IMPROVING QUALITY IN RESIDENTIAL PROJECTS USING KEY CHARACTERISTICS

Lessons learned from the manufacturing industry

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Abstract

Poor construction quality disrupts construction projects, causing reworks, delays, cost overrun, and customer dissatisfaction, all of which can be prevented. This has served as the motivation for the implementation of many quality improvement techniques that have been borrowed from other industries and applied to construction. One such technique is Key Characteristics (KC), which is a methodology that has been successfully applied in manufacturing for decades. Its main purpose is to improve quality by identifying important product requirements and specifications that have a negative impact on the overall cost and final performance of a product, through a systematic, quantitative, and hierarchical approach. The goal of this study is to investigate the applicability and benefits of KC methodology in the construction industry. First, KC methodology and its processes as they apply to the manufacturing industry are introduced. For a better understanding of KC's relevancy to construction, a case study of KC was conducted to improve project quality by reducing change orders in residential projects. Project change order and quality data was collected from a residential construction firm, architectural firm, and general contractors. The case study shows that KC provides a systematic and quantitative approach for improving quality and encourages better integration between design and construction teams.

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Chapter 1. Introduction

1.1 Problem Statement

Reaching acceptable levels of quality in the residential construction industry as well as the industry in general, has long been both a goal and a problem. By definition, quality entails conformance to established customer requirements, in the construction industry, quality can be defined as meeting the requirements of the owner, the designer, the constructor and any regulatory agencies. Any variations in said requirements are therefore considered quality deficiencies. Quality deficiencies and quality management practices account for great expenditure of time, money and resources. The cost of quality deficiencies leading to rework varies from 5% to 10% and even 15% of the total contract value (Sun, 2008). Furthermore, studies show that the main cause of project quality deficiencies are a direct result of design defects: almost 78% of the total quality deficiencies are caused by design and account for 79% of the total cost increase (Burati, 1992). These statistics are a constant reminder of the need for reducing deficiencies and improving construction quality.

Although, there are a number of quality control methods, the residential industry is faced with its own set of implementation challenges; there is no clear consensus on methodology among the industry, if guidelines do exist, they differ from company to company, and the amount of available literature on the subject varies widely. A major challenge for the industry during the past decades has been to deliver high quality projects efficiently and effectively. Research shows that most of the industry's quality improvement processes, if any, are done in the field without any particular methodology (Graham, 2006).

Despite the fact that there is extensive research on current methods to improve quality, there is still a need for a more systematic method that can identify the main causes of variation, provide a more efficient way of prioritizing, controlling and preventing such causes and, at the same time, support the integration of design and construction practices throughout the construction process.

1.2 Motivation and Background

The industry as a whole has been working towards achieving high quality projects while meeting budget and schedule. While progress has been made, the results have been incremental rather than transformative. As an active participant of the residential industry, and with the current downturn in the economy and the constant pressure to produce a final product as efficiently as possible, the author has experienced first-hand the need to improve current quality improvement processes, which has served as a motivation for this research.

The construction industry has widely learned from partner industries, given the nature of the construction industry and it's similarities to the manufacturing industry, some of the most widely used concepts have been borrowed from the manufacturing industry. Concepts such as lean manufacturing and TQM have been embraced and applied successfully and it is this notion what motivated a search for a new approach to quality improvement. Key Characteristics or KC was first introduced in the aircraft industry in the early 1980s (Zheng, McMahon, Li, et al., 2008) and seems to keep gaining popularity in many US companies as a way to focus an organization "on important product features that have as significant impact on product and customer requirements" (Lee et al., 1995). Since its inception KC methodology has greatly evolved and provides a solid method for quality control throughout the product lifecycle. Companies such as Boeing, GM, Xerox and the US Department of Defense have been successfully implementing key characteristics methodology to a variety of products ranging from simple panels to complex aircrafts, as a means to reduce product variation and improve overall product quality.

1.2.1 Literature Review

There has been mention of KC methodology in existing construction research (Shen, Hao, Mak, et. al., 2009), however there is currently no available research on KC implementation in the construction industry. Most literature review efforts were focused on understanding current practices and methodology in the manufacturing industry. The findings related to key characteristics and manufacturing will be discussed in a later section of this research.

There are a number of studies that focus on current industry practices, methods such as TQM provide teams with tools to identify causes of problems (Arditi, 1997), however, goals are often broad and lack specificity. Lean construction efforts share the same principle of KC methodology; however, it does not provide a prioritization system to identify the best improvement areas. Others such as statistical process control (SPC) is used to monitor quality during production process (Krajewski and Ritzman, 1998), however, it is mainly specific to a single quality area and does not provide a systematic view of the project as a whole, similarly, six sigma overlooks systematic methods for identifying the best opportunities for improvement. While these methods have improved quality control, research suggests the proposed KC methodology has the potential of supporting and improving said methods.

1.3 Project Scope and Objectives

The main goal of this project is to use the concept of Key Characteristics to improve the quality of residential construction projects. Specific objectives were:

1. To provide a systematic approach that identifies key sources of variation,
2. To identify the best areas for improvement,
3. To facilitate integration between design and construction.

Subsequently, it is also the goal of this study to:

1. Understand, introduce, and analyze the Key Characteristics concept and it's applicability in the construction industry through a case study,
2. Serve as the basis for future studies and implementations.

It is important to note that the scope of this project was limited to the residential construction industry only and it relied heavily on published sources and data from a single construction company therefore, it should be considered as exploratory in nature rather than exhaustive.

1.4 Research Approach

The details of the research methods are presented in Chapters 2 and 3. However it is useful to understand the approach from an overall perspective. The approach to this problem was as follows: First, extensive literature review was conducted on KC methodology as it applies to the manufacturing processes in order to fully understand the method and its possible applications. As a result, a generic process map was developed and subsequently applied to a case study in the residential construction industry.

Chapter 2. KC Methodology and Manufacturing

2.1 Background

Key Characteristics play a significant role in the manufacturing industry from product design to manufacturing process planning to production, testing and information management. Like construction, the manufacturing industry deals with a number of parts that come together to form a product. Products such as buildings are complex and are comprised of many parts from many sources, designed by different people at different times (Whitney, 2006). During assembly and during construction it is necessary to continually monitor the construction process to ensure that requirements are met. However, due to the large quantity of specifications, tolerances and requirements specified in a drawing set, it is not logistically or economically feasible to control and monitor every single part of a product (Boukamp, 2007) or building. KC methodology is used to address the problem of what to improve and what to improve first, and is used to indicate what product features require special attention (Lee and Thornton 1996). KC is a simple principle that has not only been improving quality in the manufacturing industry but has also improved and promotes integration.

2.2 Methodology

Key Characteristics methodology relies on the identification of key areas of variation, the identification process enables the team to determine what processes, parts and parameters are likely to impact final product quality (Thornton, 1996). Selection and evaluation of Key characteristics is encouraged to be performed throughout the whole product lifecycle. In manufacturing, there are a number of tools in use for the identification process and the use of a specific method depends on the company's available data. Most identification tools cover variation, loss function, risk, variation analysis, historical data analysis, etc. Some of the most common tools will be discussed in section 2.2.1.2. However, regardless of the tool that is selected for a given product, in theory, the typical identification process consists of three steps: Critical System Requirements (CSR), System KC and KC flowdown. Figure 1 shows a generic theoretical map for KC methodology. It is important to note that the identification process can vary and will most likely vary from company to company. For the purpose of this study, the above mentioned identification method will be used as it is considered to best fit the industry. This study will focus on the identification process only as the subsequent steps are specific to every project or company and are not part of the scope of this study.

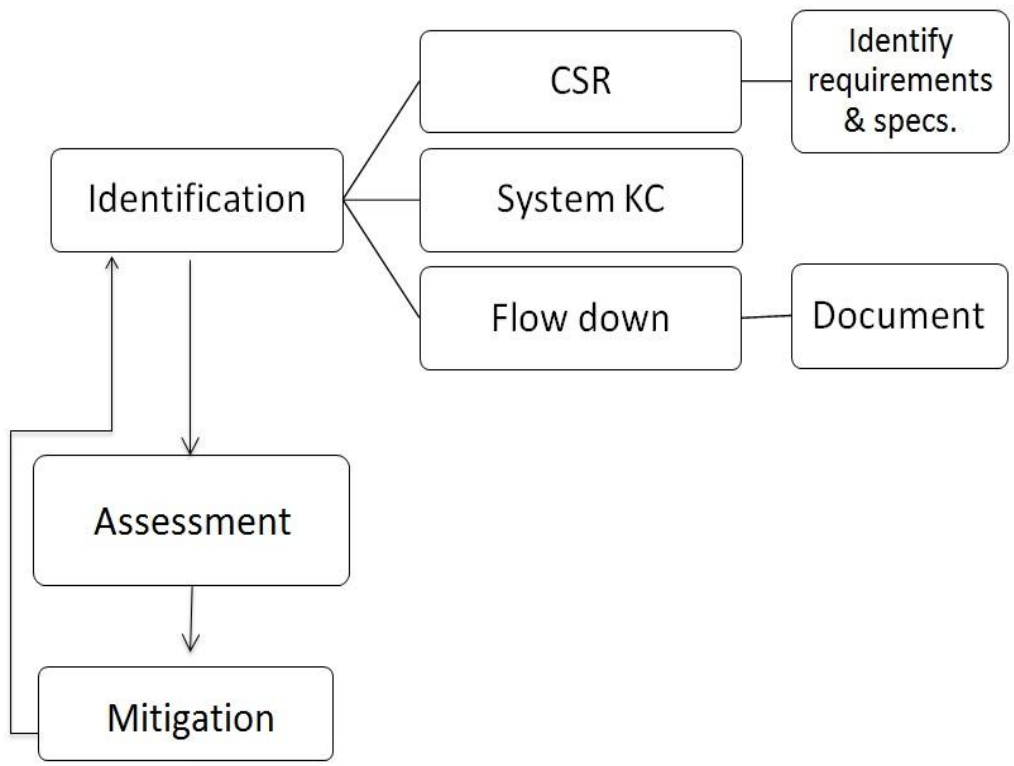


Figure 1. Theoretical Framework

2.2.1 KC Identification Process

The first step is the identification of the Key Characteristics. During this process teams should perform the following activities: quantify variation and cost parameters, identify when variation is most detrimental to the product, classify and rank KCs. The first goal in improving quality is to quickly verify areas where variation has the largest impact on the project. The identification process develops and records a holistic view of how the final quality of the product is delivered and, it links customer requirements to parts and processes (Lee and Thornton, 1996). During this process the team should constantly ask the question: "Will variation affect final product quality?". Before the identification process can begin the scope and requirements should be clearly defined and understood. The identification process consists of three main steps: Critical system requirements list (CSR), system KC identification and KC flowdown.

2.2.1.1 Critical System Requirements (CSR)

The first step in the identification process is to identify critical system requirements CSR, the ultimate goal is to deliver what the customer wants, therefore, the starting point is identifying the voice of customer and designer and translating it into a list of critical system requirements. "The voice of the customer" refers to the set of requirements that will ultimately deliver what the customer wants (Mathieu, 2001). For both new and existing products, a list of possible CSR candidates should be identified and then the team will determine if these items are most likely to be susceptible to variation. A number of sources can contribute to the CSR documentation process, sources can include the following:

- **Drawings and specifications:** In some cases a product can include hundreds of specifications and it would be too time consuming to examine each one of them. Instead, the team should prioritize specifications to create a shorter list.
- **Quality plans and reports:** In the manufacturing industry, these reports are directly tied to critical parts and processes and can be a significant source for CSR identification.
- **Customer complaint and warranty data:** customer reports of defects can help identify root causes of failure.
- **Producibility requirements:** CSRs can also be related to the ease of manufacturing for example: tolerances and clearances that will affect the overall production's ability to build the product in the most efficient way (Thornton, 1999).

Some of the above mentioned sources do not directly apply to construction or are not typical of a construction project; however, there are similar items in the construction industry that will provide the intended insight, for instance: change orders, warranty data, historical data, etc. It is necessary to highlight the importance of collecting project data during construction projects, as it can help in future CSR identification processes.

2.2.1.2 Identify System Key Characteristics

The second step in the identification process is to identify the system key characteristics from the critical system requirement list. A CSR list can have multiple requirements, depending on the number and impact all CSRs can become KCs, however, typically only a few CSRs become KCs. What is a KC? The answer should be clear to all project members. Per definition, a KC is a feature or component, assembly or process whose *variation* has an unacceptable impact on cost, performance or safety of the final product. It is during this stage that identification tools are most useful, and help prioritize identified KCs. KC tools are used as best fit for the available data and the type of project; it is up to the team to decide which would work best for the project. Ultimately, a System KC is ranked quantitatively based on both cost and variation. As a common rule among the industry, a feature is designated a KC if there is a steep loss function, or based on their relative contribution to variation. Below is a list of the most common practices used in the manufacturing industry to identify and prioritize KCs to determine which should be monitored, changed and/or controlled:

- **Statistical processes:** this method is used to track the behavior of a system to determine where processes are going out of control because of variation (Ertrugul, 2009).
- **Analysis of previous products:** in some instances the use of historical data can be used to predict the performance of future designs. Historical data can be used to provide a quantitative analysis for future products and can be used in combination with statistical processes or software models.
- **Tolerance analysis:** this method is used to examine the capability of individual processes and determine the impact of variation on requirements.
- **Variation analysis:** this method establishes a target value and monitors such value to ensure that it is maintained within the acceptable limits.
- **Variation models:** these models describe quantitatively how variation in specific parts or process will impact the system KC and can serve as a prediction tool for final product quality (Zheng, McMahon, et al, 2008).

2.2.1.3 Creating KC flowdowns

Once the system KCs have been identified and quantified, a variation flowdown should be created for each identified KC. The goal of the flowdown is to capture in diagram form the knowledge about which requirements are sensitive to variation and what contributes to the variation (Zheng, McMahon, et al, 2008). Figure 2 shows a generic flowdown as it pertains to the manufacturing industry, Figure 3 illustrates the flowdow process for a car door. The flowdown will not always follow the pattern shown depending on the complexity of the product and how it is produced. It is essential to note that KC classification and layers are a source of constant debate in the manufacturing industry, a number of studies in KC methodology often differ in the classification and terminology of a KC, some studies have even created new terminology for KC classification that is directly linked to a specific identification method. The terms described below were used for the purpose of this study and were based on the most used form of classification within the manufacturing industry. A generic flowdown can have as little as 3 branches and as many as 10, if more than 10 branches are included, there needs to be a reevaluation of the flowdown as 10 branches is considered to be difficult to effectively monitor (Thornton, 2004). A generic flowdown will typically consist of the following layers and definitions:

System KCs: These KCs represent the requirements that are the most sensitive to variation. The combination of all KCs together, makes up the final product.

Assembly KCs: These are requirements that contribute variation to system KCs.

Part KCs: These are requirements for individual parts that contribute variation to the assembly KCs.

Process KCs: These are process requirements that contribute variation to part or assembly KCs.

A variation flowdown is critical to the entire methodology for the following reasons:

- Links requirements with processes, understanding this link will greatly impact the overall final product and provide a guide as to what can be and should be controlled.
- Provides a map for ease of communication and visualization.
- Provides a product history, it can used for future products.
- Serves as a framework for the implementation, assessment and mitigation procedures.

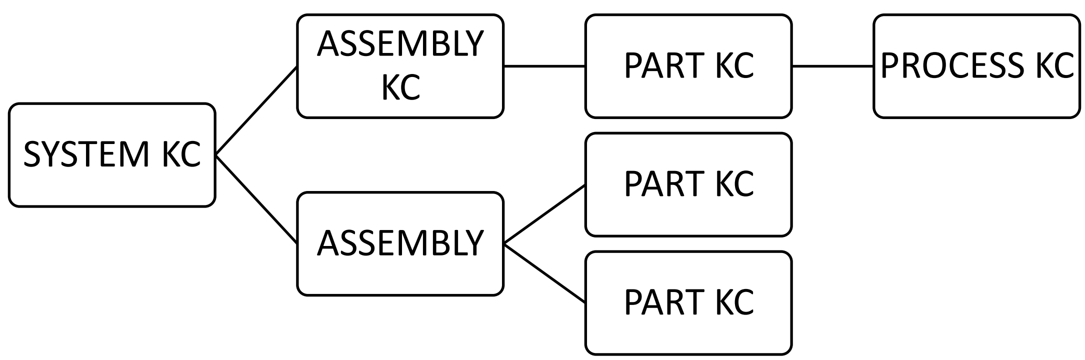


Figure 2. Generic Flowdown

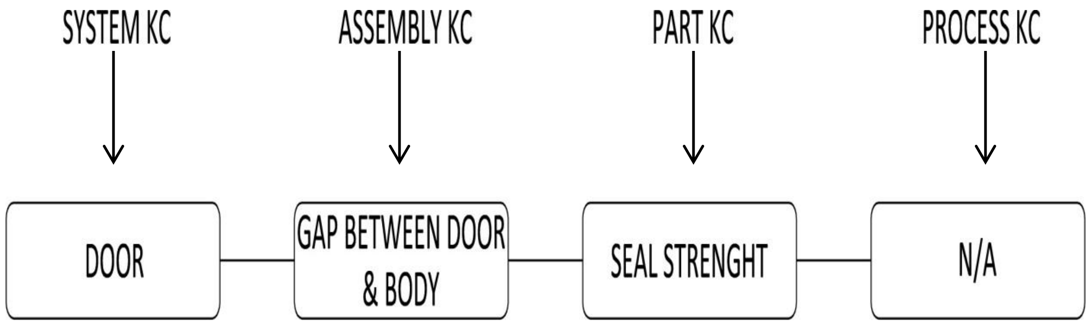


Figure 3. Car door KC flowdown

2.2.2 Assessment and Mitigation

As stated in the previous sections, the identification process yields two results: KCs have been identified and flowdowns have been created, the next steps are assessment and mitigation. These steps vary depending on the specific needs of the company using them, and the assessment phase also varies on the timing it is applied. For the purpose of this research, this study will follow the steps in Figure 1 and use the following assessment definition: assessment refers to the analysis of risk involved in not achieving a KC (Lee and Thornton, 1996). This step is usually performed in order to choose the best mitigation strategy to all identified KCs. Given the specific nature of this step, all mitigation processes are related to the nature of the manufacturing product, therefore, do not apply to the construction industry and further research is needed to identify mitigation processes for the manufacturing industry.

2.3 Current Implementation

Currently, in the manufacturing industry the KC methodology is implemented with great success throughout the product lifecycle to allow teams to focus on key elements that will affect the overall product quality. KCs provide flexibility and robustness to be applied in all stages of product development. Figure 4 provides an overview of the manufacturing process, and presents a summary of KC methodology and its current applications.

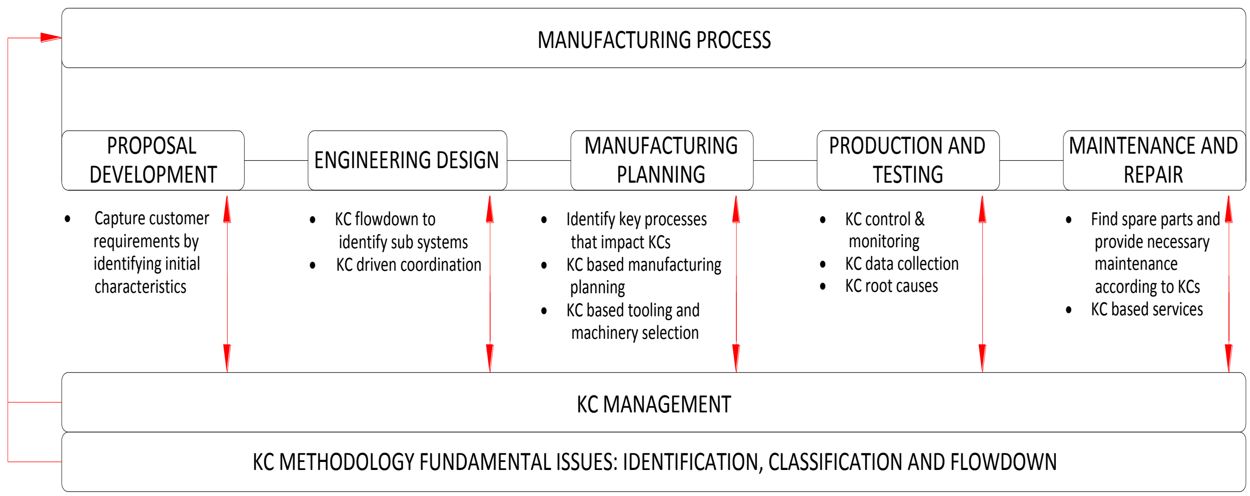


Figure 4. KC methodology and applications / Manufacturing Process

Beginning with the project design, KCs are used to reduce variation in assembly design, a number of studies have been published regarding methods to incorporate KC into project design. Natajara, et al. discusses how KCs can be used to express and capture the product design intent and developed a software program to house all the critical design data. The software is intended to identify, assess and mitigate variation in early design stages.

During the manufacturing process planning, KCs are necessary to select the essential part features, tools, capabilities, etc., that contribute to quality requirements.

Most of the research in this area focuses on developing manufacturing guidelines to deliver high quality products by using KCs. Whitney (2006) proposes using KC methodology to select the necessary part features, tools and machinery, the study highlights the importance of the flowdown as a means to communicate to assembly workers and serves as a starting point of the assembly analysis.

In the production and testing phase, KCs provide a powerful tool that identifies sources of variation, which in turn, can be monitored and eventually resulting in better allocation of resources, greater performance, fewer defects and lower costs. During this stage KCs can also be of great contribution to prediction modeling tools. The majority of research focuses on applying KC to reduce variation and focus on final quality of the product, software products including 3D products are currently being tested in the automotive and aerospace industry.

Finally, as knowledge and information increase along with technology, recent studies have directed their efforts in managing and using KC information and knowledge to improve product development. Rezayat (2000) has proposed to use the concept of Key Characteristics to serve as a basis for a communication dictionary, the ultimate goal of which is to integrate and globalize communication between all phases and parties involved. Rezayat argued that KC methodology along with XML provide a practical shared vocabulary and communication tool to be shared among all levels of communication for the entire product lifecycle. This notion has also served as the basis for multiple supporting studies on how KC methodology can be implemented to track and assure key information is properly distributed and monitored, ultimately leading to a better product performance and higher product quality.

2.4 Benefits

After discussing the Key Characteristics methodology and identification process, this section describes the benefits the manufacturing industry has obtained from applying KC methods. The main contribution has been the ability to improve quality in the overall product process. The manufacturing industry has benefited from KCs by determining and communicating critical design features, this proactive design approach has helped improve activities within an organization and with supporting organizations by focusing teams on decisions and attention on the critical product parameters. Communication is encouraged, therefore creating tighter integration and relations. KC has been successful in identifying key weaknesses bases on historical data of rework and product failures, these trends can be analyzed for strategic product planning and manufacturing and have been helpful to mitigate future failures and rework. KC methodology has also contributed to investment and equipment decisions based on the use of KCs to identify key manufacturing capabilities and key processes where expenditure is required to improve capabilities. Finally, the KC flowdown has also been successfully used to assist in the search of root causes of problems occurring during the product production.

In conclusion, many manufacturing companies are increasingly aware of the importance of key characteristics due to the fact that KC methodology is a power tool for improving communication, production, decision making and most of all, it helps in the production and delivery of high quality products that meet all design and customer requirements.

Chapter 3. KC Implementation in Residential Construction Projects

3.1 Introduction

In order to fully understand the KC methodology and the applicability to the construction industry, this research presents a case study in residential construction projects. The goal of this case study is to implement KC methodology as a means to improve quality by performing an analysis of change orders in residential projects using KC methodology and exploring all the possible benefits including prioritization and integration between design and construction processes. Change order data was selected for this case study since, by definition, change orders are linked to quality defects in the project delivery process, including design and construction. A change order can be defined as "any deviation from what was intended and be agreed, or any event which yields to modification of original scope, time or cost of the work." (Ibbs and Allen, 1995). For the purpose of this research quality is defined as adherence to previously established requirements, and requirements refer to customer and design requirements, therefore any subsequent changes are considered quality deficiencies.

Much of the time delays, cost overruns and quality defects of construction are attributed to changes at various stages of a project. In the construction industry, a change refers to an alteration to design, planning, project work, project scope, construction methods or other aspects caused by modification to preexisting conditions, or requirements. Given the nature of the construction process, it is particularly prone to changes for a variety of reasons; variation in any of the requirements during construction will lead to changes. The cost of project changes has been found to be as high as 15% of the project's cost, in addition to cost, other negative effects include loss of productivity, disputes and claims, and most of all quality defects (Sun and Meng, 2008).

Change occurrence during the construction process and its effects on quality is a common concern among all parties involved in a project. Hence, identifying and controlling them to mitigate their negative impact is critical (Almasi, 2011). This research classified change order data based on literature review regarding change order classification and also based on the company from which the data was received. Following are the data collection methods and implementation steps followed by the results and limitations of the study performed.

3.2 Data Collection

The data collection process was based on professional experience, after being exposed to construction processes and having experienced the need to provide a method for quality improvement. Change order data was collected from a well-known residential construction firm based in Houston, the change order data collected consisted of change order documentation in the form of hard copies for seven residential construction projects. The data collected included change order proposals, change order requests, change order invoices, supplier invoices, project estimates, periodic project cost reports, and AIA certificates of payment. Refer to Appendix A for a sample of the data collected.

The change order data collected contained a total of seven projects which had been labeled as "change order prone" by the construction firm and included both remodeling and new construction projects, the projects ranged in price from $600,000 to $2,000,000, and were completed within the last 3 years. In order to provide a more accurate analysis, data was examined to confirm change order costs could be verified, data was also examined for thoroughness of change order description, cost and filing method. Since new construction and remodeling projects are different in nature, they should be studied separately. In this study, only new construction projects were considered, leaving a total of four projects ranging in price from $1,000,000 to close to $2,000,000. These projects were all new homes with an average size of 6,500 square feet and did not include additional outbuildings such as garage quarters, guest quarters, pool houses or others. The average scheduled construction time was 18 months, and although schedule plays an important role in final product satisfaction, schedule was not analyzed in this study due to insufficient information in such area.

Before the data analysis could begin and after the data collection and selection process was finished, the collected change order data was carefully classified and sorted out to include and reconcile both proposal and final cost and traced back to the overall project cost. All change orders were grouped with their supporting invoices and any other available data. Figure 5 shows the collection and sorting process. After data collection was finalize, the data analysis process was performed, and data analysis is discussed in detail in the next section. However, it is important to note that during the analysis process, additional supporting data was collected in the form of phone interviews, discussions and face to face interviews with architects, project architects, superintendents and general contractor. This data was limited to the employees of the construction firm providing the change order data and interviews with architects were done through the author's current employer. The purpose for conducting interviews and engaging dialogs was to collect additional data not included in change orders such as personal expertise and most importantly to collect feedback, identify current needs and evaluate interest in the proposed methodology.

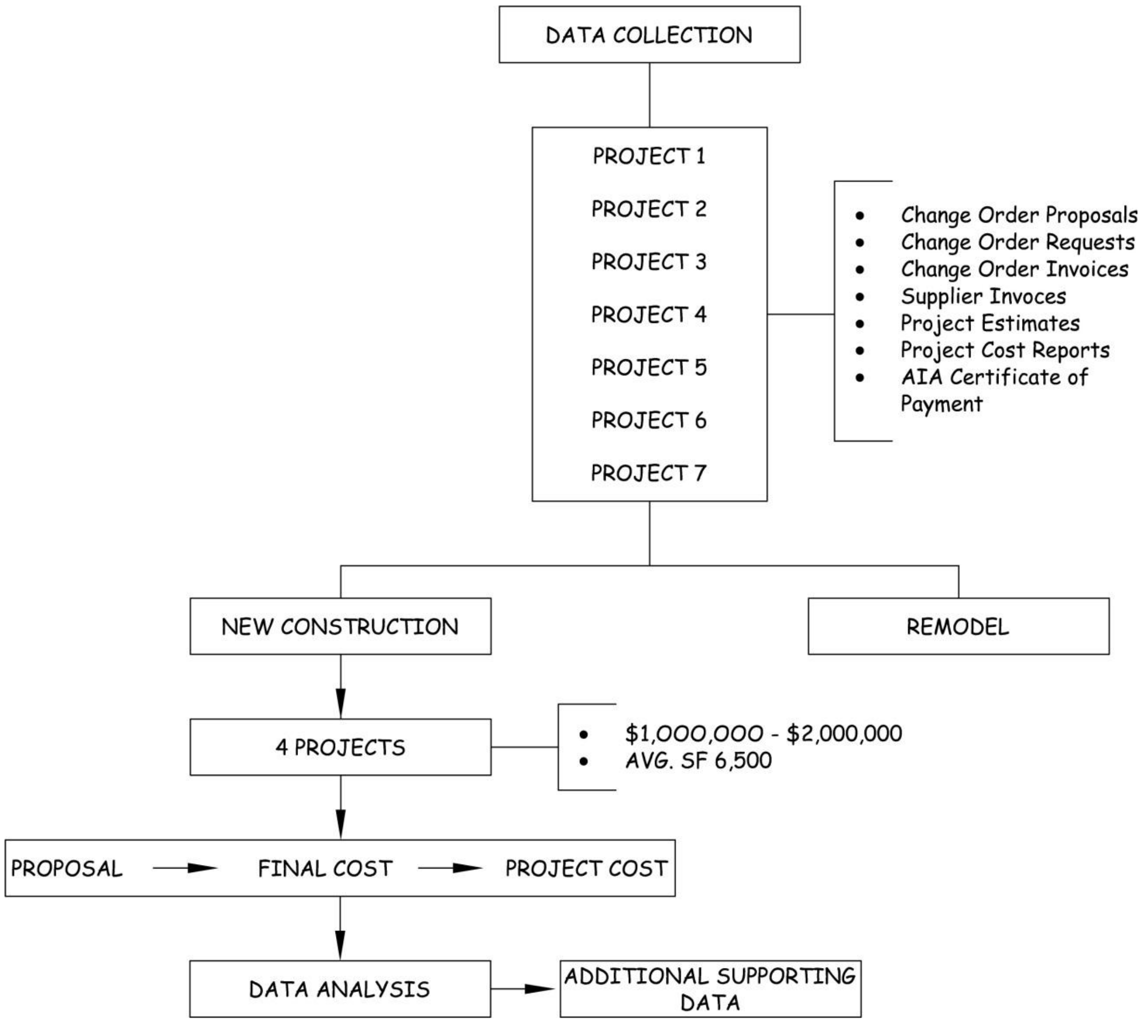


Figure 5. Data Collection flow chart

3.3 Data Analysis

The analysis process began with the selected documentation. A total of 224 change orders where documented for the four new residential construction projects totaling more than $520,000 in cost increase and a change order ratio of more than 10% of the total project cost. The data was analyzed based on the KC methodology and was therefore divided into five levels, providing a work breakdown structure type of format for analyzing the collected data. The goal was to successfully apply and identify KCs. Figure 6 below provides a summary of the methodology and levels of data analysis performed.

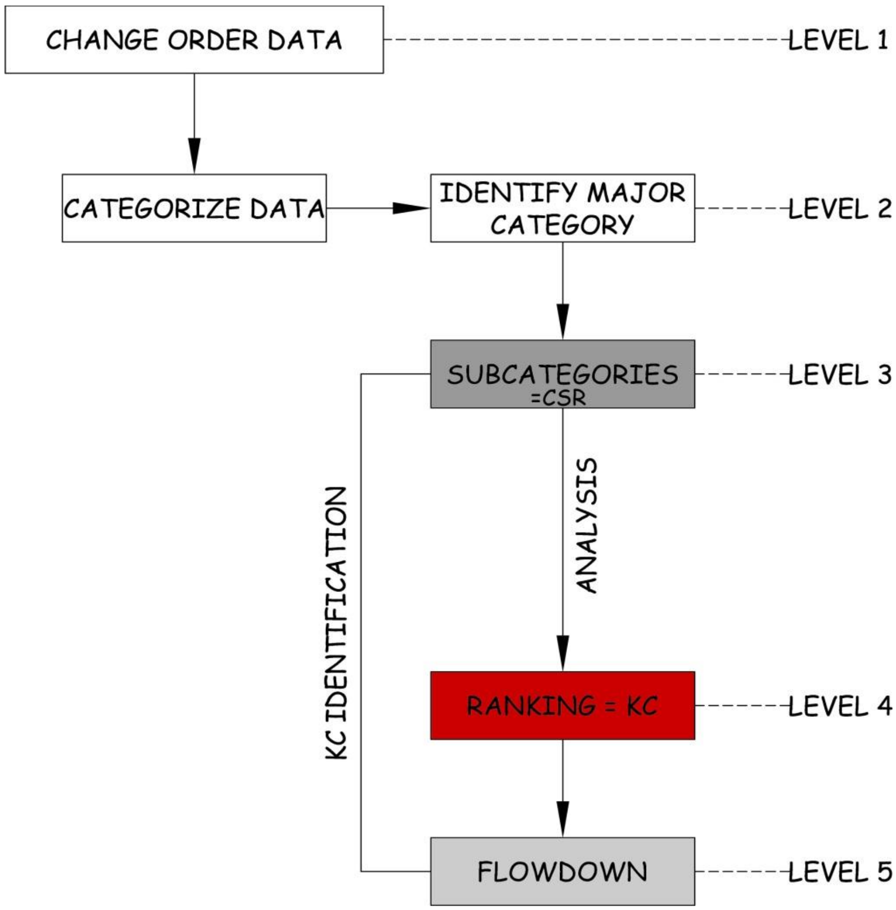


Figure 6. Levels of data analysis

- **Level 1:** During this stage, change order data along with overall project cost was combined, the goal during this stage was to provide an overview of the four projects as a whole.
- **Level 2:** The goal for this stage was to categorize change orders based on their cause and identify the type of cause where most change orders occur, and where

most money is spent. Therefore, each construction project was categorized based on the cause of the change order. Five different causes were identified:

- Safety: This type of change order refers to any unforeseen site safety considerations and site security.
- Change in codes and regulations: codes and regulations are constantly changing, what was implemented at the beginning stage of the process might not be in place by the time construction begins. This type of change order also refers to such changes including code misinterpretations.
- Unknown site condition: Once construction begins, there are times when unforeseen site conditions surface, some might be due to underground conditions or additional requirements.
- Change in decision making: This type of change order refers to changes in the authority of decision making. Sometimes third parties are involved at later stages and create an additional layer of communication changing the sequential order of decision making.
- Planning and design: This type of change order is primarily the result of defects, errors, and omissions in design and planning, such as inconsistencies between drawings, citation of inadequate or erroneous specifications, etc.

After the categorization process, a descriptive statistical analysis was performed in order to identify the category where most defects occurred. As part of this level, the change order data was compared based on the following parameters:

- Relative frequency: provides the ratio of observed frequency and total frequency:

  Relative frequency = # of occurrences of a given category / total number of change orders

- Total cost per change order category: provides the total number of change orders per category.

- Average cost: provides the average value of a change order category (Figure 8).

- Contribution Degree (CD): measures the degree of contribution of a given cause of change in the project cost (Figure 9).

  CD = Addition value of a given cause / original cost of projects x 100%

It was found that planning and design accounted for the most change order occurrences with more than half of the total number of change orders (113) at 53% of the total number of change orders and also contributed to the most cost increase with a CD of 7.1%, this category also had the highest average cost per category. Given the overwhelming difference between the rest of the categories, this study will focus on implementing KC quality improvement methodology to requirements within this category. Figure 7 provides a summary of the categories used for this analysis and Table 1 presents an overview of the analysis process; for further information and database material see Appendix B.

Table 1. Data analysis for change orders per category

CATEGORY	RELATIVE FREQ.	#	TTL COST PER CATEG.	AVERAGE COST	CD
PLANNING & DESIGN	53%	113	$365,721.00	$3,236.47	7.1%
CHANGE DECISION MAKING	27%	57	$107,972.68	$1,894.26	2.1%
UNKNOWN SITE CONDITIONS	9%	19	$35,041.12	$1,844.27	0.7%
CHANGE CODES/REGULATIONS	8%	18	$16,140.01	$896.67	0.3%
SAFETY	3%	7	$3,371.50	$481.64	0.1%
TOTAL	**100%**	**214**	**$528,246.31**	**$2,468.44**	

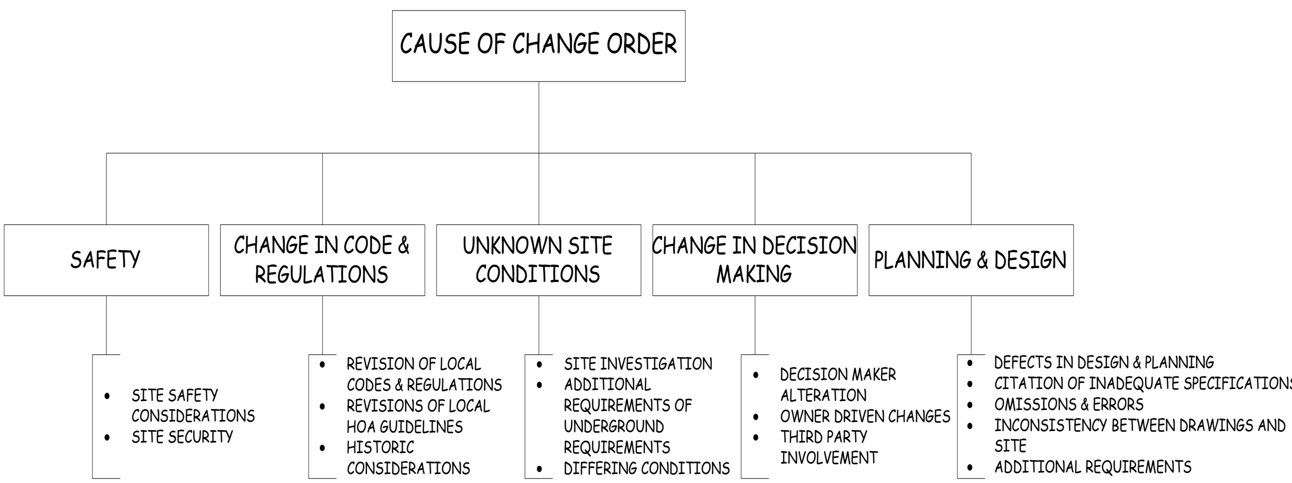


Figure 7. Change order categories by cause

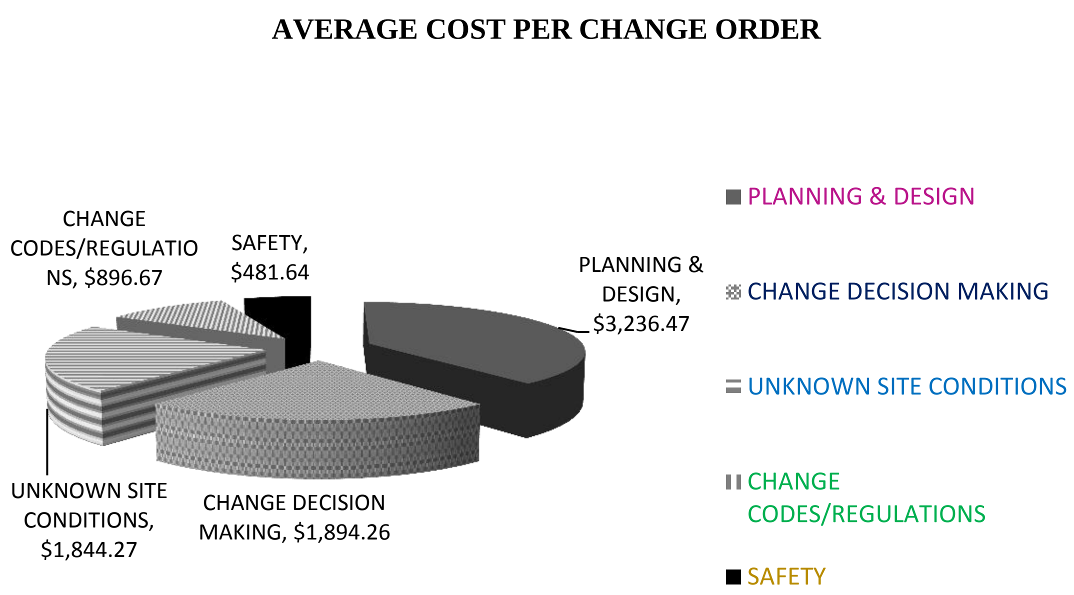


Figure 8. Average cost per change order

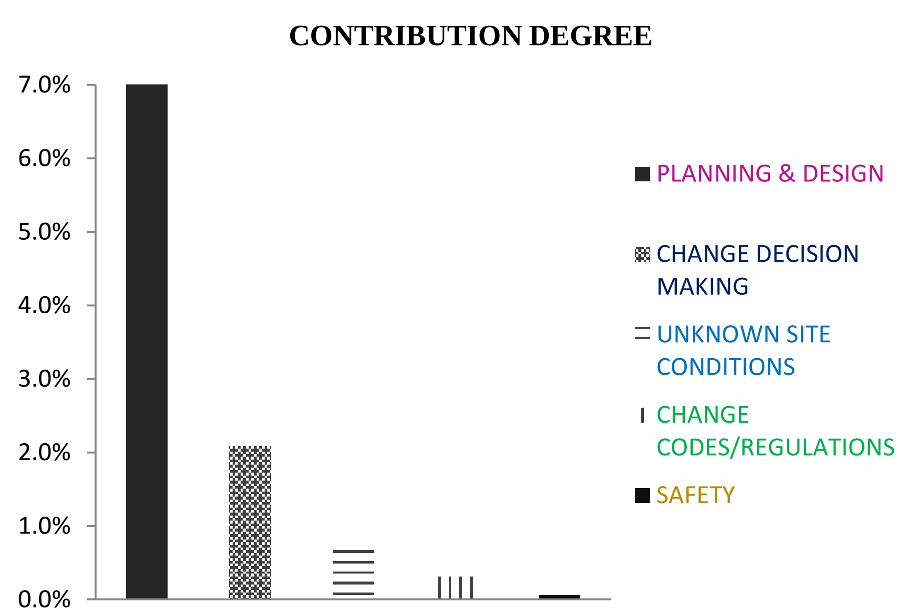


Figure 9. Degree of contribution per change order category

- **Level 3 – Critical System Requirements:** The goal of this step was to identify critical system requirements (CSR). Once planning and design was identified as the main contributor to changes, this data then became of critical importance for KC identification. With a total of 113 change orders related to planning and design, the change orders were then subcategorized based on construction stages in order to identify critical system requirements that contribute to variation within this category. The sub-categorization was based on analyzing the specific cause of the change order as it relates to construction activities, in other words, change orders were studied to identify when and where the change occurred. Using the terminology and coding employed by the construction firm, seven subcategories were identified, and defined as critical system requirements. Table 2 below is a list of the identified CSRs:

Table 2. Critical System Requirements

CRITICAL SYSTEM REQUIREMENTS		
CODE	OCURRENCE	ACTIVITY
3.3	5	CONCRETE
4.2	16	MASONRY
6.1	26	FRAMING
6.2	8	FINISH CARPENTRY
7.6	9	ROOFING
8.5	8	WINDOWS
9.2	6	SIDING
9.5	3	FLOORING
9.9	9	PAINTING
15.4	2	PLUMBING
15.8	2	HVAC
16.1	19	ELECTRICAL
TOTAL	113	

- **Level 4 – Identify System KCs and Ranking:** After identifying the project's critical system requirements, the next step in the KC process is to identify and rank System KCs. A system KC is a CSR that has been identified as a variation contributor negatively affecting the overall final product quality.

  Three rankings were developed to analyze the contribution of each CSR to variation and the overall building quality, and each ranking was developed in order to facilitate the measurement of cost variation and the impact on quality resulting from change orders.

  The first ranking was based on the relative frequency of change orders; each activity was ranked from the highest frequency to the lowest frequency. This ranking assumes that most of the cost variation and defects are based on the number of change orders per activity and ranks them accordingly. The formula used is the same as stated in level 2. Although this ranking identifies which activity has the most number of change orders, it does not consider cost therefore it is only useful as a frequency index. The results were as follows (Table 3).

Table 3. Rank 1 Relative Frequency Results

	RANK 1
	RELATIVE FREQ.
FRAMING	23%
ELECTRICAL	17%
MASONRY	14%
ROOFING	8%
PAINTING	8%
FINISH CARPENTRY	7%
WINDOWS	7%
SIDING	5%
CONCRETE	4%
FLOORING	3%
PLUMBING	2%
HVAC	2%

The second ranking combines both frequency and average cost to create a cost index which provides a normalized average of the cost per change order compared to its frequency. This ranking is more beneficial to the construction industry since the main concern is cost increase due to change orders and this index provides a ranking based on cost. The results for Ranking 2 are shown in Table 4.

Table 4. Rank 2 Cost Index Results

	RANK 2
	COST INDEX
FRAMING	803.96
ELECTRICAL	475.6
MASONRY	386
SIDING	339.33
ROOFING	335.02
PAINTING	279.72
FINISH CARPENTRY	244.68
PLUMBING	155.3
WINDOWS	134.07
CONCRETE	100.77
HVAC	92.81
FLOORING	42.25

The third and last ranking consisted of more than one step and was based on variation and statistical analysis currently used in the manufacturing industry. The third ranking considered both cost and variation. For this ranking, the standard deviation was calculated for each activity and then divided by the mean cost per change order per activity. This index provides an overview of how much risk there is for each category. It is important to note that standard deviation measures the deviation from the mean, the smallest the deviation the closer the data is to the mean, the largest the deviation, the further the data is from its mean. Therefore, it is considered statistically significant. In this case, standard deviation alone was not an effective ranking. For example, siding has the largest standard deviation among all the activities, meaning it has the most variation from its mean. Therefore, it could be concluded that it needs to be monitored. Even though siding has the most variation, it is not possible to determine whether or not siding has the most detrimental effect in cost and quality at the same time. It is for this reason that the third ranking incorporates both deviation and cost analysis, by comparing both parameters, thus, a more accurate ranking method can be achieved. The goal of this rank is to successfully identify and rank system KCs by analyzing how big or small fluctuations (i.e. variation) are relative to the average cost. A smaller risk index indicates a tightly controlled process, whereas a larger value is an indication of a process that is not well controlled. See Appendix C for detailed calculations. Table 5 shows the results for ranking 3.

Table 5. Rank 3 Risk Index Results

	RANK 3
	RISK INDEX
CONCRETE	1.13
ROOFING	1.06
MASONRY	1.04
FRAMING	0.93
HVAC	0.90
ELECTRICAL	0.88
WINDOWS	0.80
SIDING	0.70
PAINTING	0.59
PLUMBING	0.51
FINISH CARPENTRY	0.49
FLOORING	0.37

Table 6 below shows a comparison between all ranks, as can be seen in the chart, for example framing is ranked first in both ranks 1 and 2, however, rank 3 ranks framing fourth. While framing has the highest frequency and cost index, the risk or fluctuation associated with framing in relative to cost is not the highest.

Table 6. Ranking Comparison

	RANK 1		RANK 2		RANK 3
	RELATIVE FREQ.		COST INDEX		RISK INDEX
FRAMING	23%	FRAMING	803.96	CONCRETE	1.13
ELECTRICAL	17%	ELECTRICAL	475.6	ROOFING	1.06
MASONRY	14%	MASONRY	386	MASONRY	1.04
ROOFING	8%	SIDING	339.33	FRAMING	0.93
PAINTING	8%	ROOFING	335.02	HVAC	0.90
FINISH CARPENTRY	7%	PAINTING	279.72	ELECTRICAL	0.88
WINDOWS	7%	FINISH CARPENTRY	244.68	WINDOWS	0.80
SIDING	5%	PLUMBING	155.3	SIDING	0.70
CONCRETE	4%	WINDOWS	134.07	PAINTING	0.59
FLOORING	3%	CONCRETE	100.77	PLUMBING	0.51
PLUMBING	2%	HVAC	92.81	FINISH CARPENTRY	0.49
HVAC	2%	FLOORING	42.25	FLOORING	0.37

For the purpose of this research, ranking #3 will be used as a means to prioritize and determine which system KCs have the greatest impact on the variation of the overall quality. The next step is to determine which activities are considered system KCs. For the next step, the author relied on the above mentioned analysis and comparison between rankings but also conducted numerous interviews with the general contractor, superintendents and architects to determine which activities were considered vital to the overall quality of the building. Cross examination of interviews and change order data was used to determine the following KCs prioritized according to ranking #3 (Table 7):

Table 7. KC Prioritization per Rank 3

SYSTEM KCs PRIORITIZATION:	RANK 3
	RISK INDEX
CONCRETE	1.13
ROOFING	1.06
MASONRY	1.04
FRAMING	0.93
HVAC	0.90

As can be seen in the Table 6 above, it can be concluded that concrete provides the greatest source of variation and is the main contributor to quality defects and cost increases, even though the frequency of occurrence is not significant, the risk of having a concrete related deviation is high and therefore should be monitored.

- **Level 5 – KC flowdow:** The last step in the KC identification process is the KC flowdown; this step provides the team with a critical visualization tool of how to achieve the specified requirements. After our data analysis and ranking, the study has found that the above mentioned System KCs need to be controlled and monitored to avoid future defects. The KC flowdown for the KCs provides a clear view of the subsystems affecting the identified KC. To illustrate this notion, Figures 10 presents a flowdown for the system KCs (Roofing system), as can be seen, the flowdown identified areas of defects and traces them back to the assembly or part where the defect occurs, for example: splitting and blistering were identified as defects which are caused by flashing defects which are located around penetration which in turn are performed during the actual roof framing. By providing a visual aid, it is easier for workers and management to identify and mitigate the root cause of the defect. Refer to Appendix C for additional KC flowdowns.

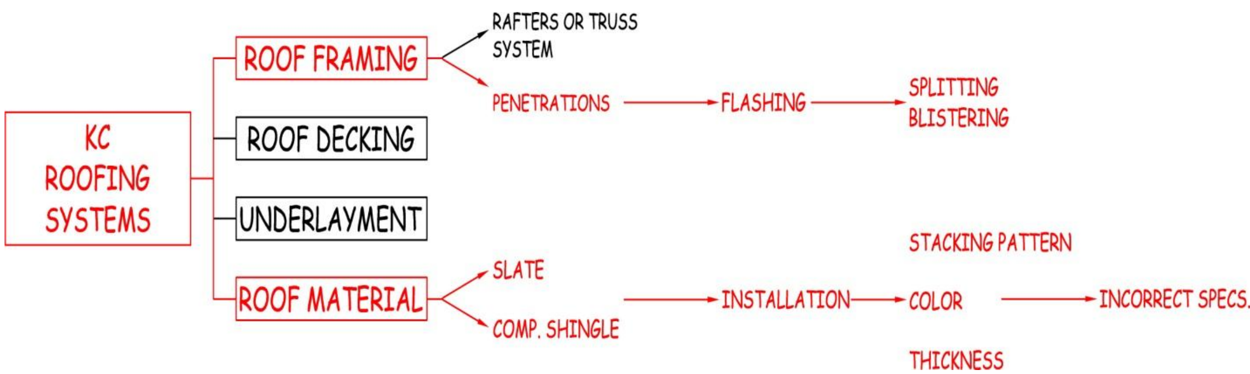


Figure 10. Roofing System KC flowdown

3.4 Results

Based on the finding from this research, it can be concluded that KC methodology can be successfully applied to the industry. The holistic KC approach provides a number of benefits and opportunities for improvement. The study shows that based on the analysis of change orders, the most frequent and detrimental type of change orders occur during the planning and design stages, although the general contractor has little input or control over this stage, this provides the contractor with an effective tool to initiate conversation with designers and architects and also provides a basis for quality control. After the employment of KC methodology it was found that concrete, followed by roofing, masonry, framing and HVAC should be controlled to avoid costly quality variations. The flowdown of each will present the team from general contractor to field operator what contributes to variation on system KCs. All of this combined in a simple tree format can be easily distributed and understood by all members of the construction team.

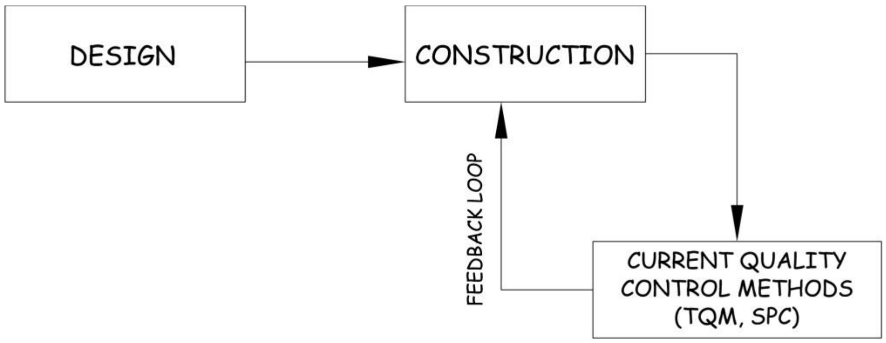
The findings of this study were shared among the firm who provided the data and the architects and it was particularly surprising for the architecture firm to realize how much weight they have in both quality and quality defects. The construction firm agreed with the findings and hoped they could expand and apply the findings of this study to future projects and include all contributing categories. While future collaborations are not part of this study, it is important to note that this has opened a door of collaboration and integration between architects and contractors and it is the intent of the author to keep working jointly to improve quality of residential projects by applying KC methodology.

Chapter 4. Conclusions

Based on both theory and application it is important to note that KC methodology can become a powerful tool for constructors for quality improvement. KC methodology provides a systematic, hierarchical approach of identifying key areas where quality can be improved and identifies all subsequent requirements that contribute to quality improvements and failures of a system KC. This method provides a holistic view of the project starting from the big picture to the smallest work breakdown structure. It serves not only as a learning tool but by identifying which areas to improve, monitor, control, and communicate, KC helps close the loop in the current practices of quality control. Figure 11 shows the current practice vs. the enhanced practices with KC methodology and it can be seen that the proposed methodology provides a more robust process during the course of the project lifecycle. It is important to note that in order to achieve a tighter integration; the contractor must be willing to share information and data with the architect and engineer, although there is a reluctance to share certain information, it is crucial for the industry to understand the benefits of a tighter integration among designers and constructors. It is here where KC could provide a foundation for a tighter collaborative process. However, this research acknowledges the fact that more efforts need to be made in order to close the communication loop within the industry.

Furthermore, this paper presents the starting point for future studies and confirms that the proposed methodology can be applied to the construction industry, the ability to quantify, identify and prioritize key areas of improvement along with flowdowns can be powerful tools for improving communications, construction systems and customer satisfaction as well as assisting in the future planning and making of decisions.

Current QC Practices



QC Practices with KC methodology

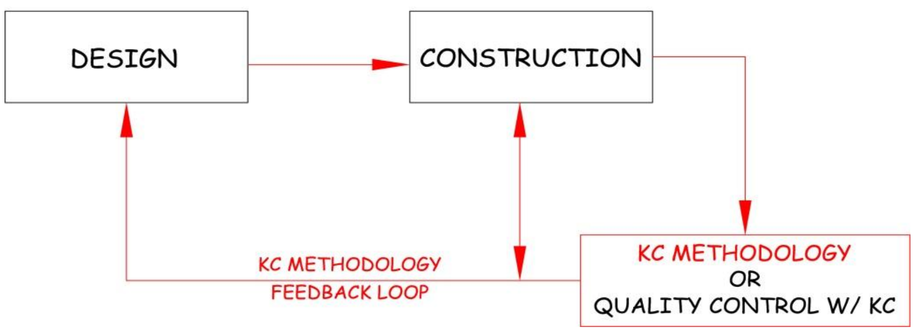


Figure 11. Current Practices vs. enhanced practice using KC methodology

4.1 Scope Limitations and future studies

It is also important to note that the findings of this study are limited by the amount of data collected and it is important to note the importance of having a solid database. Being the results based on one construction firm only, it is therefore limited by the amount of data and methodology for collecting data, which might not reflect the residential industry as a whole, nonetheless it provides useful insight information.

Future studies are greatly encouraged to further analyze the applicability of KCs in the construction industry as a whole and could be applied to larger projects outside of the residential industry. Studies in different identification tools are also encouraged and the need to combine this methodology with 3D modeling could provide contractors with important tools for achieving quality projects. It is the goal of this study to serve as the basis for future studies and ultimately KC implementation and adoption.

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