect	Low defect	Medium defect	11-25	0-1	2-4	Very high defect	Very low defect	Low defect	Medium defect
103	Very high defect	Very low defect	Medium defect	Medium defect	11-25	0-1	5-7	Very high defect	Very low defect	Medium defect	Medium defect
104	Very high defect	Very low defect	High defect	High defect	11-25	0-1	8-10	Very high defect	Very low defect	High defect	High defect
105	Very high defect	Very low defect	Very high defect	Very high defect	11-25	0-1	11-25	Very high defect	Very low defect	Very high defect	Very high defect
106	Very high defect	Low defect	Very low defect	Low defect	11-25	2-4	0-1	Very high defect	Low defect	Very low defect	Low defect
107	Very high defect	Low defect	Low defect	Medium defect	11-25	2-4	2-4	Very high defect	Low defect	Low defect	Medium defect
108	Very high defect	Low defect	Medium defect	Medium defect	11-25	2-4	5-7	Very high defect	Low defect	Medium defect	Medium defect
109	Very high defect	Low defect	High defect	High defect	11-25	2-4	8-10	Very high defect	Low defect	High defect	High defect
110	Very high defect	Low defect	Very high defect	Very high defect	11-25	2-4	11-25	Very high defect	Low defect	Very high defect	Very high defect
111	Very high defect	Medium defect	Very low defect	Medium defect	11-25	5-7	0-1	Very high defect	Medium defect	Very low defect	Medium defect
112	Very high defect	Medium defect	Low defect	Medium defect	11-25	5-7	2-4	Very high defect	Medium defect	Low defect	Medium defect
113	Very high defect	Medium defect	Medium defect	Medium defect	11-25	5-7	5-7	Very high defect	Medium defect	Medium defect	Medium defect
114	Very high defect	Medium defect	High defect	High defect	11-25	5-7	8-10	Very high defect	Medium defect	High defect	High defect
115	Very high defect	Medium defect	Very high defect	Very high defect	11-25	5-7	11-25	Very high defect	Medium defect	Very high defect	Very high defect
116	Very high defect	High defect	Very low defect	Medium defect	11-25	8-10	0-1	Very high defect	High defect	Very low defect	Medium defect
117	Very high defect	High defect	Low defect	Medium defect	11-25	8-10	2-4	Very high defect	High defect	Low defect	Medium defect
118	Very high defect	High defect	Medium defect	Medium defect	11-25	8-10	5-7	Very high defect	High defect	Medium defect	Medium defect
119	Very high defect	High defect	High defect	High defect	11-25	8-10	8-10	Very high defect	High defect	High defect	High defect
120	Very high defect	High defect	Very high defect	Very high defect	11-25	8-10	11-25	Very high defect	High defect	Very high defect	Very high defect
121	Very high defect	Very high defect	Very low defect	Medium defect	11-25	11-25	0-1	Very high defect	Very high defect	Very low defect	Medium defect
122	Very high defect	Very high defect	Low defect	Medium defect	11-25	11-25	2-4	Very high defect	Very high defect	Low defect	Medium defect
123	Very high defect	Very high defect	Medium defect	High defect	11-25	11-25	5-7	Very high defect	Very high defect	Medium defect	High defect
124	Very high defect	Very high defect	High defect	High defect	11-25	11-25	8-10	Very high defect	Very high defect	High defect	High defect
125	Very high defect	Very high defect	Very high defect	Very high defect	11-25	11-25	11-25	Very high defect	Very high defect	Very high defect	Very high defect

Table 6.14 Results of testing the proposed system (F2)

Identified fuzzy rule bases				Numerical value input		Results of proposed system		
Rule	**IF f_{21} is**	**AND f_{22} is**	**THEN F2 is**	**f_{21}**	**f_{22}**	**IF f_{21} is**	**AND f_{22} is**	**THEN F2 is**
1	Very low defect	Very low defect	Very low defect	0-2000	0-1	Very low defect	Very low defect	Very low defect
2	Very low defect	Low defect	Very low defect	0-2000	2-4	Very low defect	Low defect	Very low defect
3	Very low defect	Medium defect	Low defect	0-2000	5-7	Very low defect	Medium defect	Low defect
4	Very low defect	High defect	Medium defect	0-2000	8-10	Very low defect	High defect	Medium defect
5	Very low defect	Very high defect	High defect	0-2000	11-25	Very low defect	Very high defect	High defect
6	Low defect	Very low defect	Very low defect	2001-4000	0-1	Low defect	Very low defect	Very low defect
7	Low defect	Low defect	Low defect	2001-4000	2-4	Low defect	Low defect	Low defect
8	Low defect	Medium defect	Low defect	2001-4000	5-7	Low defect	Medium defect	Low defect
9	Low defect	High defect	Medium defect	2001-4000	8-10	Low defect	High defect	Medium defect
10	Low defect	Very high defect	High defect	2001-4000	11-25	Low defect	Very high defect	High defect
11	Medium defect	Very low defect	Low defect	4001-7000	0-1	Medium defect	Very low defect	Low defect
12	Medium defect	Low defect	Low defect	4001-7000	2-4	Medium defect	Low defect	Low defect
13	Medium defect	Medium defect	Medium defect	4001-7000	5-7	Medium defect	Medium defect	Medium defect
14	Medium defect	High defect	High defect	4001-7000	8-10	Medium defect	High defect	High defect
15	Medium defect	Very high defect	High defect	4001-7000	11-25	Medium defect	Very high defect	High defect
16	High defect	Very low defect	Low defect	7001-10000	0-1	High defect	Very low defect	Low defect
17	High defect	Low defect	Medium defect	7001-10000	2-4	High defect	Low defect	Medium defect
18	High defect	Medium defect	Medium defect	7001-10000	5-7	High defect	Medium defect	Medium defect
19	High defect	High defect	High defect	7001-10000	8-10	High defect	High defect	High defect
20	High defect	Very high defect	Very high defect	7001-10000	11-25	High defect	Very high defect	Very high defect
21	Very high defect	Very low defect	Low defect	10001-16000	0-1	Very high defect	Very low defect	Low defect
22	Very high defect	Low defect	Medium defect	10001-16000	2-4	Very high defect	Low defect	Medium defect
23	Very high defect	Medium defect	Medium defect	10001-16000	5-7	Very high defect	Medium defect	Medium defect
24	Very high defect	High defect	High defect	10001-16000	8-10	Very high defect	High defect	High defect
25	Very high defect	Very high defect	Very high defect	10001-16000	11-25	Very high defect	Very high defect	Very high defect

Table 6.15 Results of testing the proposed system (F3)

Identified fuzzy rule bases				Numerical value input		Results of proposed system		
Rule	**IF f_{31} is**	**AND f_{32} is**	**THEN F3 is**	**f_{31}**	**f_{32}**	**IF f_{31} is**	**AND f_{32} is**	**THEN F3 is**
1	Very low defect	Very low defect	Very low defect	0-8	0-1	Very low defect	Very low defect	Very low defect
2	Very low defect	Low defect	Low defect	0-8	2-4	Very low defect	Low defect	Low defect
3	Very low defect	Medium defect	Medium defect	0-8	5-7	Very low defect	Medium defect	Medium defect
4	Very low defect	High defect	High defect	0-8	8-10	Very low defect	High defect	High defect
5	Very low defect	Very high defect	Very high defect	0-8	11-25	Very low defect	Very high defect	Very high defect
6	Low defect	Very low defect	Very low defect	9-19	0-1	Low defect	Very low defect	Very low defect
7	Low defect	Low defect	Low defect	9-19	2-4	Low defect	Low defect	Low defect
8	Low defect	Medium defect	Medium defect	9-19	5-7	Low defect	Medium defect	Medium defect
9	Low defect	High defect	High defect	9-19	8-10	Low defect	High defect	High defect
10	Low defect	Very high defect	Very high defect	9-19	11-25	Low defect	Very high defect	Very high defect
11	Medium defect	Very low defect	Low defect	20-32	0-1	Medium defect	Very low defect	Low defect
12	Medium defect	Low defect	Low defect	20-32	2-4	Medium defect	Low defect	Low defect
13	Medium defect	Medium defect	Medium defect	20-32	5-7	Medium defect	Medium defect	Medium defect
14	Medium defect	High defect	High defect	20-32	8-10	Medium defect	High defect	High defect
15	Medium defect	Very high defect	Very high defect	20-32	11-25	Medium defect	Very high defect	Very high defect
16	High defect	Very low defect	Low defect	33-43	0-1	High defect	Very low defect	Low defect
17	High defect	Low defect	Low defect	33-43	2-4	High defect	Low defect	Low defect
18	High defect	Medium defect	Medium defect	33-43	5-7	High defect	Medium defect	Medium defect
19	High defect	High defect	High defect	33-43	8-10	High defect	High defect	High defect
20	High defect	Very high defect	Very high defect	33-43	11-25	High defect	Very high defect	Very high defect
21	Very high defect	Very low defect	Low defect	44-64	0-1	Very high defect	Very low defect	Low defect
22	Very high defect	Low defect	Low defect	44-64	2-4	Very high defect	Low defect	Low defect
23	Very high defect	Medium defect	Medium defect	44-64	5-7	Very high defect	Medium defect	Medium defect
24	Very high defect	High defect	High defect	44-64	8-10	Very high defect	High defect	High defect
25	Very high defect	Very high defect	Very high defect	44-64	11-25	Very high defect	Very high defect	Very high defect

Table 6.16 Results of testing the proposed system (F4)

Identified fuzzy rule bases				Numerical value input		Results of proposed system		
Rule	**IF f_{41} is**	**AND f_{42} is**	**THEN F4 is**	**f_{41}**	**f_{42}**	**IF f_{41} is**	**AND f_{42} is**	**THEN F4 is**
1	Very low defect	Very low defect	Very low defect	0-1	0-1	Very low defect	Very low defect	Very low defect
2	Very low defect	Low defect	Low defect	0-1	2-3	Very low defect	Low defect	Low defect
3	Very low defect	Medium defect	Medium defect	0-1	4-7	Very low defect	Medium defect	Medium defect
4	Very low defect	High defect	High defect	0-1	8-10	Very low defect	High defect	High defect
5	Very low defect	Very high defect	Very high defect	0-1	11-25	Very low defect	Very high defect	Very high defect
6	Low defect	Very low defect	Very low defect	2-4	0-1	Low defect	Very low defect	Very low defect
7	Low defect	Low defect	Low defect	2-4	2-3	Low defect	Low defect	Low defect
8	Low defect	Medium defect	Medium defect	2-4	4-7	Low defect	Medium defect	Medium defect
9	Low defect	High defect	High defect	2-4	8-10	Low defect	High defect	High defect
10	Low defect	Very high defect	Very high defect	2-4	11-25	Low defect	Very high defect	Very high defect
11	Medium defect	Very low defect	Low defect	5-7	0-1	Medium defect	Very low defect	Low defect
12	Medium defect	Low defect	Medium defect	5-7	2-3	Medium defect	Low defect	Medium defect
13	Medium defect	Medium defect	Medium defect	5-7	4-7	Medium defect	Medium defect	Medium defect
14	Medium defect	High defect	High defect	5-7	8-10	Medium defect	High defect	High defect
15	Medium defect	Very high defect	Very high defect	5-7	11-25	Medium defect	Very high defect	Very high defect
16	High defect	Very low defect	Low defect	8-10	0-1	High defect	Very low defect	Low defect
17	High defect	Low defect	Medium defect	8-10	2-3	High defect	Low defect	Medium defect
18	High defect	Medium defect	Medium defect	8-10	4-7	High defect	Medium defect	Medium defect
19	High defect	High defect	High defect	8-10	8-10	High defect	High defect	High defect
20	High defect	Very high defect	Very high defect	8-10	11-25	High defect	Very high defect	Very high defect
21	Very high defect	Very low defect	Medium defect	11-25	0-1	Very high defect	Very low defect	Medium defect
22	Very high defect	Low defect	Medium defect	11-25	2-3	Very high defect	Low defect	Medium defect
23	Very high defect	Medium defect	High defect	11-25	4-7	Very high defect	Medium defect	High defect
24	Very high defect	High defect	High defect	11-25	8-10	Very high defect	High defect	High defect
25	Very high defect	Very high defect	Very high defect	11-25	11-25	Very high defect	Very high defect	Very high defect

CHAPTER VII
EXPERIMENTAL SYSTEM, VERIFICATION AND VALIDATION

7.1 Introduction

This chapter aims to prove the possibility of conceptual framework for developing defect evaluation system supporting visual inspection in architectural work. The digital image processing technique was applied to develop the defect detection and quantification system for subjective visual inspection. Moreover, the fuzzy logic and knowledge management theories were applied to develop the defect level evaluation system. The proposed system needs to be experimented for determining limitations of implementation on an actual construction site. The environments are controlled to ensure that the proposed system can accurately analyze before comparing with visual inspection by inspectors. Especially, the digital image processing technique was implemented to overcome problems in construction industry. Therefore, the contents in this chapter include the experimental system and verification for testing the accuracy of defect detection and quantification system. After that both defect detection and quantification system and defect level evaluation system were validated by comparing with visual inspection by inspectors. There are details as follows.

7.2 Experimental system

This section aims to study the conditions of real environment in construction site for determining what affect to the potential of system. Especially, defect detection and quantification system is developed from digital image processing technique. We have to determine a method to control these limitations. Therefore, the following topics are described to (1) several conditions of real environment in construction site with system implementation, and (2) experimental system in conditions of lighting value and camera distance.

7.2.1 Conditions of real environment in construction site

Implementation of the system in the real environment in construction site revealed certain problems and limitations. We determine a method that controls these limitations in system implementation in correspondence with actual conditions on the construction site. Next we explain what conditions we encounter in the real environment in construction site, and which conditions may affect to the accuracy of detecting defect positions from defect detection and quantification system.

There are several conditions to be considered, as revealed in the case study of tiling work inspection on an actual construction site, including, tile appearance, light value, camera distance, image size and angle of photograph.

7.2.1.1 Tile appearance

Tile manufacturers have many specifications for tiles such as material types, size, shape, colour and pattern. Our proposed system was tested on each appearance specification as follows.

7.2.1.1.1 Tile size

There are many tile sizes in use. The standards of tile size in current production are shown in Table 7.1. In fact, the proposed algorithms in our system can be applied to all tile sizes, but on an actual construction site, there is a limitation in that the image acquisition panel area is restricted by the width of the room and lens specifications.

Table 7.1 Standard tile sizes

Tile size (inch)	Tile size (cm)	Tile size (inch)	Tile size (cm)
4x4	10x10	12x12	30x30
6x6	15x15	13x13	33x33
8x8	20x20	16x16	40x40
8x10	20x25	18x18	45x45
8x12	20x30	20x20	50x50
8x16	20x40	24x24	60x60

This study used a Macro lens to reduce the problem of image distortion. Macro lens is limited in that the images can be taken cover a narrow area. To capture a larger area, it requires more distance. In actual situations, especially bathrooms and kitchens have very limited area. Therefore, the proposed system in this study was only able to test tile sizes of 4”x4” or 10x10 cm, and 8”x8” or 20x20 cm. However, other tile sizes can be used when the proposed system supports an un-distorted image method allowing the use of other specifications of lens and camera distances.

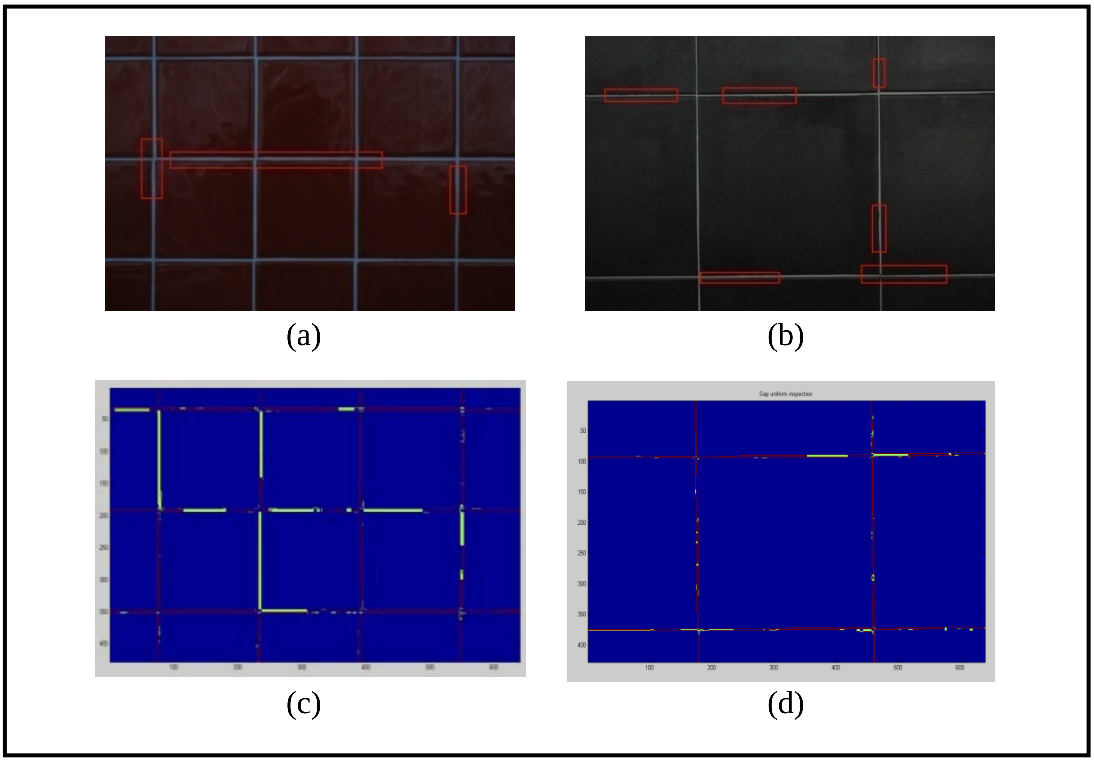


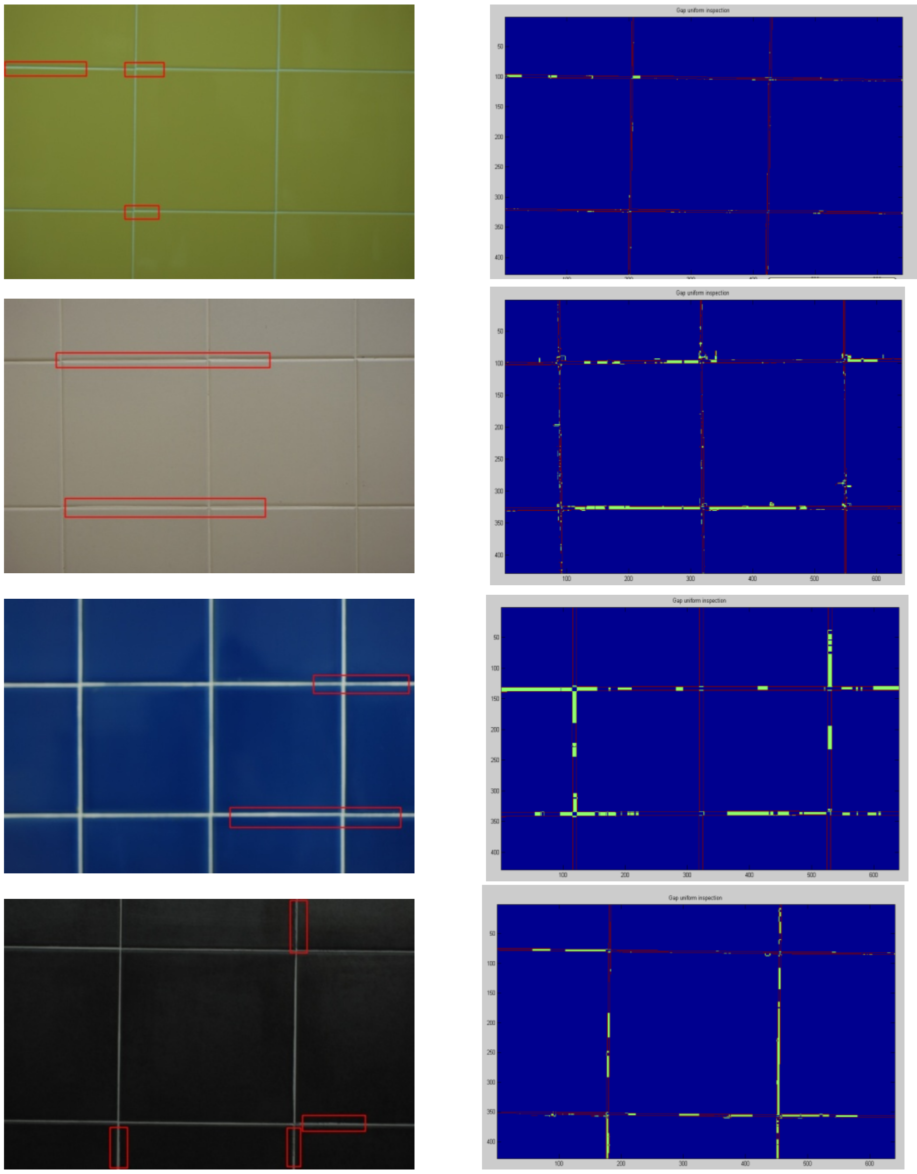
Figure 7.1 Examples of tile size: (a) 4”x4” and (b) 8”x8”, and defect detection of tile size of (c) 4”x4” and (b) 8”x8” at camera distance 1 m

7.2.1.1.2 Tile shape

As square and rectangular tile shapes are the most commonly used, our algorithm is developed to support these two common shapes. We suggest that the different algorithms should be developed if require to support other shapes.

7.2.1.1.3 Tile color

The proposed system can be used with all types of color. In practice, a contrast between tile color and gap color is very important. The edge detection is quite clearly. If the tile color and gap color are different.



(b) Original image (a) Detected image

Figure 7.2 Example of tile color detection

7.2.1.1.4 Tile pattern

Tiles may be colored or patterned. The proposed system can support tile which is colored certainly. In case of patterned tile, tile's pattern is noise that must be removed for simplicity in finding its edge by using digital image processing technique or the developed algorithm. Our method, we develop algorithm to detect edge of tile. However, our algorithm in the current system cannot support in all case. Therefore, the future work will have to find a method to support in all cases of tile pattern.

7.2.1.1.5 Tile alignment

The tile alignment is one of the conditions that system should be concerned. However, the proposed system can only be used with uniform tile alignment.

7.2.1.2 Light value

Lighting is one of the main conditions affecting image acquisition because light value varies on the construction site. A light meter can be used to determine the proper exposure for photography at the construction site. The ISO value, shutter speed and f-number should be selected for an optimum exposure. However, image acquisition still encounters problems due to the image acquisition from different light value will have the different results. Therefore, the experimental system in next topic will explains testing of the proposed system in different light value to determine an optimum light value for highest accuracy.

Figure 7.3 Light meter

7.2.1.3 Camera distance

Figure 5.11 shows that camera distance from the object is related to measurement scale and image size. On actual construction sites, rooms, especially bathrooms and kitchens, tend to be quite narrow, therefore photographs can be taken at a distance of only 0.5 to 2.0 m.

7.2.1.4 Image size

In the same figure (5.11), we can see that image size is related to measurement scale and camera distance from the object. A large image size allows the resolution of the pixel scale in millimeters to be more detailed. However, this also causes of slow image processing.

7.2.1.5 Angle of photograph

The angle of the photograph leads to the perspective of an image. In practical terms, it is difficult to take a photo with the front of the camera placed at a perfect right angle to the object without measurement. This affects the accuracy of the proposed system. Representative images used in this study set the photograph angle by measuring the front of the camera so that it was at a right angle to the object in order to reduce this limitation. However, future work will have to develop a more practical perspective adjustment method to support the proposed system.

As above-mentioned, the conditions of real environment in construction site affect to system implementation, especially the defect detection and quantification system using the digital image processing technique. Therefore, we suggest the methods that are used in our research to control these conditions. For example, the conditions of tile appearance and image size can be controlled by developed algorithms to support the system. The distorted image can be solved by the innovation of lens. Our research uses Macro lens to overcome the distortion of image. In addition, we suggest practical method for taking photo to reduce the limitation of perspective image. The method is recommended to take the photo at a right angle from in front of object. Although, several conditions can be controlled, the conditions of the lighting value and the camera distance still need to find answers that are related to the accuracy of the system. Therefore, we have to experiment the proposed system in vary of lighting value and camera distance to determine the optimum of light value and camera distance for highest accuracy.

7.2.2 Experimental system for defect detection and quantification system

This topic deals with experimental system in the conditions of lighting value and the camera distance. We need to find answers on how much light is influence to the accuracy of the system. The results are used to control the system implementation in real construction site.

7.2.2.1 Experimental method

We use three cases of tile panel. Steps of experiment in each case are shown in Figure 7.4. There are details as follows.

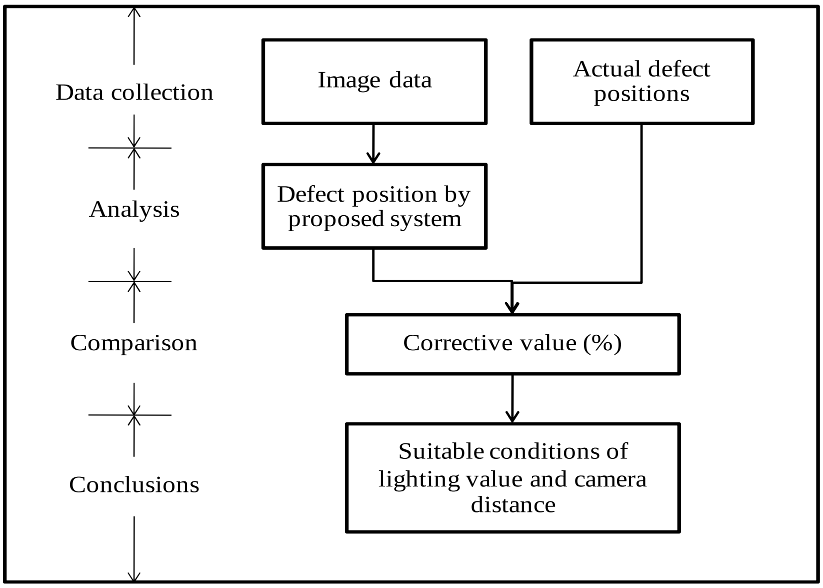


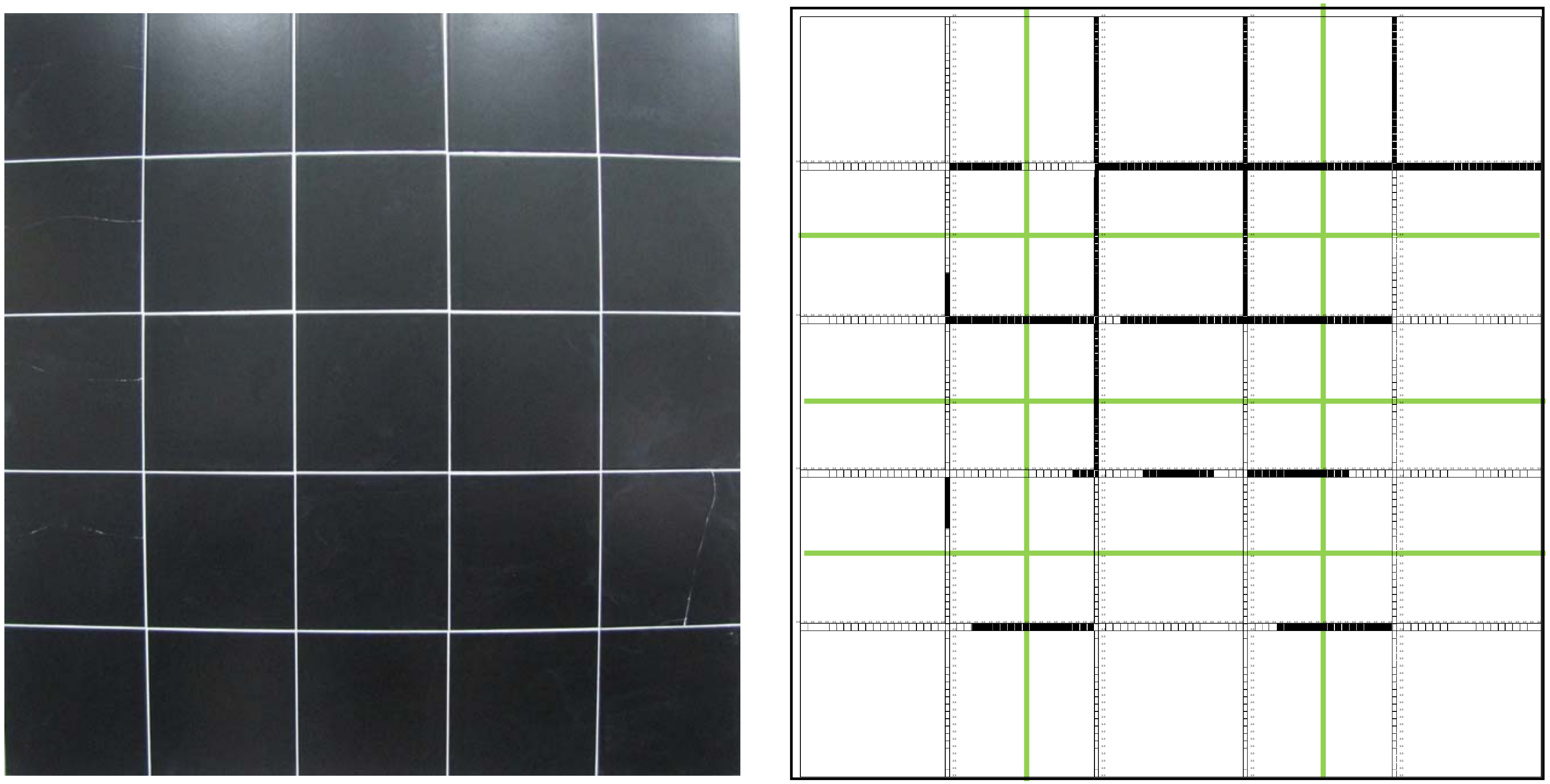
Figure 7.4 Steps of experimental method

We started with data collection. The collected data includes; (1) the actual defect positions are detected by using measurement tool and (2) image data for detecting defect positions by proposed system. Both are used to verify the accuracy of proposed system.

(1) The actual defect positions are detected by using measurement tool

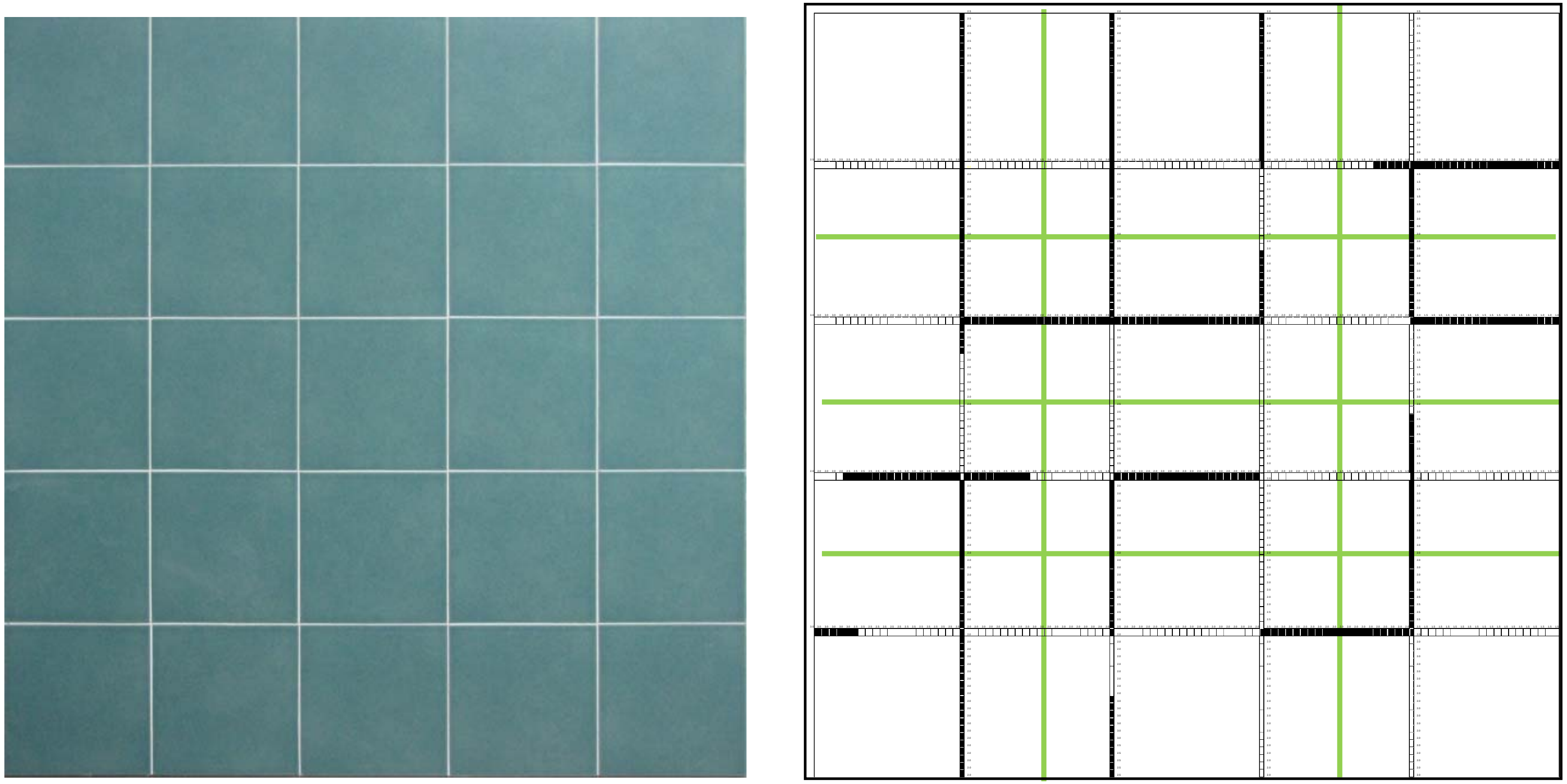
The actual defect positions are detected by using ruler (measurement tool). The smallest scale on a ruler is 0.5 millimeter in Figure 7.5. We measure gap size and record it in every one centimeter along the line. The actual defect positions are the black color area that gap size deviates from tolerance value. The actual defect positions for case 1, 2 and 3 are shown in Figure 7.6, 7.7 and 7.8 respectively.

Figure 7.5 Measurement tool



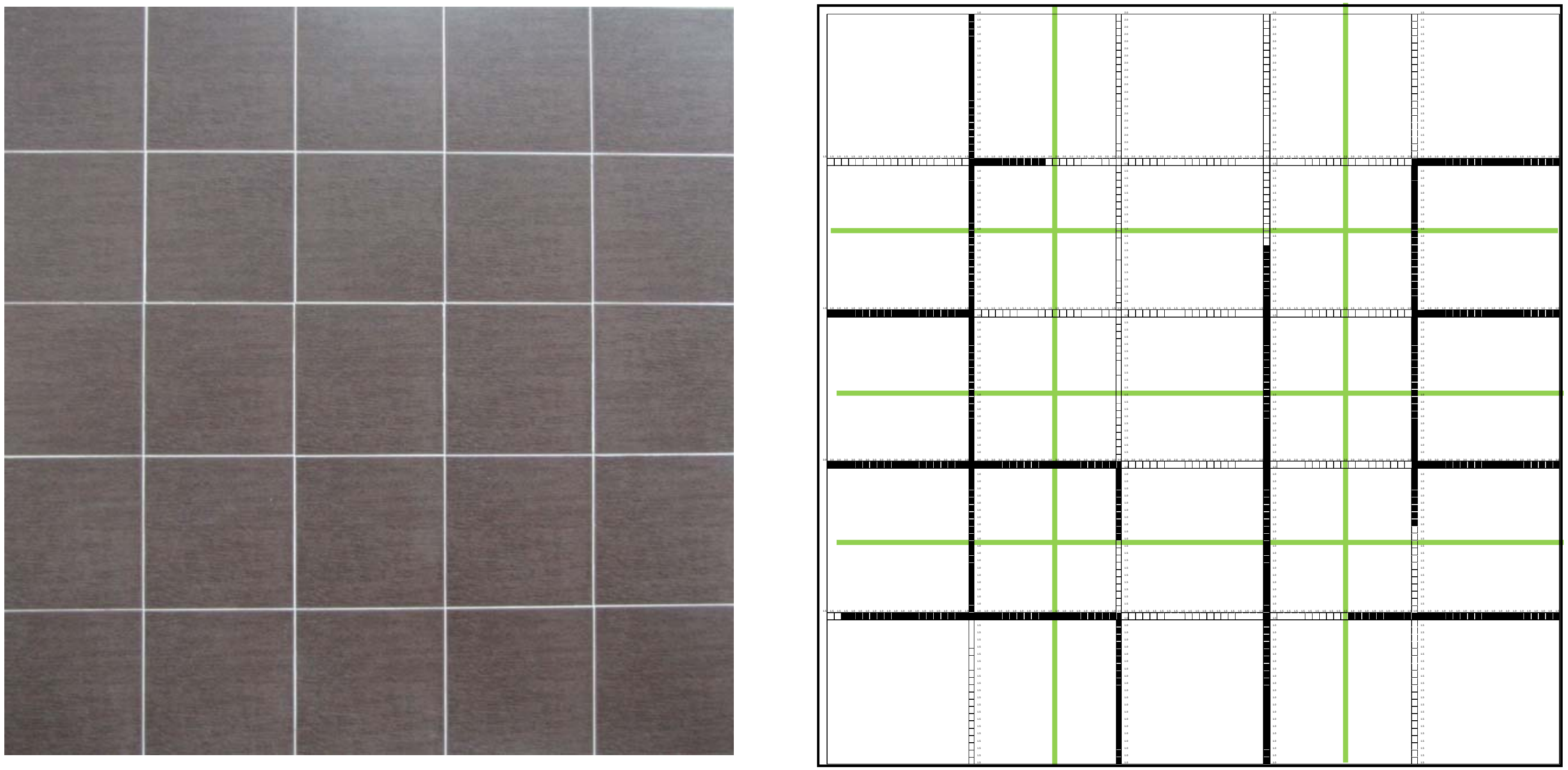
(a) (b)

Figure 7.6 The actual defect positions by measurement tool for case 1 (a) original image and (b) defect positions in black color area (gap size is not equal 3±0.5 mm)



(a) (b)

Figure 7.7 The actual defect positions by measurement tool for case 2 (a) original image and (b) defect positions in black color area (gap size is not equal 2±0.5 mm)



(a) (b)

Figure 7.8 The actual defect positions by measurement tool for case 3 (a) original image and (b) defect positions in black color area (gap size is not equal 2±0.5 mm)

(2) Image data for detecting defect positions by proposed system.

The representative images for testing are collected according to the research constraints. We use Macro lens for overcoming the problems of image distortion. The images are taken from the front of panel for overcoming the problem of perspective image. Our data collection method can be explained as follows.

We collect image data from 3 cases in several criteria (468 representative images per one case) that there are the camera distance (m) at 0.8, 0.9 and 1.0 m, different light value (ISO (100), Shutter speed (4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s), Aperture (4), panel size (1mx1m) and image size (640x428 pixels). The data collection was summarized into Table 7.2. Moreover, we have to collect other conditions that are tile size (cm), standard of gap size (mm) and lighting value around tile in each case (we use light meter). These conditions are used to specify in processing of defect detection and quantification system.

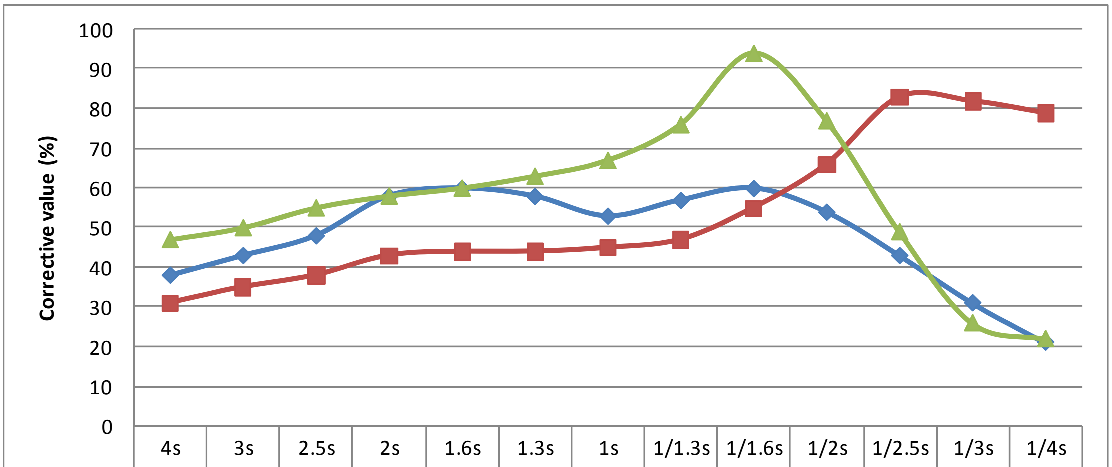
Table 7.2 Summary of data collection

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)
1	0.8	3±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	0.9	3±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	1	3±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
2	0.8	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	0.9	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	1	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
3	0.8	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	0.9	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s
	1	2±0.5	1	20	100	4	4s, 3s, 2,5s, 2s, 1.6s, 1.3s, 1s,1/1.3s,1/1.6s.1/2s,1/2.5s,1/3s and 1/4s

After that the results of defect positions are detected by using proposed system and compared with the actual defect positions. These results are used to determine the suitable conditions that the proposed system has the highest accuracy.

7.2.2.2 Results of experiment

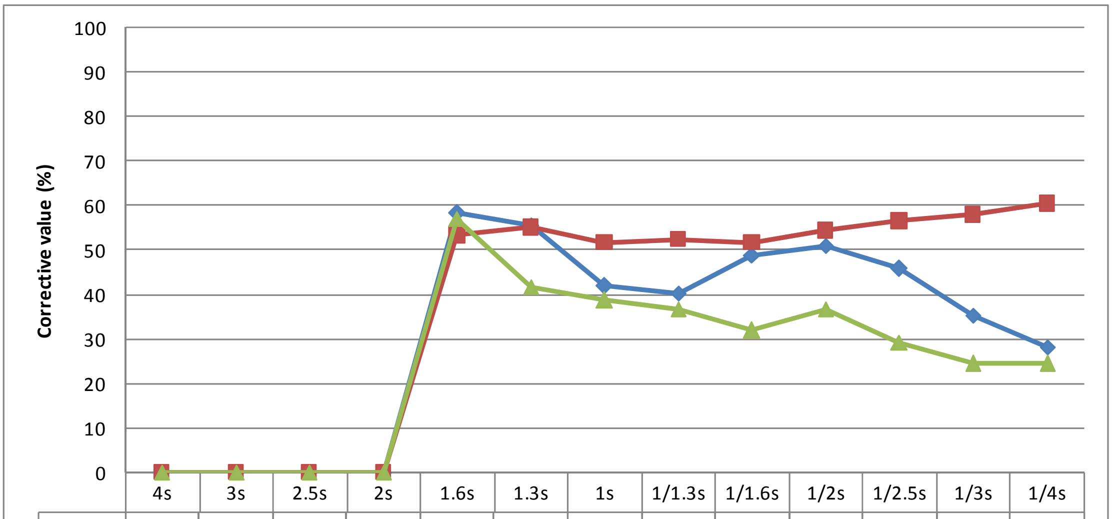
Our initial experiment is to find the suitable condition of camera distance and lighting value for controlling the accuracy of the system implementation before comparing with human inspectors. The details are shown in Table A-1 to A-3 of Appendix A. The results are concluded as follows.



	4s	3s	2.5s	2s	1.6s	1.3s	1s	1/1.3s	1/1.6s	1/2s	1/2.5s	1/3s	1/4s
0.8	38	43	48	58	60	58	53	57	60	54	43	31	21
0.9	31	35	38	43	44	44	45	47	55	66	83	82	79
1	47	50	55	58	60	63	67	76	94	77	49	26	22

Figure 7.9 Results of experiment in conditions of camera distance and light value for case 1

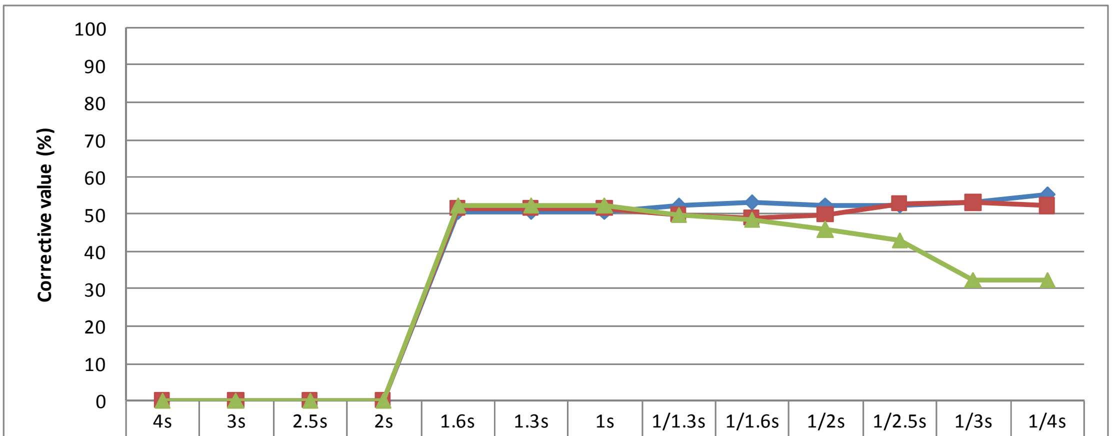
For the experiment of case 1, the conditions of tile size is equal to 20 cm x 20 cm and standard of gap size is equal to 3±0.5 mm. The accuracy of proposed system can be determined by comparing with the actual defect position in Figure 7.6 (we used the measurement tool at the smallest scale is 0.5 millimeter). The results of experiment are shown in Appendix A-1 and Figure 7.9. The representative images were taken the camera distance at 1.0 m, and the lighting value; ISO100, Aperture at 4 and Speed shutter at 1/1.6s, which were given the most accuracy at 94%.



	4s	3s	2.5s	2s	1.6s	1.3s	1s	1/1.3s	1/1.6s	1/2s	1/2.5s	1/3s	1/4s
0.8	0	0	0	0	58	56	42	40	49	51	46	35	28
0.9	0	0	0	0	53	55	52	53	52	54	57	58	60
1	0	0	0	0	57	42	39	37	32	37	29	24	24

Figure 7.10 Results of experiment in conditions of camera distance and light value for case 2

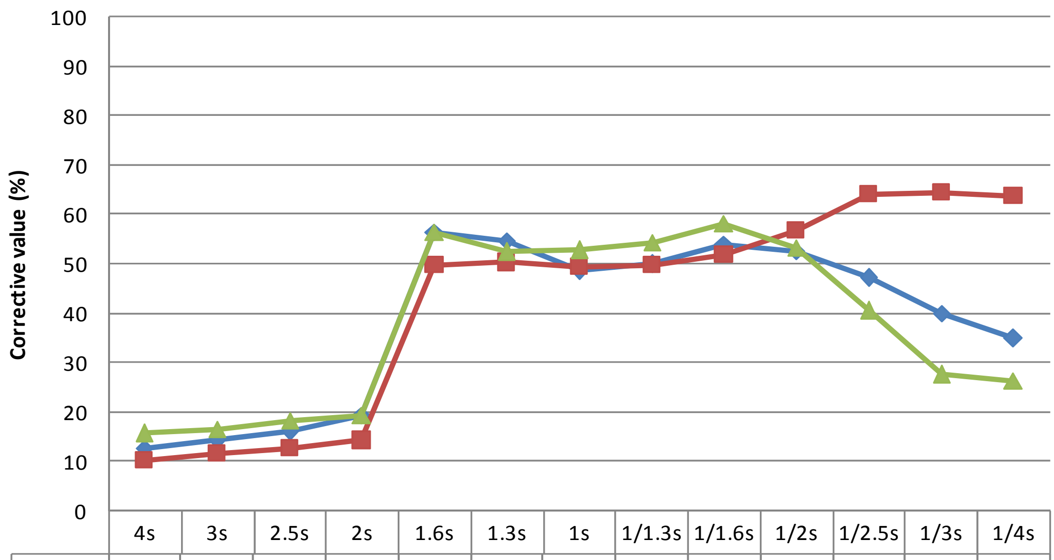
For the experiment of case 2, the conditions of tile size is equal to 20 cm x 20 cm and standard of gap size is equal to 2±0.5 mm. The accuracy of proposed system can be determined by comparing with the actual defect position in Figure 7.7 (we used the measurement tool at the smallest scale is 0.5 millimeter). The results of experiment are shown in Appendix A-2 and Figure 7.10. The representative images were taken the camera distance at 0.90 m, and the lighting value; ISO100, Aperture at 4 and Speed shutter at 1/4s, which were given the most accuracy at 60%.



	4s	3s	2.5s	2s	1.6s	1.3s	1s	1/1.3s	1/1.6s	1/2s	1/2.5s	1/3s	1/4s
0.8	0	0	0	0	51	51	51	53	53	53	53	53	55
0.9	0	0	0	0	52	52	52	50	49	50	53	53	52
1	0	0	0	0	52	52	52	50	49	46	43	32	32

Figure 7.11 Results of experiment in conditions of camera distance and light value for case 3

For the experiment of case 3, the conditions of tile size is equal to 20 cm x 20 cm and standard of gap size is equal to 2±0.5 mm. The accuracy of proposed system can be determined by comparing with the actual defect position in Figure 7.8 (we used the measurement tool at the smallest scale is 0.5 millimeter). The results of experiment are shown in Appendix A-3 and Figure 7.11. The representative images were taken the camera distance at 0.8 m, and the lighting value; ISO100, Aperture at 4 and Speed shutter at 1/4s, which were given the most accuracy at 55%.



	4s	3s	2.5s	2s	1.6s	1.3s	1s	1/1.3s	1/1.6s	1/2s	1/2.5s	1/3s	1/4s
0.8	13	14	16	19	56	55	49	50	54	53	47	40	35
0.9	10	12	13	14	50	50	50	50	52	57	64	64	64
1	16	17	18	19	57	52	53	54	58	53	41	28	26

Figure 7.12 Results of experiment in conditions of camera distance and light value by averaging from three cases

Results of experiment in conditions of camera distance and light value by averaging from three cases can be summarized in Figure 7.12. The representative images were taken the camera distance at 0.9 m, and the lighting value; ISO100, Aperture at 4 and Speed shutter at 1/2.5s, 1/3s and 1/4s, which were given the most accuracy at 64%.

After that we measure the light value around tile for determining the conditions of light value from environment. Light value is measured as a result of reflexive light after light from the source reflected on different colors tiles and return. Therefore, the color of the tiles is a condition that makes light value to distort from source. Figure 7.13, 7.14 and 7.15 show the layout of light value for three cases representatively. These figures are summarized in Table 7.3.

7.2.2.3 Conclusions of experiment

We can summarize that the images of tile should be taken in condition of the camera distance at 0.9 m and the proper exposure for photography about 0.292 to 0.438 cd/m^2 (our experiment use ISO at 100, Aperture at 4 and Speed shutter at 1/2.5s-1/3s), which were given the most accuracy at 64%. These conditions can be used when the light value around tile about 0.043 to 0.292 cd/m^2.

	1/2s Above			1/2s			1/2s			1/2s			1/2s	
1s Left	1/2s Front	1s Right	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s
	4s Below			4s			4s			4s			4s	
	1s			1s			1/2s			1/2s			1/2s	
2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1/2s	1s	2s	1/2s	1s	2s	1/2s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	2s			2s			2s			2s			2s	

(a)

	0.292			0.292			0.292			0.292			0.292	
0.146	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.292			0.292			0.292	
0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.073			0.073			0.073			0.073			0.073	

(b)

Figure 7.13 Layout of lighting value for case 1 (a) lighting value from light meter and (b) lighting value in unit of cd/m^2

	1s Above			1s			1s			1s			1s	
4s Left	1s Front	1s Right	2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	4s Below			4s			4s			4s			2s	
	1s			1s			1s			1s			1s	
4s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	4s			4s			4s			2s			2s	
	1s			1s			1s			1s			1s	
4s	1s	1s	4s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	4s			4s			4s			4s			2s	
	1s			1s			1s			1s			1s	
4s	1s	2s	4s	1s	1s	4s	1s	1s	4s	1s	1s	2s	1s	1s
	4s			4s			4s			4s			2s	
	1s			2s			2s			1s			1s	
4s	2s	2s	4s	2s	2s	4s	2s	1s	4s	1s	1s	2s	1s	1s
	4s			4s			4s			2s			2s	

(a)

	0.146			0.146			0.146			0.146			0.146	
0.036	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.036			0.073	
	0.146			0.146			0.146			0.146			0.146	
0.036	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.073			0.073	
	0.146			0.146			0.146			0.146			0.146	
0.036	0.146	0.146	0.036	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.036			0.073	
	0.146			0.146			0.146			0.146			0.146	
0.036	0.146	0.073	0.036	0.146	0.146	0.036	0.146	0.146	0.036	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.036			0.073	
	0.146			0.073			0.073			0.146			0.146	
0.036	0.073	0.073	0.036	0.073	0.073	0.036	0.073	0.146	0.036	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.073			0.073	

(b)

Figure 7.14 Layout of lighting value for case 2 (a) lighting value from light meter and (b) lighting value in unit of cd/m^2

	1/2s Above			1s			1/2s			1/2s			1/2s	
2s Left	1/2s Front	1s Right	2s	1/2s	1s	2s	1/2s	1s	1s	1/2s	1s	1s	1/2s	1s
	2s Below			4s			4s			2s			2s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1/2s	1s	1s	1/2s	1s	1s	1/2s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1s	1s	1s	1s	1s	1s	1s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	4s			4s			4s			4s			4s	
	1s			1s			1s			1s			1s	
2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s	2s	1s	1s
	4s			4s			4s			4s			4s	

(a)

	0.292			0.146			0.292			0.292			0.292	
0.073	0.292	0.146	0.073	0.292	0.146	0.073	0.292	0.146	0.146	0.292	0.146	0.146	0.292	0.146
	0.073			0.036			0.036			0.073			0.073	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.292	0.146	0.146	0.292	0.146	0.146	0.292	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.146	0.146	0.146	0.146	0.146	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.036			0.036	
	0.146			0.146			0.146			0.146			0.146	
0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146	0.073	0.146	0.146
	0.036			0.036			0.036			0.036			0.036	

(b)

Figure 7.15 Layout of lighting value for case 3 (a) lighting value from light meter and (b) lighting value in unit of cd/m^2

Table 7.3 Summary of lighting value

	Case 1			Case 2			Case 3			All		
Direction	Min	Max	Average	Min	Max	Average	Min	Max	Average	Min	Max	Average
Front	0.146 (1s)	0.292 (1/2s)	0.257	0.073 (2s)	0.146 (1s)	0.137	0.146 (1s)	0.292 (1/2s)	0.193	0.073 (2s)	0.292 (1/2s)	0.196
Above	0.146 (1s)	0.292 (1/2s)	0.193	0.073 (2s)	0.146 (1s)	0.140	0.146 (1s)	0.292 (1/2s)	0.169	0.073 (2s)	0.292 (1/2s)	0.167
Below	0.036 (4s)	0.073 (2s)	0.044	0.036 (4s)	0.073 (2s)	0.046	0.036 (4s)	0.073 (2s)	0.040	0.036 (4s)	0.073 (2s)	0.043
Left	0.073 (2s)	0.146 (1s)	0.076	0.036 (4s)	0.073 (2s)	0.055	0.073 (2s)	0.146 (1s)	0.091	0.073 (2s)	0.146 (1s)	0.074
Right		0.146 (1s)	0.146	0.073 (2s)	0.146 (1s)	0.137		0.146 (1s)	0.146		0.146 (1s)	0.143

7.3 Verification

This section aims to verify that the condition for photography from the above experiment can be used. Therefore, we tested again by taking the representative images in three cases with such conditions. The images of tile are taken in condition of the camera distance at 0.9 m, ISO100, Aperture at 4 and Speed shutter at 1/2.5s. We can use these conditions because the light value around tile is about 0.043-0.292 cd/m^2. Figure 7.16, 7.17 and 7.18 show the results of defect positions which are detected by proposed system. Moreover, Table 7.4, 7.5 and 7.6 show the results of accuracy of proposed system. Case 1 is the most accuracy equal 94%. The accuracy of Case 2 and Case 3 are 74% and 70% respectively. Average of three cases is equal 79%.

The results of verification like the experiment in previous section. Accuracy of case 1 is quite different from the case 2 and 3, although there are similar light value and photography conditions. Therefore, a hypothesis is discovered that is the difference of tile colors which may effect to the results of accuracy in three cases. When we consider these results corresponding theory of digital image processing, the intensity of color in histogram graphs of the black tile and the white gap for Case 1 is more different. It is easy to detect the actual edge of tile on image. Thus, the result of defect position detection is more accuracy. While the intensity of color in histogram graphs of other colors tile and white gap in case 2 and 3 can be not clearly separated, it is difficult to detect the actual edge of tile on image. Although this problem is overcome by morphological method already, it can only overcome in some images. Thus, the result of defect position detection may show error from actual defect position. This limitation is also found in several researches of applying digital image processing technique. At present, it can be overcome in case by case. Therefore, the proposed system is more accuracy and used in several cases when this limitation is overcome in future research.

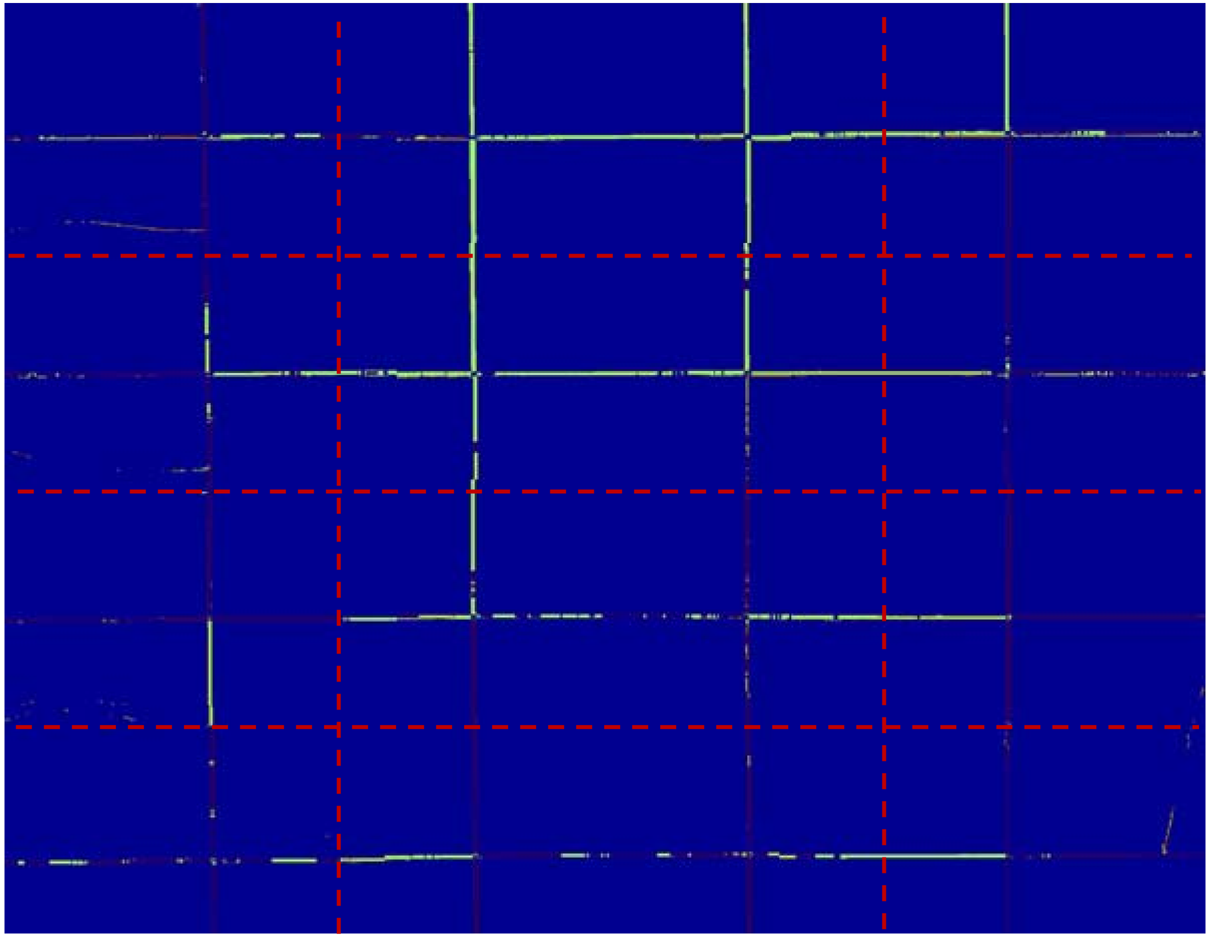


Figure 7.16 Defect positions are detected by proposed system for case 1

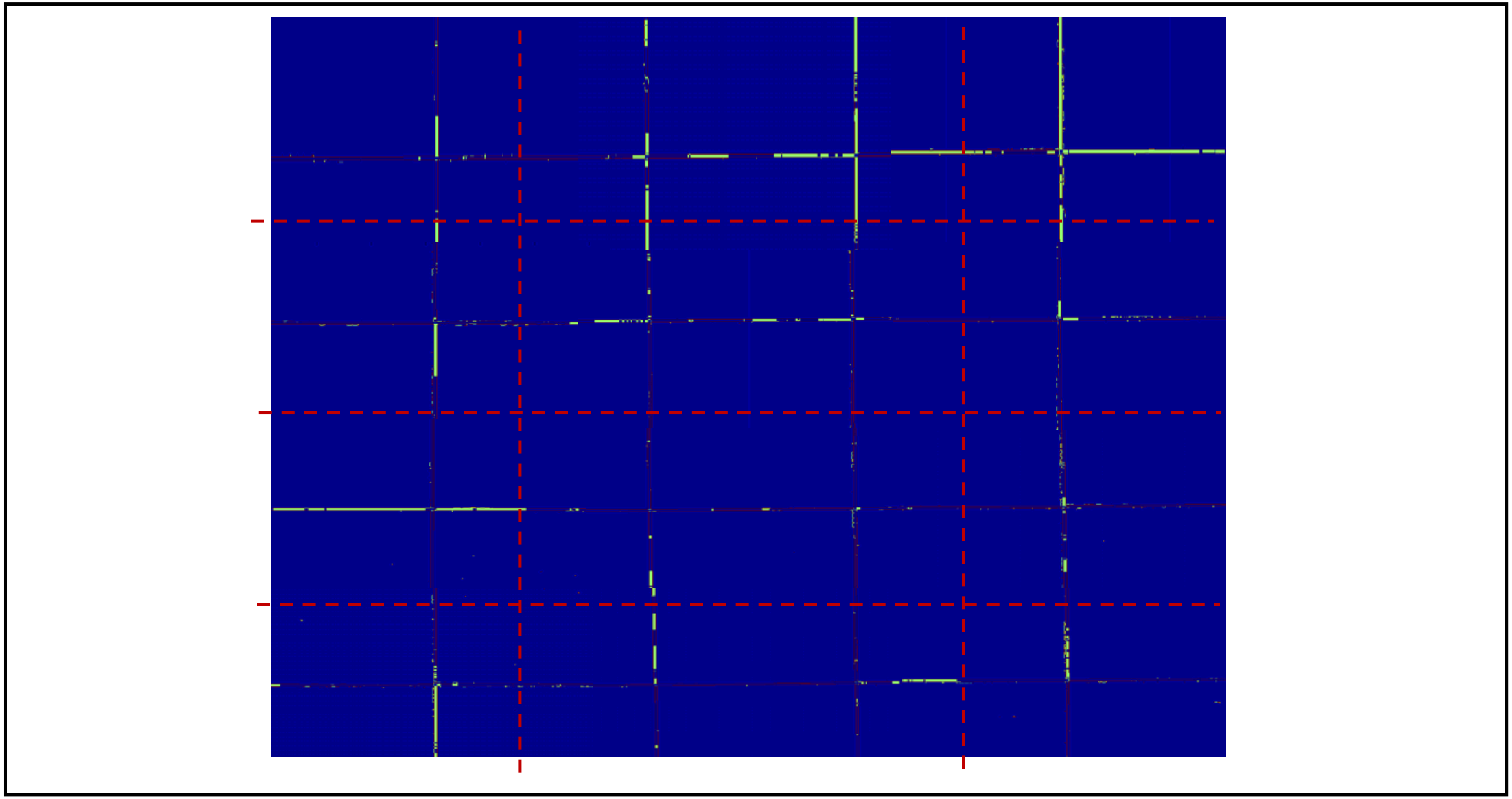


Figure 7.17 Defect positions are detected by proposed system for case 2

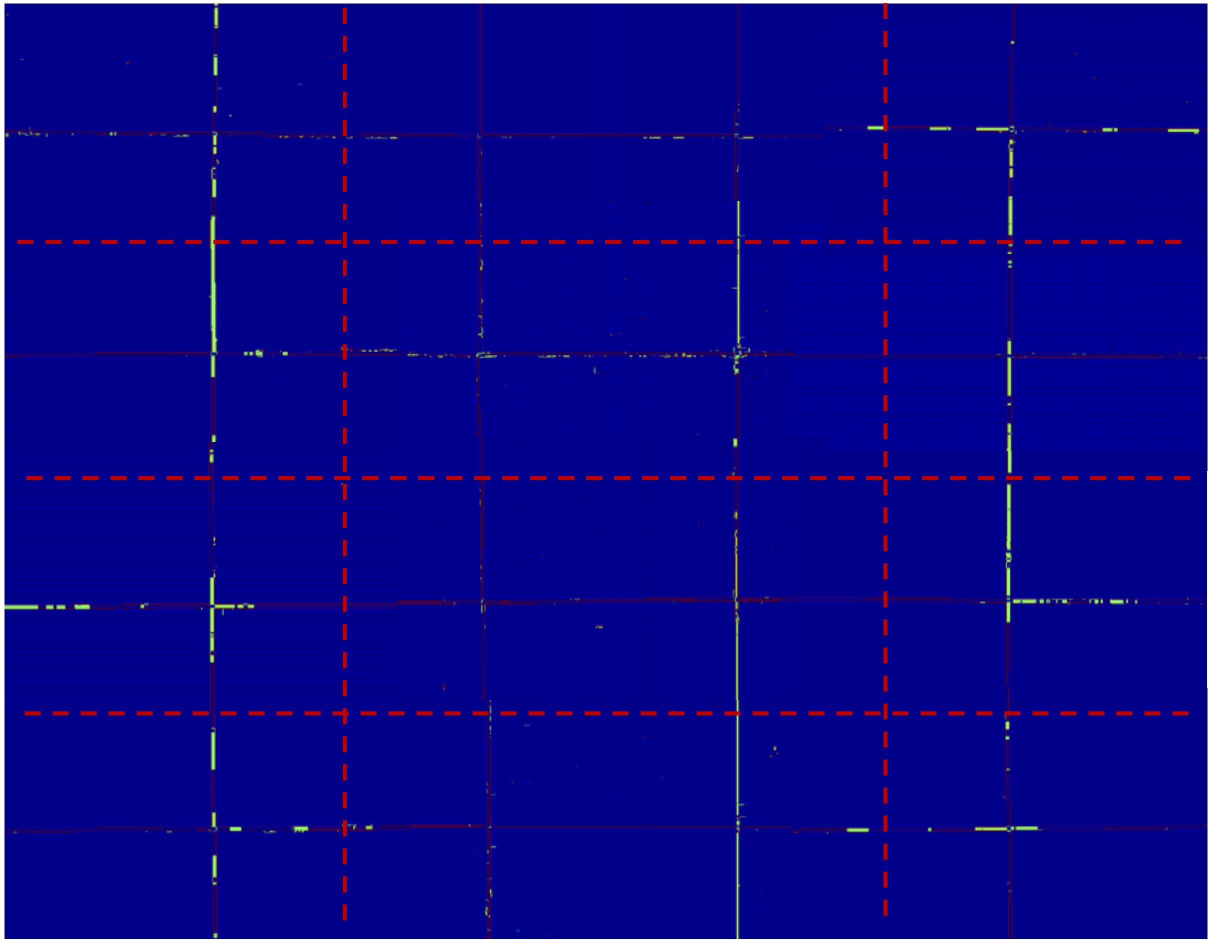


Figure 7.18 Defect positions are detected by proposed system for case 3

Table 7.4 Results of defect detection by proposed system for case 1

Case	Layout	Defect detection from system	Correct result	Total error			Actual number of defect	Correct(%)	Error(%)
				Not correct	Not found	Total			
1	1	1	1	0	0	0	1	100	0
	2	6	6	0	0	0	6	100	0
	3	3	3	0	0	0	3	100	0
	4	2	2	0	0	0	2	100	0
	5	6	6	0	0	0	6	100	0
	6	1	1	0	0	0	1	100	0
	7	1	1	0	0	0	1	100	0
	8	4	4	0	0	0	4	100	0
	9	1	1	0	0	0	1	100	0
	10	2	1	1	0	1	1	50	50
	11	3	2	1	0	1	2	67	33
	12	1	1	0	0	0	1	100	0
	sum	31	29	2	0	2	29	94	6

Table 7.5 Results of defect detection by proposed system for case 2

Case	Layout	Defect detection from system	Correct result	Total error			Actual number of defect	Correct(%)	Error(%)
				Not correct	Not found	Total			
2	1	2	2	0	0	0	2	100	0
	2	6	3	3	0	3	3	50	50
	3	4	3	1	0	1	3	75	25
	4	2	2	0	1	1	3	67	33
	5	4	3	1	1	2	4	60	40
	6	2	2	0	0	0	2	100	0
	7	2	2	0	1	1	3	67	33
	8	2	2	0	0	0	2	100	0
	9	2	2	0	0	0	2	100	0
	10	4	3	1	0	1	3	75	25
	11	4	3	1	0	1	3	75	25
	12	2	2	0	0	0	2	100	0
	sum	36	29	7	3	10	32	74	26

Table 7.6 Results of defect detection by proposed system for case 3

Case	Layout	Defect detection from system	Correct result	Total error			Actual number of defect	Correct(%)	Error(%)
				Not correct	Not found	Total			
3	1	2	2	0	1	1	3	67	33
	2	0	0	0	0	0	0	100	0
	3	3	2	1	0	1	2	67	33
	4	3	2	1	1	2	3	50	50
	5	2	2	0	0	0	2	100	0
	6	3	3	0	0	0	3	100	0
	7	4	4	0	0	0	4	100	0
	8	2	2	0	2	2	4	50	50
	9	3	3	0	0	0	3	100	0
	10	3	2	1	1	2	3	50	50
	11	2	2	0	2	2	4	50	50
	12	3	2	1	0	1	2	67	33
	sum	30	26	4	7	11	33	70	30

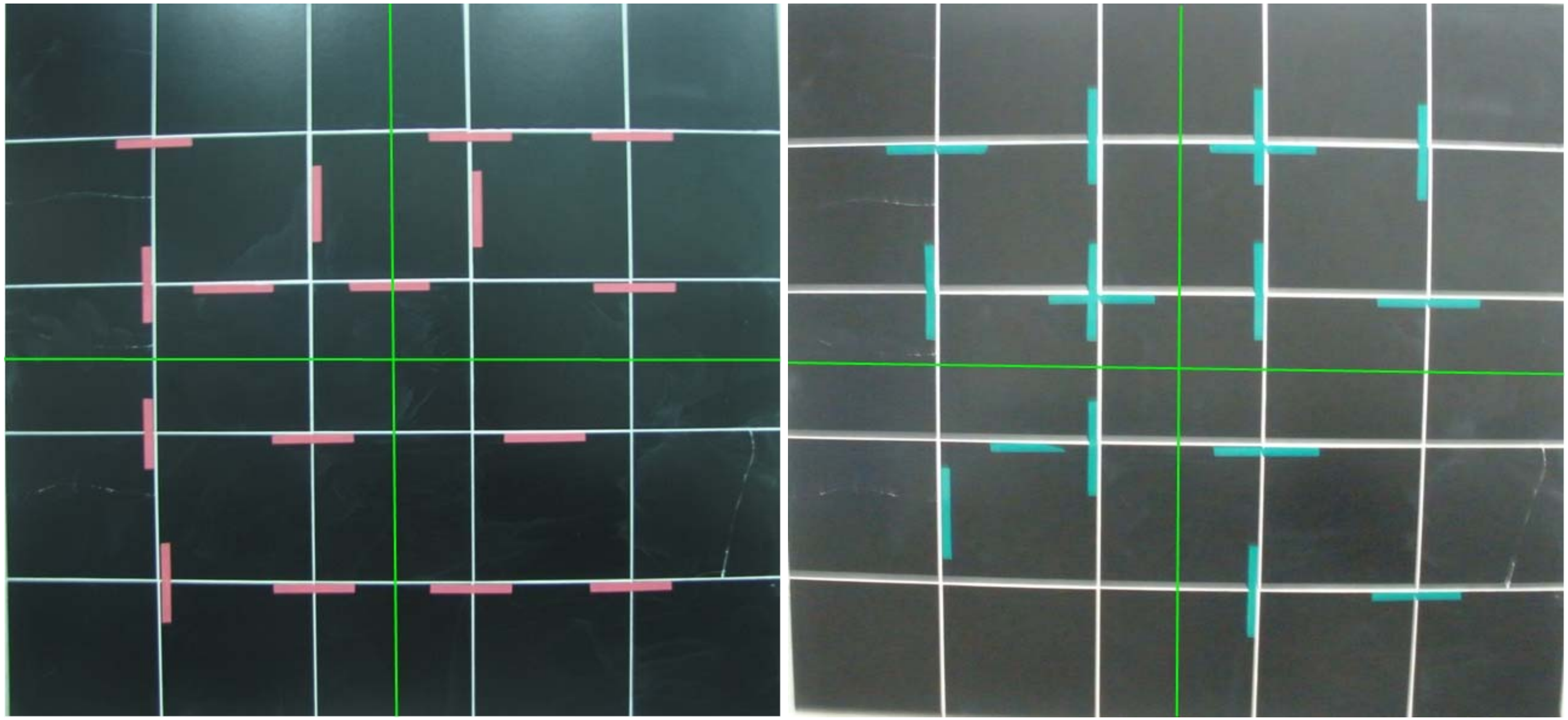


Figure 7.19 The defect positions are detected by inspector 1 for case 1 (a) first time and (b) second time

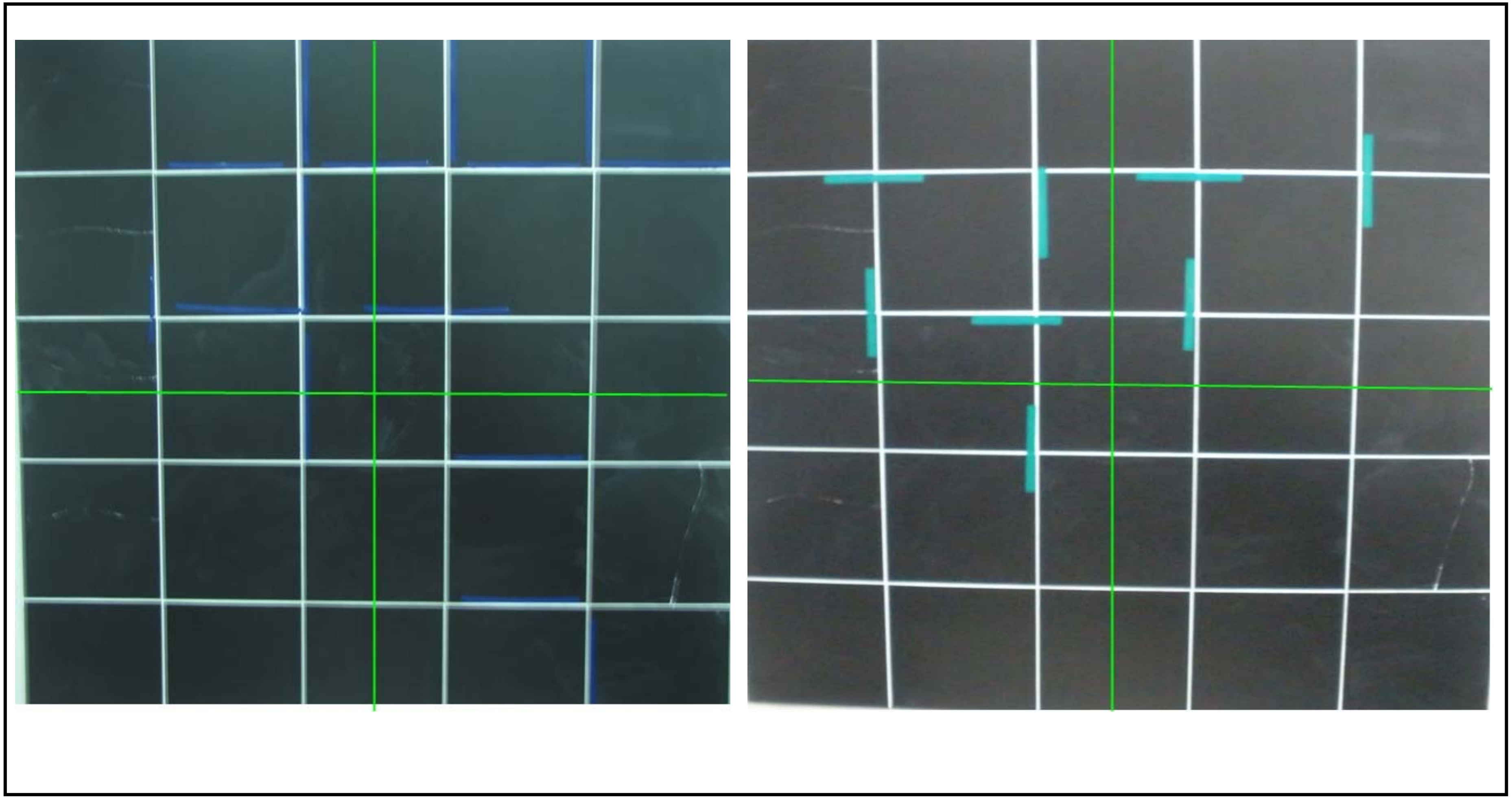


Figure 7.20 The defect positions are detected by inspector 2 for case 1 (a) first time and (b) second time

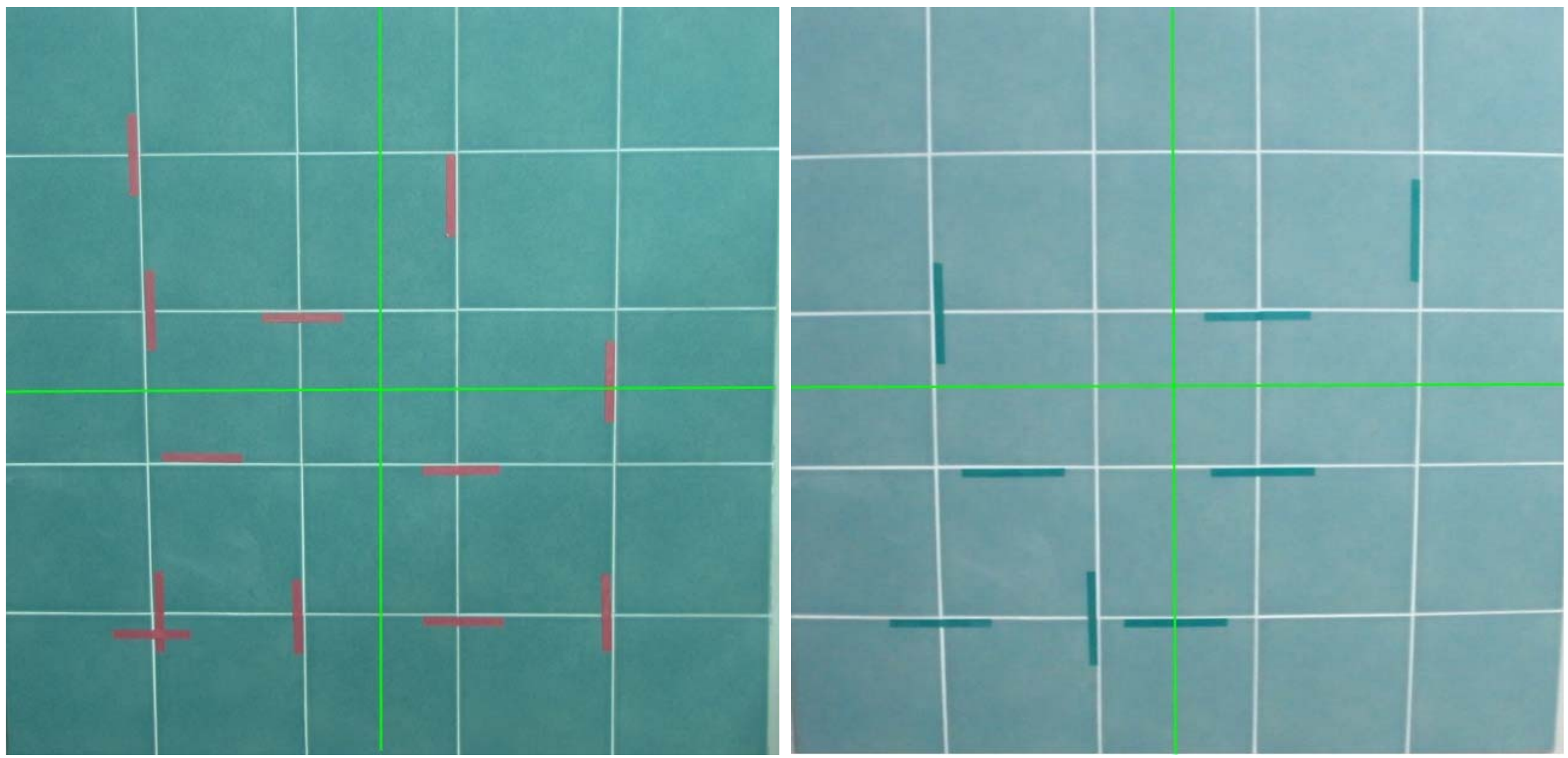


Figure 7.21 The defect positions are detected by inspector 1 for case 2 (a) first time and (b) second time

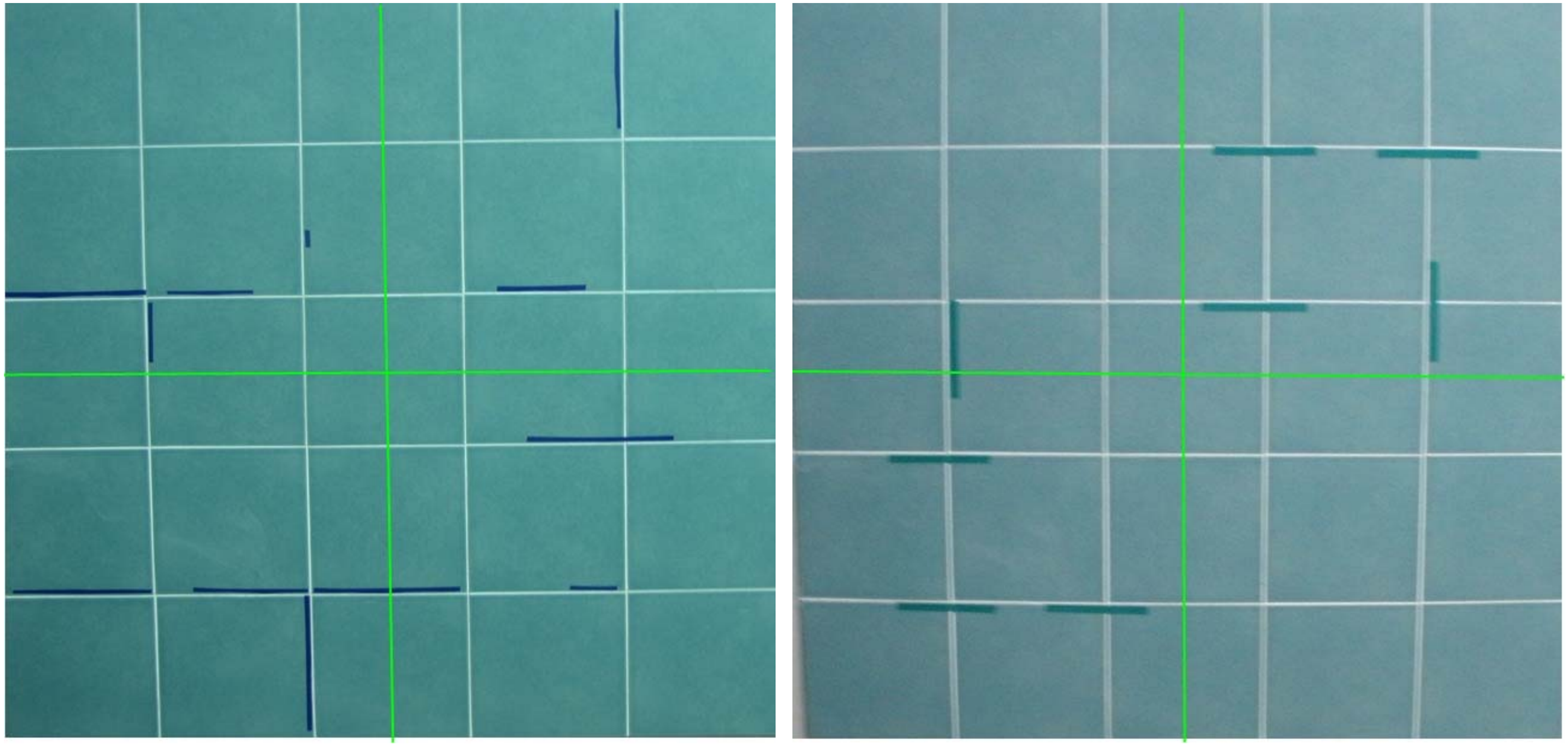


Figure 7.22 The defect positions are detected by inspector 2 for case2 (a) first time and (b) second time

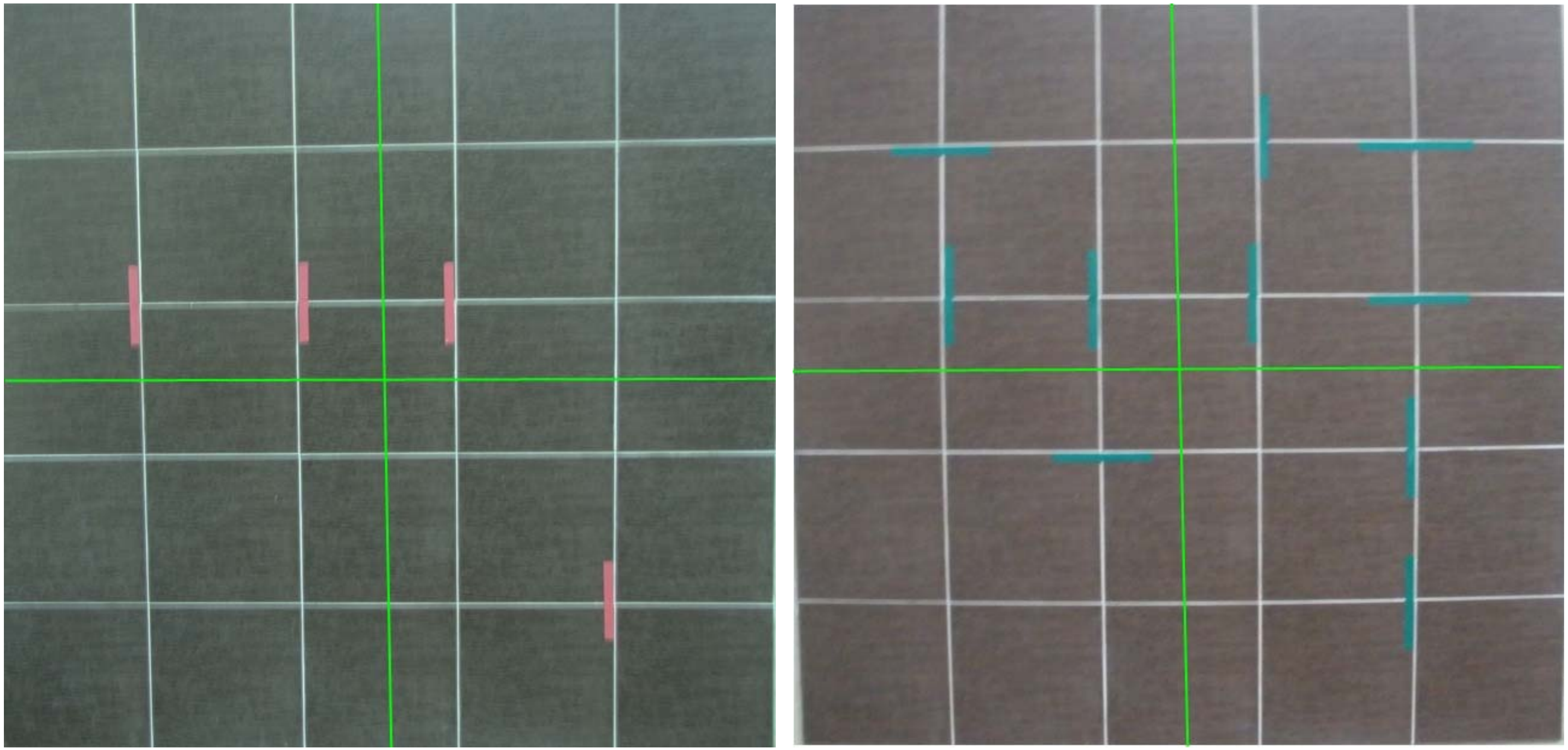


Figure 7.23 The defect positions are detected by inspector 1 for case 3 (a) first time and (b) second time

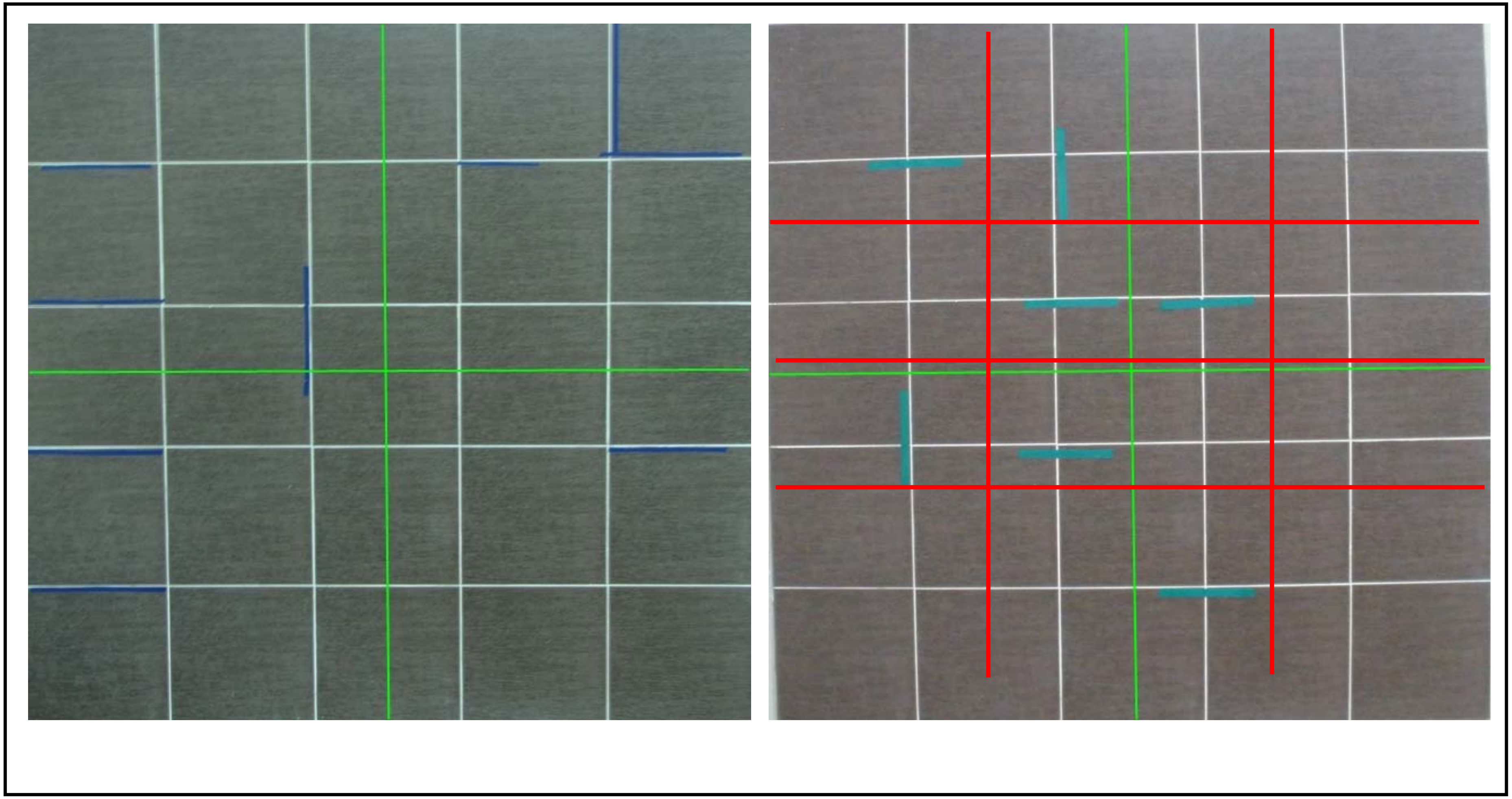


Figure 7.24 The defect positions are detected by inspector 2 for case 3 (a) first time and (b) second time

7.4 Validation

7.4.1 The validation of defect detection and quantification system

7.4.1.1 Algorithm for the inspection of the distance between neighboring tiles

This section is to validate that the proposed system is more accuracy than the human inspection when controlling the conditions of lighting value and camera distance. We compare the results of defect detection from the proposed system and human inspections with the actual defect positions in Figure 7.6, 7.7 and 7.8. The results of defect detection from proposed system are shown in Figure 7.16, 7.17 and 7.18 (we used the camera distance at 0.9 m, and the lighting value; ISO100, Aperture at 4 and Speed shutter at 1/2.5s). For the results of defect detection from human inspection, we collect the data of defect positions which are detected by visual inspection from two inspectors. Each inspector inspects two times per case. They inspect the first and the second time one week apart. The defect positions are detected that are shown in Figure 7.19 to 7.24.

The results of comparing accuracy for the uniform gap inspection are shown in Table 7.7. The proposed system is more accurate than both human inspectors when controlling the conditions of lighting value and camera distance, especially case 1 has the most accuracy equal 94%. Averaging accuracy of three cases is equal 79%. The proposed system can detect the defect positions corresponding with the actual defect position that is 84 positions from actual defect positions of 94 positions. While the inspectors found defects which are very small amount (about 21 to 42 positions or 18% to 38%). Moreover, the inspectors found defects in the same and in different positions because defect evaluation uses subjective judgment that is based on individual perception. The proposed system is capable of detecting many defects. It is noted that some defects cannot be detected by human inspectors.

Table 7.7 Comparison of the accuracy of defect positions for the uniform gap inspection

Case	Layout	Defect detection from system	Correct result	Total error			Actual number of defect	Correct(%)	Error(%)
				Not correct	Not found	Total			
1	Proposed system	31	29	2	0	2	29	94	6
	Human inspector 1st (first time)	30	22	8	7	15	29	59	41
	Human inspector 1st (second time)	32	21	11	8	19	29	53	48
	Human inspector 2nd (first time)	24	21	3	8	11	29	66	34
	Human inspector 2nd (second time)	15	10	5	19	24	29	29	71
2	Proposed system	36	29	7	3	10	32	74	26
	Human inspector 1st (first time)	22	16	6	16	22	32	42	58
	Human inspector 1st (second time)	15	10	5	22	27	32	27	73
	Human inspector 2nd (first time)	15	7	8	25	33	32	18	83
	Human inspector 2nd (second time)	15	8	7	24	31	32	21	79
3	Proposed system	30	26	4	7	11	33	70	30
	Human inspector 1st (first time)	8	4	4	29	33	33	11	89
	Human inspector 1st (second time)	20	10	10	22	32	33	24	76
	Human inspector 2nd (first time)	10	5	5	27	32	33	14	86
	Human inspector 2nd (second time)	13	3	10	29	39	33	7	93
sum	Proposed system	97	84	13	10	23	94	79	21
	Human inspector 1st (first time)	60	42	18	52	70	94	38	63
	Human inspector 1st (second time)	67	41	26	52	78	94	34	66
	Human inspector 2nd (first time)	49	33	16	60	76	94	30	70
	Human inspector 2nd (second time)	43	21	22	72	94	94	18	82

7.4.1.2 Algorithm for inspecting angle of intersecting straight line

Figure 7.25 shows the example of defect detection for the angle inspection of intersecting straight lines from the proposed system. Generally, it is very difficult for detecting from human inspectors because of the human vision limitation. The human inspectors can detect when the angle error is high value. While the proposed system can detects all defect positions which angle value errors from right angle. Therefore, it is difficult to validate in this algorithm.

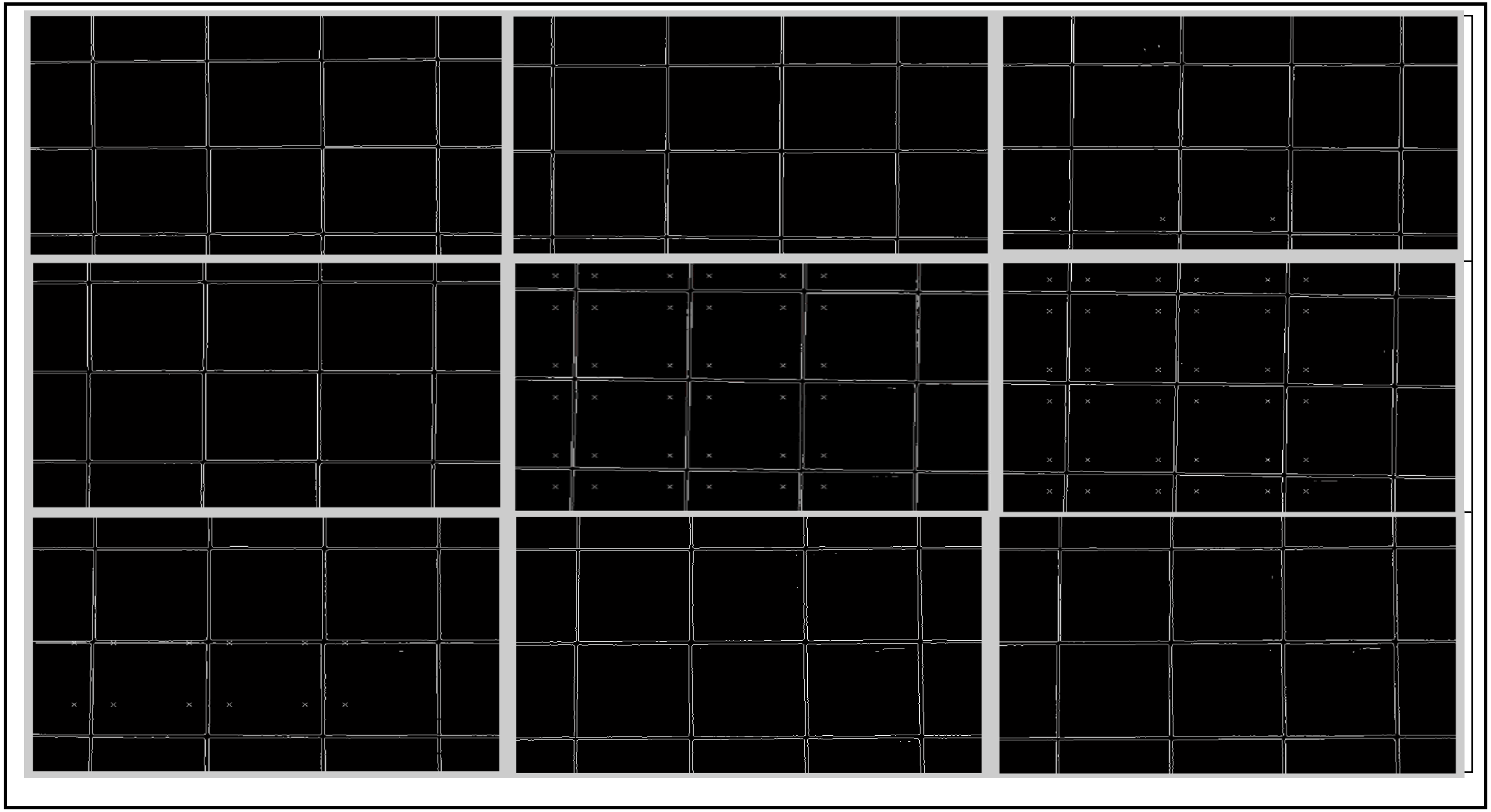


Figure 7.25 The results of detecting angle of intersecting straight line

7.4.2 The validation of the defect level evaluation system

The validation of the defect level evaluation system was done to validate that the proposed evaluation standard in system can evaluate defects more reliably than visual inspection by inspectors. The methodology used to collect data and steps of system validation are shown in Figure 7.26. The details are as follows.

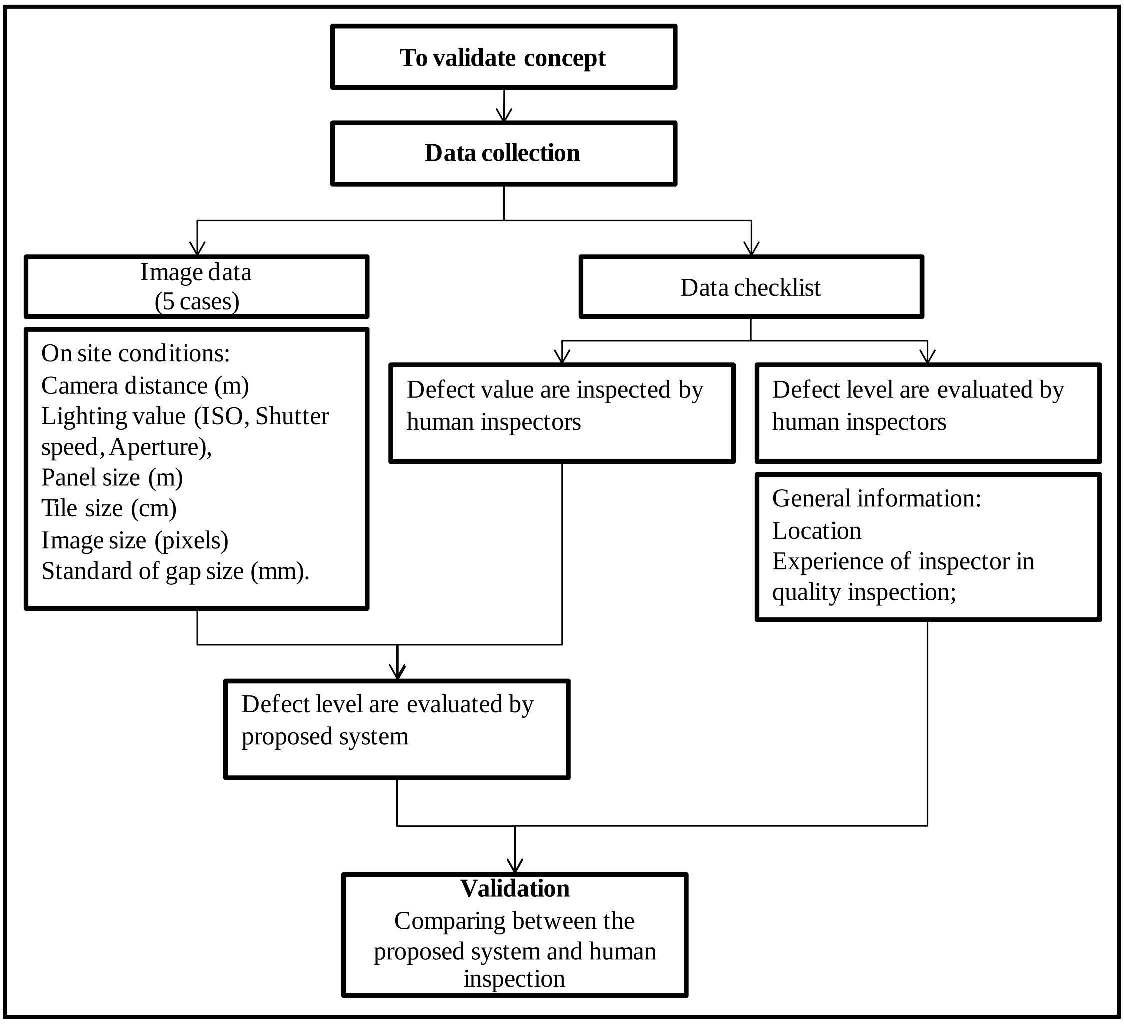


Figure 7.26 Steps in the validation of defect level evaluation system

7.4.2.1 Data collection

We started by collecting data from five cases. The data included, (1) image data; (2) on site conditions: camera distance, lighting value (ISO, shutter speed, aperture), panel size (m), tile size (cm), image size (pixels) and standard of gap size (mm); (3) the defect value and defect levels evaluated according to the data checklist in Table 7.8 by two inspectors per panel; (4) general information including location and experience of inspector in quality inspection. The defect level was evaluated by inspectors for five cases as shown in Appendix B. The image data was used to quantify the defect value supporting defect level evaluation system in criteria of f_{21} and f_{31} by the defect detection and quantification system. Other criterions use the defect value which can be observed by human visual inspection for defect level evaluation of proposed system.

7.4.2.2 Validation

We compared the results of defect level evaluation system by the proposed system with inspectors. The results of defect level evaluation system by the proposed evaluation standard and the subjective evaluation of human inspectors are compared in Table 7.9. The results show that the proposed model for defect level evaluation in aesthetic fault is able to evaluate the defect level corresponding with the most inspectors. There are few different defect levels in some inspectors. However, the inspectors had different perceptions of defect level evaluation at the same defect value. For example, the defect level evaluation of tiling which are not pressed evenly against the panel, the inspectors evaluated different defect levels at the same defect value. This is in contrast with the defect level evaluation system which can evaluate the same defect level every time. The inspectors have different perceptions in defect level evaluation as their visual inspection skills depend on individual experience. This leads to unreliability of defect evaluation in the absence of an evaluation standard which subsequently results in conflict about judgments of acceptable defect levels in aesthetic issues in architectural work. Therefore, the development of the evaluation standard using within organizations or projects can increase the reliability of visual quality inspection and reduce the conflict from different perception.

Table 7.8 Data checklist for rating by inspector and data collection on site

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	d_1	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		d_0	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification		d_0	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification		d_0	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash		d_0	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	d_1	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	d_1	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line		d_0	d_1	d_2	d_3	d_4
	F3		**Inspecting tile alignment**		d_0	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		d_0	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level		d_0	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	d_1	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile		d_0	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel		d_0	d_1	d_2	d_3	d_4

General information

Location:

Experience of inspector in quality inspection (years): Image no. layout:

Conditions

Camera distance (m)

Light vaue ISO

Shutter speed

Aperture

Panel size: Width (m)

Height (m)

Tile size: Width (cm)

Lenght (cm)

Standard of gap size (mm)

Image size (pixels)

Table 7.9 The summary of comparing defect level evaluation between subjective judgment by inspectors and the proposed system

			Case 1					Case 2					Case 3					Case 4					Case 5				
			defect level evaluation method					defect level evaluation method					defect level evaluation method					defect level evaluation method					defect level evaluation method				
			Subjective judgment by inspectors			Proposed system		Subjective judgment by inspectors			Proposed system		Subjective judgment by inspectors			Proposed system		Subjective judgment by inspectors			Proposed system		Subjective judgment by inspectors			Proposed system	
Stage 3	Stage 2	Stage 1	Defect value	Subjective judgment by inspector 1st	Subjective judgment by inspector 2nd	Defect value	Proposed system	Defect value	Subjective judgment by inspector 1st	Subjective judgment by inspector 2nd	Defect value	Proposed system	Defect value	Subjective judgment by inspector 1st	Subjective judgment by inspector 2nd	Defect value	Proposed system	Defect value	Subjective judgment by inspector 1st	Subjective judgment by inspector 2nd	Defect value	Proposed system	Defect value	Subjective judgment by inspector 1st	Subjective judgment by inspector 2nd	Defect value	Proposed system
Overall of work			*	d_0	d_0	**	d_0	*	d_1	d_1	**	d_2	*	d_1	d_1	**	d_0	*	d_2	d_1	**	d_1	*	d_1	d_1	**	d_0
	F1		*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_0	*	d_2	d_1	**	d_1	*	d_0	d_0	**	d_0
		f_{11}	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0
		f_{12}	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0
		f_{13}	3 tiles	d_0	d_0	3 tiles	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	3 tiles	d_3	d_2	3 tiles	d_1	0 tile	d_0	d_0	0 tile	d_0
	F2		*	d_0	d_1	**	d_1	*	d_3	d_2	**	d_3	*	d_3	d_2	**	d_3	*	d_1	d_1	**	d_4	*	d_1	d_1	**	d_3
		f_{21}	*	d_1	d_1	15,617 squ.mm	d_2	*	d_1	d_1	7,717 squ.mm	d_1	*	d_1	d_1	5,568 squ.mm	d_1	*	d_3	d_4	22,822 squ.mm	d_4	*	d_3	d_2	18,152 squ.mm	d_4
		f_{22}	0 point	d_0	d_0	0 point	d_0	20 points	d_3	d_4	20 points	d_4	22 points	d_3	d_3	22 points	d_4	14 points	d_2	d_2	14 points	d_4	10 points	d_2	d_1	10 points	d_3
	F3		*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_0	*	d_0	d_0	**	d_1
		f_{31}	*	d_0	d_0	30 points	d_0	*	d_0	d_0	5 points	d_0	*	d_0	d_0	20 points	d_1	*	d_0	d_0	2 point	d_0	*	d_0	d_0	32 points	d_2
		f_{32}	2 tiles	d_0	d_0	2 tiles	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0
	F4		*	d_0	d_0	**	d_0	*	d_1	d_0	**	d_1	*	d_0	d_0	**	d_0	*	d_2	d_1	**	d_1	*	d_1	d_1	**	d_0
		f_{41}	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0	0 tile	d_0	d_0	0 tile	d_0
		f_{42}	2 tiles	d_0	d_0	2 tiles	d_0	3 tiles	d_1	d_0	3 tiles	d_1	1 tile	d_0	d_0	1 tile	d_0	2 tiles	d_3	d_2	2 tiles	d_1	1 tile	d_1	d_1	1 tile	d_0

* = Inspectors cannot quantify defect value so they evaluate defect level by using sense from individual experience and perception

**= Defect value and defect level can evaluate from the standard of defect level classification and evaluation mechanism containing in the proposed system

7.5 Conclusions

The results of validation of the two components of the proposed system allow us to summarize that the concept of applying digital image processing techniques, fuzzy logic and knowledge management concepts reducing the subjective attributes in visual quality inspection can be successfully implemented in actual construction projects. The first component, the defect detection and quantification system, can detect defect positions more thoroughly than inspectors. Moreover, the system can quantify defect values to reduce the subjective attribute of visual quality inspection. The second component, the defect level evaluation system, can be used as an evaluation standard in organizations. It can help reduce conflicts from differences of perception between the people involved in quality evaluation. Moreover, it is used to improve construction quality continuously. However, the first component still needs improvement to overcome limitations to correspond more appropriately to the environments encountered on actual construction sites. The second component needs to be adapted for suitable implementation in specific organizations.

CHAPTER VIII
RESEARCH CONCLUSIONS AND RECOMMENDATIONS

8.1 Conclusions of overall research

At present the quality inspection process encounters conflicts regarding the judgment of acceptable defect levels between people involved in a building project such as inspectors, contractors and customers. The nature of quality evaluation has two attributes i.e. the measurable and the subjective. The quality evaluation of subjective attributes relating to aesthetic faults in architectural work is the main source of problems leading to conflicts in evaluation. Quality inspection in this area relies on subjective visual inspection. A person’s ability to judge aesthetic faults is limited in that it cannot quantify the value of a given defect. Subjective evaluation depends on the individual experience of the inspectors and different perceptions. The judgment is without a uniform standard. Therefore, a method must be devised to avoid the problem of subjectivity in quality evaluation.

The purpose of this study is to present a concept of developing defect evaluation system for supporting visual quality inspection in aesthetic issue of architectural work. Our defect evaluation system can reduce the subjective human element in judgments of aesthetic issues. The system is made more reliable through the use of digital image processing (DIP), fuzzy logic and a knowledge base to overcome the limitations of human perception. A case of tiling work inspection was selected to develop a prototype of the system to demonstrate the viability of application. Digital image processing was applied to detect defect positions and quantify defect values. In addition, fuzzy logic and the knowledge base were applied to develop the evaluation standard for using in organizations or construction projects.

The system’s development was divided into two main components: (1) a defect detection and quantification system, (2) the defect level evaluation system.

The methodology used in the development of the defect detection and quantification system in the first component was divided into six steps: 1) input (image acquisition) 2) noise reduction module 3) edge detection module 4) unit transformation module 5) defect detection and quantification module 6) output (result of defect value). MATLAB was used to develop image processing in this system. Next, the second component was to store the defect values of quality criteria from representative images to develop a knowledge base for the quality standard. Fuzzy logic and knowledge base theory were applied to develop criteria of evaluation, defect level classification in fuzzy set form, and a rule base for analyzing defect level. Finally, the last component is the output of the system that can be translated into a defect level by comparing the results from defect quantification of the first component with the standard requirement from defect classification in the knowledge base of the quality standard in the second component.

The proposed system was tested in two ways: 1) system accuracy testing, and 2) system validation on an actual construction site in comparison with human inspectors. In order to verify the accuracy of the system, the algorithms used to detect defects in position and calculate defect values were tested with several instances of proposed tile panel models from Photoshop. The results of testing the algorithm for gap inspection show that the calculation from the proposed algorithms is able to detect gap size defect positions accurately. The defect quantification closes to manual calculation from coordinate values. Defect value errors from the proposed algorithm using manual calculation did not exceed 2%. Moreover, algorithm testing of angle inspection of intersecting straight lines checks angle value and counts the number of angles which are not right angles. The comparison of angle values shows that the proposed algorithm is able to determine the angle value with an error less than 0.38%. The count of the number of angles deviating from a right angle over tolerance value satisfied the results of calculation. The purpose of testing the system was to demonstrate its accuracy before application on an actual construction site.

Next, the proposed system was tested on an actual construction site to determine its performance potential and limitations. The limitations need to be controlled during the system implementation in correspondence to the conditions found on-site. The case study of tiling work inspection on an actual construction site demonstrated that several conditions are need to be carefully controlled such as tile appearance, light value, camera distance, image size and angle of photograph. Some conditions can be solved by the developed the different algorithms to support the system, the application of new technology, or the limited practical method. While the lighting value and the camera distance are still need to find answers that are related to the accuracy of the system, especially the defect detection and quantification system using the digital image processing technique. The experiment and verification system can be summarized that the images of tile are taken in condition of the camera distance at 0.9 m and the proper exposure for photography about 0.292 cd/m^2 (our experiment use ISO at 100, Aperture at 4 and Speed shutter at 1/2.5s), which were given the most accuracy at 79%. These conditions can be used when the light value around tile about 0.043 to 0.292 cd/m^2.

Next, the proposed system was validated by comparison with the results of evaluations by human inspectors in the context of an actual tiling work inspection. Two issues were validated: 1) defect positions in both algorithms of gap size and angle inspection of intersecting straight lines and (2) the defect level evaluation.

Regarding the results of accuracy validation of the defect detection and quantification system with the first algorithm for distance inspection between neighbouring tiles (gap), inspector 1 and inspector 2 identified different defect positions and errors from the actual defect positions a lot. Each person detects different defect positions in each time while the proposed system was able to detect rather to the same positions. Moreover, the proposed system can detect more defect positions than both the inspectors. There are few defect positions that the proposed system cannot detect. This demonstrates that the proposed system is more accurate than purely visual inspection by inspectors since a person's ability to judge aesthetic faults is limited in that it cannot quantify defect value. Therefore, inspectors using only visual inspection cannot cover all defect positions consistently, especially in the case of massive products or large areas. Therefore, the development of a defect detection and quantification system can provide accurate support to visual inspection.

The results of the defect level evaluation system validation also show that inspectors have different perceptions of defect level evaluation since they depend on visual inspection and individual experience. The human evaluation of defect level is unreliable because lack of an explicit evaluation standard, conflicts regarding judgments of acceptable defect levels in aesthetic issues in architectural work are bound to arise. Therefore, the development of the second component of the defect level evaluation system is an attempt to apply the concept of a knowledge based model developed from Fuzzy logic theory. This evaluation standard helps to increase the reliability of visual quality inspection and can be used to develop a standard for defect level evaluation in quality inspection for organizational use.

Our research conclusions demonstrate that the proposed system can be implemented although it requires improvement to overcome its limitations for more accurate defect detection and to correspond to the environment of an actual construction site. The defect level evaluation system must be adapted to a standard of defect classification suitable for using in each organization and each project.

8.2 Applications and benefits of the proposed system

The proposed system can support the decision-making process of inspectors in visual quality inspection, especially with regard to aesthetic faults in architectural work. There are three main applications for the system: 1) the detection of defect positions 2) the quantification of defect value, and 3) defect level evaluation. The system can be used in two situations: 1) to support inspectors who lack experience and 2) to reduce conflicts by using it as an evaluation standard within an organization.

8.3 Research outcomes

8.3.1 A new conceptual framework applying DIP, Fuzzy logic and KMS to develop a defect level evaluation system for each organizational use to support visual quality inspection in architectural work.

8.3.2 Two new algorithms proposed to support the system and used in a case study of tiling work: one algorithm for gap size inspection and another for right angle inspection.

8.3.3 Prototypes for the defect detection and quantification system, and the defect level evaluation system for tiling inspection.

8.3.4 A new concept to develop a knowledge based model and evaluation mechanism derived from fuzzy logic theory to use as the standard of defect level evaluation in aesthetic issues for use in organizations. The evaluation standard increases the reliability of visual quality inspection.

8.3.5 Information from the results of the experimental system demonstrating the applicability, problems and limitations of the proposed evaluation concept on an actual construction site will be used for other researchers.

8.4 Research contributions

8.4.1 The concept of applying a defect detection and quantification system can increase the reliability of visual inspection of defect positions because a person's ability to judge aesthetic faults is limited. People have some limitation in quantifying defect values. So, inspectors using a visual inspection method cannot cover all defect positions, especially in the case of massive products or large areas, and respective evaluations may not be consistent. The proposed system can detect defect positions more thoroughly and consistently than unaided human visual inspection. Moreover, the proposed system can quantify defect values. These defect values can be applied to classify defect levels as an evaluation standard in each organization and used it for continuous quality improvement.

8.4.2 The proposed defect level evaluation system can increase the reliability of visual inspection. As traditional visual methods of defect level evaluation of aesthetic architectural issues depend on the inspectors' individual experience, each one will have a different perception without an evaluation standard. Such evaluations may also be inconsistent. The proposed defect level evaluation system evaluates the defect level using a uniform standard leading to greater reliability and consistency when used on actual building projects.

8.4.3 The evaluation standard is based on input from all major participants in a project or organization to ensure the reduction of sources of conflict among project participants who are involved in evaluating work defects such as inspectors, contractors and customers.

8.4.4 The proposed system can be used to improve inspector knowledge, workers' skills and quality of product. The quality standard knowledge base can support inspectors who inexperienced in quality evaluation decision making.

8.4.5 The proposed conceptual framework can be used to develop defect level evaluation systems for quality inspection in other types of work.

8.5 Recommendations and limitations

8.5.1 The prototype of the proposed system in this study was developed only on a tiling work inspection. Moreover, our concept did not intend to evaluate all quality requirements using only image processing techniques. We limited our focus on supporting visual quality inspection with respect to selected quality requirements.

8.5.2 The environment of an actual construction site presents several conditions which must be controlled or set as limitations before implementation of the evaluation system e.g. tile appearance, light value, camera distance, image size and angle of photograph.

8.5.3 In the proposed prototype, the image must be transferred to a computer by users. The system is not automatically transferable by data link.

8.6 Future research

Future research should involve detailed study:

8.6.1 To find a method to control conditions or propose algorithms for implementation that correspond to actual conditions on a construction site such as variety in tile appearance, light value, camera distance, image size and angle of photograph. These conditions need to be improved in future research for increasing accuracy of system.

8.6.2 To develop automatic defect detection for more practical inspection.

8.6.3 To propose algorithms for use in inspection of a variety of tiling situations, other criteria of tiling work, and for application in other case studies.

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Appendix A

Experiment system, Verification and Validation

Table A-1 Results of experiment in conditions of camera distance and light value for case 1

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
1	0.8	3±0.5	1x1	20x20	100	4	4s	44	20	24	9	33	29	38	62
							3s	37	20	17	9	26	29	43	57
							2.5s	36	21	15	8	23	29	48	52
							2s	34	23	11	6	17	29	58	43
							1.6s	35	24	11	5	16	29	60	40
							1.3s	39	25	14	4	18	29	58	42
							1s	43	25	18	4	22	29	53	47
							1/1.3s	43	26	17	3	20	29	57	43
							1/1.6s	40	26	14	3	17	29	60	40
							1/2s	42	25	17	4	21	29	54	46
							1/2.5s	44	22	22	7	29	29	43	57
							1/3s	43	17	26	12	38	29	31	69
							1/4s	41	12	29	17	46	29	21	79

Table A-1 Results of experiment in conditions of camera distance and light value for case 1 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
1	0.9	3±0.5	1x1	20x20	100	4	4s	47	18	29	11	40	29	31	69
							3s	52	21	31	8	39	29	35	65
							2.5s	54	23	31	6	37	29	38	62
							2s	54	25	29	4	33	29	43	57
							1.6s	53	25	28	4	32	29	44	56
							1.3s	53	25	28	4	32	29	44	56
							1s	51	25	26	4	30	29	45	55
							1/1.3s	49	25	24	4	28	29	47	53
							1/1.6s	50	28	22	1	23	29	55	45
							1/2s	44	29	15	0	15	29	66	34
							1/2.5s	35	29	6	0	6	29	83	17
							1/3s	33	28	5	1	6	29	82	18
							1/4s	32	27	5	2	7	29	79	21

Table A-1 Results of experiment in conditions of camera distance and light value for case 1 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
1	1	3±0.5	1x1	20x20	100	4	4s	55	27	28	2	30	29	47	53
							3s	52	27	25	2	27	29	50	50
							2.5s	50	28	22	1	23	29	55	45
							2s	50	29	21	0	21	29	58	42
							1.6s	48	29	19	0	19	29	60	40
							1.3s	46	29	17	0	17	29	63	37
							1s	43	29	14	0	14	29	67	33
							1/1.3s	38	29	9	0	9	29	76	24
							1/1.6s	31	29	2	0	2	29	94	6
							1/2s	33	27	6	2	8	29	77	23
							1/2.5s	35	21	14	8	22	29	49	51
							1/3s	38	14	24	15	39	29	26	74
							1/4s	44	13	31	16	47	29	22	78

Table A-2 Results of experiment in conditions of camera distance and light value for case 2

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
2	0.8	2±0.5	1x1	20x20	100	4	4s	0	0	0	32	32	32	0	100
							3s	0	0	0	32	32	32	0	100
							2.5s	0	0	0	32	32	32	0	100
							2s	0	0	0	32	32	32	0	100
							1.6s	44	28	16	4	20	32	58	42
							1.3s	38	25	13	7	20	32	56	44
							1s	39	21	18	11	29	32	42	58
							1/1.3s	34	19	15	13	28	32	40	60
							1/1.6s	32	21	11	11	22	32	49	51
							1/2s	36	23	13	9	22	32	51	49
							1/2.5s	38	22	16	10	26	32	46	54
							1/3s	33	17	16	15	31	32	35	65
							1/4s	36	15	21	17	38	32	28	72

Table A-2 Results of experiment in conditions of camera distance and light value for case 2 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
2	0.9	2±0.5	1x1	20x20	100	4	4s	0	0	0	32	32	32	0	100
							3s	0	0	0	32	32	32	0	100
							2.5s	0	0	0	32	32	32	0	100
							2s	0	0	0	32	32	32	0	100
							1.6s	60	32	28	0	28	32	53	47
							1.3s	58	32	26	0	26	32	55	45
							1s	53	29	24	3	27	32	52	48
							1/1.3s	58	31	27	1	28	32	53	47
							1/1.6s	56	30	26	2	28	32	52	48
							1/2s	56	31	25	1	26	32	54	46
							1/2.5s	51	30	21	2	23	32	57	43
							1/3s	47	29	18	3	21	32	58	42
							1/4s	45	29	16	3	19	32	60	40

Table A-2 Results of experiment in conditions of camera distance and light value for case 2 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
2	1	2±0.5	1x1	20x20	100	4	4s	0	0	0	32	32	32	0	100
							3s	0	0	0	32	32	32	0	100
							2.5s	0	0	0	32	32	32	0	100
							2s	0	0	0	32	32	32	0	100
							1.6s	45	28	17	4	21	32	57	43
							1.3s	29	18	11	14	25	32	42	58
							1s	36	19	17	13	30	32	39	61
							1/1.3s	35	18	17	14	31	32	37	63
							1/1.6s	34	16	18	16	34	32	32	68
							1/2s	35	18	17	14	31	32	37	63
							1/2.5s	34	15	19	17	36	32	29	71
							1/3s	29	12	17	20	37	32	24	76
							1/4s	24	11	13	21	34	32	24	76

Table A-3 Results of experiment in conditions of camera distance and light value for case 3

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
3	0.8	2±0.5	1x1	20x20	100	4	4s	0	0	0	33	33	33	0	100
							3s	0	0	0	33	33	33	0	100
							2.5s	0	0	0	33	33	33	0	100
							2s	0	0	0	33	33	33	0	100
							1.6s	56	30	26	3	29	33	51	49
							1.3s	56	30	26	3	29	33	51	49
							1s	56	30	26	3	29	33	51	49
							1/1.3s	57	31	26	2	28	33	53	47
							1/1.6s	56	31	25	2	27	33	53	47
							1/2s	57	31	26	2	28	33	53	47
							1/2.5s	57	31	26	2	28	33	53	47
							1/3s	56	31	25	2	27	33	53	47
							1/4s	54	31	23	2	25	33	55	45

Table A-3 Results of experiment in conditions of camera distance and light value for case 3 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
3	0.9	2±0.5	1x1	20x20	100	4	4s	0	0	0	33	33	33	0	100
							3s	0	0	0	33	33	33	0	100
							2.5s	0	0	0	33	33	33	0	100
							2s	0	0	0	33	33	33	0	100
							1.6s	52	29	23	4	27	33	52	48
							1.3s	52	29	23	4	27	33	52	48
							1s	52	29	23	4	27	33	52	48
							1/1.3s	54	29	25	4	29	33	50	50
							1/1.6s	55	29	26	4	30	33	49	51
							1/2s	51	28	23	5	28	33	50	50
							1/2.5s	45	27	18	6	24	33	53	47
							1/3s	39	25	14	8	22	33	53	47
							1/4s	34	23	11	10	21	33	52	48

Table A-3 Results of experiment in conditions of camera distance and light value for case 3 (continued)

Case	Cameara distance (m)	Standard of gap size (mm)	Panel size (mxm)	Tile size (cmxcm)	ISO	Aperture	Speed shutter (Camera)	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
										Not correct	Not found	Total			
3	1	2±0.5	1x1	20x20	100	4	4s	0	0	0	33	33	33	0	100
							3s	0	0	0	33	33	33	0	100
							2.5s	0	0	0	33	33	33	0	100
							2s	0	0	0	33	33	33	0	100
							1.6s	31	22	9	11	20	33	52	48
							1.3s	31	22	9	11	20	33	52	48
							1s	31	22	9	11	20	33	52	48
							1/1.3s	30	21	9	12	21	33	50	50
							1/1.6s	28	20	8	13	21	33	49	51
							1/2s	21	17	4	16	20	33	46	54
							1/2.5s	20	16	4	17	21	33	43	57
							1/3s	12	11	1	22	23	33	32	68
							1/4s	12	11	1	22	23	33	32	68

Table A-4 Comparison of the accuracy of defect positions for the uniform gap inspection (case 1)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
1	1	Proposed system	1	1	0	0	0	1	100	0
		Human inspector 1st (first time)	2	1	1	0	1	1	50	50
		Human inspector 1st (second time)	2	1	1	0	1	1	50	50
		Human inspector 2nd (first time)	1	1	0	0	0	1	100	0
		Human inspector 2nd (second time)	2	1	1	0	1	1	50	50
	2	Proposed system	6	6	0	0	0	6	100	0
		Human inspector 1st (first time)	4	4	0	2	2	6	67	33
		Human inspector 1st (second time)	6	6	0	0	0	6	100	0
		Human inspector 2nd (first time)	6	5	1	1	2	6	71	29
		Human inspector 2nd (second time)	3	3	0	3	3	6	50	50
	3	Proposed system	3	3	0	0	0	3	100	0
		Human inspector 1st (first time)	2	2	0	1	1	3	67	33
		Human inspector 1st (second time)	2	1	1	2	3	3	25	75
		Human inspector 2nd (first time)	3	3	0	0	0	3	100	0
		Human inspector 2nd (second time)	2	1	1	2	3	3	25	75
	4	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	3	2	1	0	1	2	67	33
		Human inspector 1st (second time)	2	1	1	1	2	2	33	67
		Human inspector 2nd (first time)	3	2	1	0	1	2	67	33
		Human inspector 2nd (second time)	2	1	1	1	2	2	33	67
	5	Proposed system	6	6	0	0	0	6	100	0
		Human inspector 1st (first time)	4	4	0	2	2	6	67	33
		Human inspector 1st (second time)	6	5	1	1	2	6	71	29
		Human inspector 2nd (first time)	5	5	0	1	1	6	83	17
		Human inspector 2nd (second time)	4	3	1	3	4	6	43	57
	6	Proposed system	1	1	0	0	0	1	100	0
		Human inspector 1st (first time)	2	1	1	0	1	1	50	50
		Human inspector 1st (second time)	2	1	1	0	1	1	50	50
		Human inspector 2nd (first time)	0	0	0	1	1	1	0	100
		Human inspector 2nd (second time)	0	0	0	1	1	1	0	100
	7	Proposed system	1	1	0	0	0	1	100	0
		Human inspector 1st (first time)	2	1	1	0	1	1	50	50
		Human inspector 1st (second time)	2	1	1	0	1	1	50	50
		Human inspector 2nd (first time)	0	0	0	1	1	1	0	100
		Human inspector 2nd (second time)	0	0	0	1	1	1	0	100

Table A-4 Comparison of the accuracy of defect positions for the uniform gap inspection (case 1) (continued)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
1	8	Proposed system	4	4	0	0	0	4	100	0
		Human inspector 1st (first time)	3	3	0	1	1	4	75	25
		Human inspector 1st (second time)	5	4	1	0	1	4	80	20
		Human inspector 2nd (first time)	2	2	0	2	2	4	50	50
		Human inspector 2nd (second time)	2	1	1	3	4	4	20	80
	9	Proposed system	1	1	0	0	0	1	100	0
		Human inspector 1st (first time)	1	1	0	0	0	1	100	0
		Human inspector 1st (second time)	0	0	0	1	1	1	0	100
		Human inspector 2nd (first time)	1	1	0	0	0	1	100	0
		Human inspector 2nd (second time)	0	0	0	1	1	1	0	100
	10	Proposed system	2	1	1	0	1	1	50	50
		Human inspector 1st (first time)	2	0	2	1	3	1	0	100
		Human inspector 1st (second time)	1	0	1	1	2	1	0	100
		Human inspector 2nd (first time)	0	0	0	1	1	1	0	100
		Human inspector 2nd (second time)	0	0	0	1	1	1	0	100
	11	Proposed system	3	2	1	0	1	2	67	33
		Human inspector 1st (first time)	3	2	1	0	1	2	67	33
		Human inspector 1st (second time)	2	0	2	2	4	2	0	100
		Human inspector 2nd (first time)	1	1	0	1	1	2	50	50
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	12	Proposed system	1	1	0	0	0	1	100	0
		Human inspector 1st (first time)	2	1	1	0	1	1	50	50
		Human inspector 1st (second time)	2	1	1	0	1	1	50	50
		Human inspector 2nd (first time)	2	1	1	0	1	1	50	50
		Human inspector 2nd (second time)	0	0	0	1	1	1	0	100
	sum	Proposed system	31	29	2	0	2	29	94	6
		Human inspector 1st (first time)	30	22	8	7	15	29	59	41
		Human inspector 1st (second time)	32	21	11	8	19	29	53	48
		Human inspector 2nd (first time)	24	21	3	8	11	29	66	34
		Human inspector 2nd (second time)	15	10	5	19	24	29	29	71

Table A-5 Comparison of the accuracy of defect positions for the uniform gap inspection (case 2)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
2	1	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	2	2	0	0	0	2	100	0
		Human inspector 1st (second time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (first time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	2	Proposed system	6	3	3	0	3	3	50	50
		Human inspector 1st (first time)	1	0	1	3	4	3	0	100
		Human inspector 1st (second time)	0	0	0	3	3	3	0	100
		Human inspector 2nd (first time)	0	0	0	3	3	3	0	100
		Human inspector 2nd (second time)	2	0	2	3	5	3	0	100
	3	Proposed system	4	3	1	0	1	3	75	25
		Human inspector 1st (first time)	0	0	0	3	3	3	0	100
		Human inspector 1st (second time)	1	1	0	2	2	3	33	67
		Human inspector 2nd (first time)	1	0	1	3	4	3	0	100
		Human inspector 2nd (second time)	2	2	0	1	1	3	67	33
	4	Proposed system	2	2	0	1	1	3	67	33
		Human inspector 1st (first time)	2	2	0	1	1	3	67	33
		Human inspector 1st (second time)	2	2	0	1	1	3	67	33
		Human inspector 2nd (first time)	3	2	1	1	2	3	50	50
		Human inspector 2nd (second time)	1	1	0	2	2	3	33	67
	5	Proposed system	4	3	1	1	2	4	60	40
		Human inspector 1st (first time)	2	2	0	2	2	4	50	50
		Human inspector 1st (second time)	2	1	1	3	4	4	20	80
		Human inspector 2nd (first time)	2	1	1	3	4	4	20	80
		Human inspector 2nd (second time)	2	1	1	3	4	4	20	80
	6	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	1	0	1	2	3	2	0	100
		Human inspector 1st (second time)	1	1	0	1	1	2	50	50
		Human inspector 2nd (first time)	1	0	1	2	3	2	0	100
		Human inspector 2nd (second time)	2	1	1	1	2	2	33	67
	7	Proposed system	2	2	0	1	1	3	67	33
		Human inspector 1st (first time)	1	1	0	2	2	3	33	67
		Human inspector 1st (second time)	1	1	0	2	2	3	33	67
		Human inspector 2nd (first time)	0	0	0	3	3	3	0	100
		Human inspector 2nd (second time)	2	2	0	1	1	3	67	33

Table A-5 Comparison of the accuracy of defect positions for the uniform gap inspection (case 2) (continued)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
2	8	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	2	1	1	1	2	2	33	67
		Human inspector 1st (second time)	3	1	2	1	3	2	25	75
		Human inspector 2nd (first time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	9	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	1	1	0	1	1	2	50	50
		Human inspector 1st (second time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (first time)	2	0	2	2	4	2	0	100
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	10	Proposed system	4	3	1	0	1	3	75	25
		Human inspector 1st (first time)	4	3	1	0	1	3	75	25
		Human inspector 1st (second time)	2	1	1	2	3	3	25	75
		Human inspector 2nd (first time)	2	1	1	2	3	3	25	75
		Human inspector 2nd (second time)	2	1	1	2	3	3	25	75
	11	Proposed system	4	3	1	0	1	3	75	25
		Human inspector 1st (first time)	4	3	1	0	1	3	75	25
		Human inspector 1st (second time)	3	2	1	1	2	3	50	50
		Human inspector 2nd (first time)	3	2	1	1	2	3	50	50
		Human inspector 2nd (second time)	2	0	2	3	5	3	0	100
	12	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	2	1	1	1	2	2	33	67
		Human inspector 1st (second time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (first time)	1	1	0	1	1	2	50	50
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	sum	Proposed system	36	29	7	3	10	32	74	26
		Human inspector 1st (first time)	22	16	6	16	22	32	42	58
		Human inspector 1st (second time)	15	10	5	22	27	32	27	73
		Human inspector 2nd (first time)	15	7	8	25	33	32	18	83
		Human inspector 2nd (second time)	15	8	7	24	31	32	21	79

Table A-6 Comparison of the accuracy of defect positions for the uniform gap inspection (case 3)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
3	1	Proposed system	2	2	0	1	1	3	67	33
		Human inspector 1st (first time)	0	0	0	3	3	3	0	100
		Human inspector 1st (second time)	2	1	1	2	3	3	25	75
		Human inspector 2nd (first time)	1	0	1	3	4	3	0	100
		Human inspector 2nd (second time)	2	1	1	2	3	3	25	75
	2	Proposed system	0	0	0	0	0	0	100	0
		Human inspector 1st (first time)	0	0	0	0	0	0	100	0
		Human inspector 1st (second time)	2	0	2	0	2	0	0	100
		Human inspector 2nd (first time)	1	0	1	0	1	0	0	100
		Human inspector 2nd (second time)	2	0	2	0	2	0	0	100
	3	Proposed system	3	2	1	0	1	2	67	33
		Human inspector 1st (first time)	0	0	0	2	2	2	0	100
		Human inspector 1st (second time)	2	1	1	1	2	2	33	67
		Human inspector 2nd (first time)	2	1	1	1	2	2	33	67
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	4	Proposed system	3	2	1	1	2	3	50	50
		Human inspector 1st (first time)	2	2	0	1	1	3	67	33
		Human inspector 1st (second time)	2	2	0	1	1	3	67	33
		Human inspector 2nd (first time)	1	1	0	2	2	3	33	67
		Human inspector 2nd (second time)	0	0	0	3	3	3	0	100
	5	Proposed system	2	2	0	0	0	2	100	0
		Human inspector 1st (first time)	4	2	2	0	2	2	50	50
		Human inspector 1st (second time)	4	2	2	0	2	2	50	50
		Human inspector 2nd (first time)	2	0	2	2	4	2	0	100
		Human inspector 2nd (second time)	3	0	3	2	5	2	0	100
	6	Proposed system	3	3	0	0	0	3	100	0
		Human inspector 1st (first time)	0	0	0	3	3	3	0	100
		Human inspector 1st (second time)	2	1	1	2	3	3	25	75
		Human inspector 2nd (first time)	0	0	0	3	3	3	0	100
		Human inspector 2nd (second time)	0	0	0	3	3	3	0	100
	7	Proposed system	4	4	0	0	0	4	100	0
		Human inspector 1st (first time)	0	0	0	4	4	4	0	100
		Human inspector 1st (second time)	0	0	0	4	4	4	0	100
		Human inspector 2nd (first time)	1	1	0	3	3	4	25	75
		Human inspector 2nd (second time)	2	1	1	3	4	4	20	80

Table A-6 Comparison of the accuracy of defect positions for the uniform gap inspection (case 3) (continued)

Case	Layout	Methods	Defect positions	Correct	Total error			Actual	Correct(%)	Error(%)
					Not correct	Not found	Total			
3	8	Proposed system	2	2	0	2	2	4	50	50
		Human inspector 1st (first time)	0	0	0	4	4	4	0	100
		Human inspector 1st (second time)	2	1	1	3	4	4	20	80
		Human inspector 2nd (first time)	0	0	0	4	4	4	0	100
		Human inspector 2nd (second time)	2	1	1	3	4	4	20	80
	9	Proposed system	3	3	0	0	0	3	100	0
		Human inspector 1st (first time)	0	0	0	3	3	3	0	100
		Human inspector 1st (second time)	2	2	0	1	1	3	67	33
		Human inspector 2nd (first time)	1	1	0	2	2	3	33	67
		Human inspector 2nd (second time)	0	0	0	3	3	3	0	100
	10	Proposed system	3	2	1	1	2	3	50	50
		Human inspector 1st (first time)	0	0	0	3	3	3	0	100
		Human inspector 1st (second time)	0	0	0	3	3	3	0	100
		Human inspector 2nd (first time)	1	1	0	2	2	3	33	67
		Human inspector 2nd (second time)	0	0	0	3	3	3	0	100
	11	Proposed system	2	2	0	2	2	4	50	50
		Human inspector 1st (first time)	0	0	0	4	4	4	0	100
		Human inspector 1st (second time)	0	0	0	4	4	4	0	100
		Human inspector 2nd (first time)	0	0	0	4	4	4	0	100
		Human inspector 2nd (second time)	2	0	2	4	6	4	0	100
	12	Proposed system	3	2	1	0	1	2	67	33
		Human inspector 1st (first time)	2	0	2	2	4	2	0	100
		Human inspector 1st (second time)	2	0	2	2	4	2	0	100
		Human inspector 2nd (first time)	0	0	0	2	2	2	0	100
		Human inspector 2nd (second time)	0	0	0	2	2	2	0	100
	sum	Proposed system	30	26	4	7	11	33	70	30
		Human inspector 1st (first time)	8	4	4	29	33	33	11	89
		Human inspector 1st (second time)	20	10	10	23	33	33	23	77
		Human inspector 2nd (first time)	10	5	5	28	33	33	13	87
		Human inspector 2nd (second time)	13	3	10	30	40	33	7	93

Appendix B

Defect level evaluation by inspectors

Table B-1 Defect level evaluation by inspector for case 1

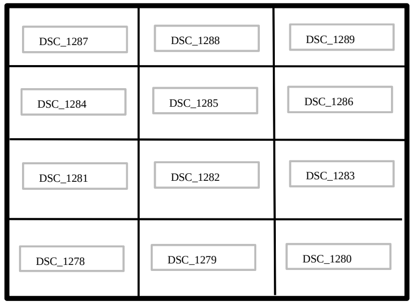
Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					(d_0)	d_1	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		(d_0)	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	3 tiles	(d_0)	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		(d_0)	d_1	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	(d_1)	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	0 point	(d_0)	d_1	d_2	d_3	d_4
	F3		**Inspecting tile alignment**		(d_0)	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		(d_0)	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	2 tiles	(d_0)	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		(d_0)	d_1	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	2 tiles	(d_0)	d_1	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 1 (3 years)

Image no. layout:



Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-1 Defect level evaluation by inspector for case 1 (continued)

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					**d_0**	d_1	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		**d_0**	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	3 tiles	**d_0**	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	**d_1**	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	**d_1**	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	0 point	**d_0**	d_1	d_2	d_3	d_4
	F3		**Inspecting tile alignment**		**d_0**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**d_0**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	2 tiles	**d_0**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		**d_0**	d_1	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	2 tiles	**d_0**	d_1	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 2 (2 years)

Image no. layout:

DSC_1287	DSC_1288	DSC_1289
DSC_1284	DSC_1285	DSC_1286
DSC_1281	DSC_1282	DSC_1283
DSC_1278	DSC_1279	DSC_1280

Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-2 Defect level evaluation by inspector for case 2

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	**d_1**	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		**d_0**	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	d_1	d_2	**d_3**	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	**d_1**	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	20 points	d_0	d_1	d_2	**d_3**	d_4
	F3		**Inspecting tile alignment**		**d_0**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**d_0**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	**d_1**	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	3 tiles	d_0	**d_1**	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 1 (3 years)

Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Image no. layout:

DSC_1299	DSC_1300	DSC_1301
DSC_1296	DSC_1297	DSC_1298
DSC_1293	DSC_1294	DSC_1295
DSC_1290	DSC_1291	DSC_1292

Table B-2 Defect level evaluation by inspector for case 2 (continued)

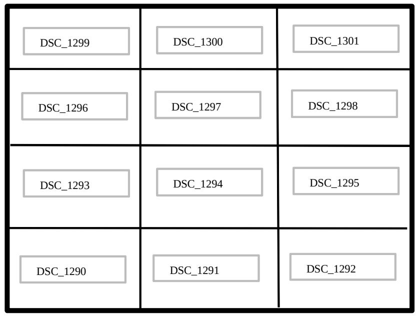
Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	**d_1**	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		**d_0**	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	d_1	**d_2**	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	**d_1**	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	20 points	d_0	d_1	d_2	d_3	**d_4**
	F3		**Inspecting tile alignment**		**d_0**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**d_0**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		**d_0**	d_1	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	3 tiles	**d_0**	d_1	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 2 (2 years)

Image no. layout:



Conditions

Camera distance (m) 0.9

Light vaue ISO 100

Shutter speed 1/2.5s

Aperture 4

Panel size: Width (m) 1.0

Height (m) 1.0

Tile size: Width (cm) 20

Lenght (cm) 20

Standard of gap size (mm) 2±0.5

Image size (pixels) 640x428

Table B-3 Defect level evaluation by inspector for case 3

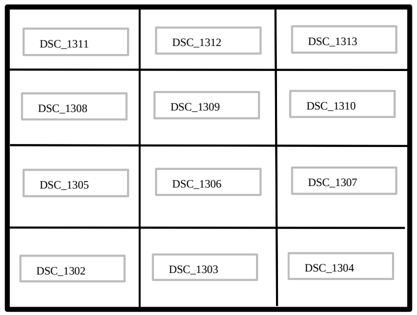
Criteria		Defect checklist	Defect value	Rating by inspector				
				Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work				d_0	**(d_1)**	d_2	d_3	d_4
F1		**Inspecting the completion of tile**		**(d_0)**	d_1	d_2	d_3	d_4
	f_{11}	Tile size meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	f_{12}	Tile pattern meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	f_{13}	The tile without nick or gash	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
F2		**Inspecting distance between neighbouring tiles**		d_0	d_1	d_2	**(d_3)**	d_4
	f_{21}	Gap size uniforms and meets standard		d_0	**(d_1)**	d_2	d_3	d_4
	f_{22}	The glue has to be spread uniformly over gap line	22 points	d_0	d_1	d_2	**(d_3)**	d_4
F3		**Inspecting tile alignment**		**(d_0)**	d_1	d_2	d_3	d_4
	f_{31}	Tiles must be set in straight parallel lines		**(d_0)**	d_1	d_2	d_3	d_4
	f_{32}	Neighbouring tiles have to be on the same level	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
F4		**Inspecting attachment between tile and panel**		**(d_0)**	d_1	d_2	d_3	d_4
	f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	f_{42}	The tile must be pressed evenly against the panel	1 tile	**(d_0)**	d_1	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 1 (3 years)

Image no. layout:



Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-3 Defect level evaluation by inspector for case 3 (continued)

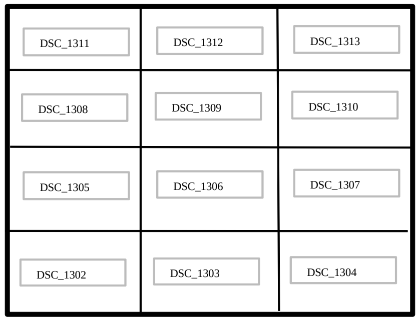
Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	**d_1**	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		**d_0**	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	d_1	**d_2**	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	**d_1**	d_2	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	22 points	d_0	d_1	d_2	**d_3**	d_4
	F3		**Inspecting tile alignment**		**d_0**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**d_0**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		**d_0**	d_1	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	1 tile	**d_0**	d_1	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 2 (2 years)

Image no. layout:



Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-4 Defect level evaluation by inspector for case 4

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	d_1	**d_2**	d_3	d_4
	F1		**Inspecting the completion of tile**		d_0	d_1	**d_2**	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	3 tiles	d_0	d_1	d_2	**d_3**	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	**d_1**	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	d_1	d_2	**d_3**	d_4
		f_{22}	The glue has to be spread uniformly over gap line	14 points	d_0	d_1	**d_2**	d_3	d_4
	F3		**Inspecting tile alignment**		**d_0**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**d_0**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**d_0**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	d_1	**d_2**	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**d_0**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	2 tiles	d_0	d_1	d_2	**d_3**	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 1 (3 years)

Image no. layout:

DSC_1323	DSC_1324	DSC_1325
DSC_1320	DSC_1321	DSC_1322
DSC_1317	DSC_1318	DSC_1319
DSC_1314	DSC_1315	DSC_1316

Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-4 Defect level evaluation by inspector for case 4 (continued)

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	**(d_1)**	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		d_0	**(d_1)**	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	3 tiles	d_0	d_1	**(d_2)**	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	**(d_1)**	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	d_1	d_2	d_3	**(d_4)**
		f_{22}	The glue has to be spread uniformly over gap line	14 points	d_0	d_1	**(d_2)**	d_3	d_4
	F3		**Inspecting tile alignment**		**(d_0)**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**(d_0)**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	**(d_1)**	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	2 tiles	d_0	d_1	**(d_2)**	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 2 (2 years)

Image no. layout:

DSC_1323	DSC_1324	DSC_1325
DSC_1320	DSC_1321	DSC_1322
DSC_1317	DSC_1318	DSC_1319
DSC_1314	DSC_1315	DSC_1316

Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-5 Defect level evaluation by inspector for case 5

Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	**(d_1)**	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		**(d_0)**	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	**(d_1)**	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	d_1	d_2	**(d_3)**	d_4
		f_{22}	The glue has to be spread uniformly over gap line	10 points	d_0	d_1	**(d_2)**	d_3	d_4
	F3		**Inspecting tile alignment**		**(d_0)**	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		**(d_0)**	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	**(d_1)**	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	**(d_0)**	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	1 tile	d_0	**(d_1)**	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 1 (3 years)

Image no. layout:

DSC_1335	DSC_1336	DSC_1337
DSC_1332	DSC_1333	DSC_1334
DSC_1329	DSC_1330	DSC_1331
DSC_1326	DSC_1327	DSC_1328

Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

Table B-5 Defect level evaluation by inspector for case 5 (continued)

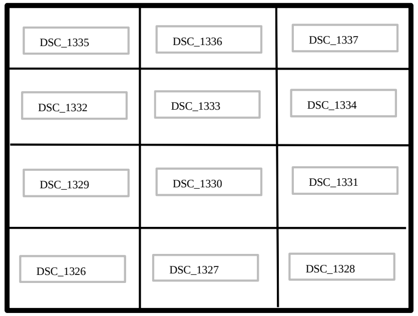
Criteria			Defect checklist	Defect value	Rating by inspector				
					Very low defect	Low defect	Medium defect	High defect	Very high defect
Overall of work					d_0	(d_1)	d_2	d_3	d_4
	F1		**Inspecting the completion of tile**		(d_0)	d_1	d_2	d_3	d_4
		f_{11}	Tile size meets specification	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{12}	Tile pattern meets specification	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{13}	The tile without nick or gash	0 tile	(d_0)	d_1	d_2	d_3	d_4
	F2		**Inspecting distance between neighbouring tiles**		d_0	(d_1)	d_2	d_3	d_4
		f_{21}	Gap size uniforms and meets standard		d_0	d_1	(d_2)	d_3	d_4
		f_{22}	The glue has to be spread uniformly over gap line	10 points	d_0	(d_1)	d_2	d_3	d_4
	F3		**Inspecting tile alignment**		(d_0)	d_1	d_2	d_3	d_4
		f_{31}	Tiles must be set in straight parallel lines		(d_0)	d_1	d_2	d_3	d_4
		f_{32}	Neighbouring tiles have to be on the same level	0 tile	(d_0)	d_1	d_2	d_3	d_4
	F4		**Inspecting attachment between tile and panel**		d_0	(d_1)	d_2	d_3	d_4
		f_{41}	The glue has to be spread uniformly back of the tile	0 tile	(d_0)	d_1	d_2	d_3	d_4
		f_{42}	The tile must be pressed evenly against the panel	1 tile	d_0	(d_1)	d_2	d_3	d_4

General information

Location: Bathroom

Experience of inspector in quality inspection (years): Inspector 2 (2 years)

Image no. layout:



Conditions

Camera distance (m)		0.9
Light vaue	ISO	100
	Shutter speed	1/2.5s
	Aperture	4
Panel size:	Width (m)	1.0
	Height (m)	1.0
Tile size:	Width (cm)	20
	Lenght (cm)	20
Standard of gap size (mm)		2±0.5
Image size (pixels)		640x428

VITAE

Chollada Laofor was born on November 4, 1978 in Nonthaburi, Thailand. She received her high school education at Satrinonthaburi School in Nonthaburi province. After finished high school, she continued her Bachelor's degree in Civil Engineering at Faculty of Engineering, Mahidol University, Thailand. After graduated in 2000, she worked as a project coordinator in a construction firm for 1 year. She continued studying her Master's degree in construction engineering and management at King Mongkut's University of Technology Thonburi in 2002 and graduated in 2005. While she was studying his Master's degree, she received scholarship from Mahidol University to be a teacher after graduated Doctor's degree. Therefore, she continued studying her Doctor's degree in construction engineering and management at Chulalongkorn University in 2005. Nowadays she and her parent live in Nonthaburi province, Thailand.