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Case Study of Real-World Emissions Rates verus EPA Emission Standards for Motor Graders

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ABSTRACT

Using the Volkswagen emissions scandal as motivation, the purpose of this case study was to investigate whether or not heavy-duty diesel construction equipment exceeds EPA emissions standards for nonroad diesel engines. The equipment analyzed included four separate motor graders with EPA emissions standards Tier 0, Tier 1, Tier 2, and Tier 3 engines. The analysis was based on a dataset of real-world emissions rates collected from in-use equipment on actual jobsites. The results showed that mass per time emissions rates for hydrocarbons, carbon monoxide, nitrogen oxides, and particulate matter decreased as the EPA emissions standards became more stringent. Furthermore, there was only one observation in which the real-world average emissions rate exceeded the EPA emissions standard. Recommendations for improving the analysis include testing more equipment to improve the diversity of the study, focusing on mass per fuel consumed analyses that have less variability in emissions rates, and conducting more refined and controlled experiments in real-world conditions.

Key Words: construction equipment, diesel engines, emissions, engine emissions standards

Boshra Karimi is an Assistant Professor of Construction Management at Northern Kentucky University. Her research interests include sustainable project management, sustainability assessment, sustainable technology implementation, supply chain management, decision-making modeling, and big data application in construction.

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INTRODUCTION

The Volkswagen emissions scandal, also known as "Dieselgate", began in September 2015 when the United States Environmental Protection Agency (EPA) issued a notice of violation of the Clean Air Act to the German automaker Volkswagen Group. EPA found that Volkswagen had intentionally programmed the diesel engines in their onroad vehicles to activate their emissions controls only during laboratory emissions testing, which permitted the vehicles' nitrogen oxides (NO_x) emissions to meet EPA standards during regulatory testing; however, the emissions controls deactivated during real-world driving which increased NO_x emissions by up to 40 times. Volkswagen embedded this program in about 11 million cars worldwide, including 500,000 in the United States, for model years 2009 – 2015 (Parloff 2020).

Could off-road vehicles, such as heavy-duty diesel construction equipment, be guilty of violating EPA emissions standards? The authors addressed this question by conducting a case study that compared real-world construction equipment emissions rates to EPA emissions standards. The purpose of the case study was to investigate whether or not the EPA emissions standards for off-road (or nonroad) diesel vehicles were being exceeded by in-use construction equipment on real-world jobsites. The case study focused on motor graders, which are used extensively in highway construction and maintenance, as well as other horizontal construction activities. Also, motor graders were the only equipment type in the available dataset which had data for four different EPA engine tiers. A typical motor grader is shown in Figure 1.

Figure 1 Typical Motor Grader

EPA regulates emissions from on-road and nonroad vehicles by establishing standards for the specific pollutants being emitted. Emissions standards limit the amount of pollution a vehicle or engine can emit. EPA set increasingly stringent emissions standards, known as engine tiers, for carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and particulate matter (PM). These standards began in the early 1990s for nonroad engines and equipment. Once EPA set emissions standards for a particular engine tier, manufacturers were required to produce engines that met those standards according to the corresponding implementation schedule (EPA 2020a).

Table 1 summarizes the EPA emissions standards that applies to the motor graders observed in the case study (EPA 2018). EPA engine tiers range from 1 to 4, with 1 being the least stringent standard and 4 being the most stringent. For this case study, four motor graders were observed. One motor grader had a model year prior to 1996, which means that its emissions were not required to meet an EPA standard. For the purposes of the case study, this particular motor grader is referred to as Tier 0. Furthermore, the case study fleet did not have a motor grader that was required to meet Tier 4 standards; thus, the case study only compared real-world emissions from motor graders that were required to meet Tier 1, 2, and 3 standards.

The case study had two primary objectives: 1) Compare the real-world, average emission rates of each motor grader to its appropriate EPA emissions standards; and 2) Determine whether or not the EPA emissions standards actually reduced real-world emissions as the standards became more stringent. The purpose of the case study was not to determine whether or not construction equipment and diesel engine manufacturers were falsifying emissions data, as was the case in Dieselgate, but to gain insight into the efficacy and impact of EPA emissions standards for nonroad diesel engines in use on real-world jobsites.

Table 1. EPA Emissions Standards for the Case Study Motor Grader Engines

Engine Horsepower	Model Year	Engine Tier	HC (g/hp-hr)	HC+NO_x (g/hp-hr)	CO (g/hp-hr)	NOx (g/hp-hr)	PM (g/hp-hr)
175 - 300	1996-2002	Tier 1	1.0		8.5	6.9	0.40
	2003-2005	Tier 2		4.9	2.6		0.15
	2006-2010	Tier 3		3.0	2.6		0.15
	2011-2013	Tier 4 Transitional		3.0	2.6		0.01
	2014-Present	Tier 4 Final	0.14		2.6	0.30	0.01

LITERATURE REVIEW

There is a rich body of knowledge related to the collection and analysis of real-world emissions data for nonroad diesel construction equipment. Much of this related work applies to this particular case study. For example, Lewis et al (2009a) examined the requirements and incentives for reducing emissions from construction equipment and compared emissions data sources for these types of vehicles. Lewis et al (2009b) also proposed a methodology for developing emissions inventories for construction equipment and presented an emissions inventory for a publicly-owned case study fleet of backhoes, motor graders, and wheel loaders. Ahn et al (2013) developed an integrated framework for estimating, benchmarking, and monitoring pollutant emissions from construction activity.

Rasdorf et al (2010) outlined field procedures for collecting real-world measurements of emissions data from construction equipment. Marshall et al (2012) presented a methodology for estimating emissions from construction equipment used for commercial building projects. Rasdorf et al (2012) evaluated pollutants emitted from construction equipment over the duration of a case study commercial building project. With regard to the specific equipment in this case study, motor graders, Frey et al (2008a) characterized real-world activity, fuel use, and emissions for selected motor graders fueled with petroleum diesel and B20 biodiesel. Frey et al (2008b) expanded this study to include backhoes and wheel loaders, in addition to motor graders.

Much of the work on the relationships between construction equipment and pollutant emissions is summarized in three in-depth papers on the topic. Frey et al (2010) presented the results of a comprehensive field study on fuel use and emissions of nonroad diesel construction equipment. Lewis et al (2015) conducted an engine variable impact analysis of fuel use and emissions for heavy duty diesel maintenance equipment. Lewis and Rasdorf (2016) summarized emissions rates based on equipment types and EPA engine tiers in a taxonomy of fuel use and emissions for heavy duty diesel construction equipment.

CASE STUDY RESULTS AND DISCUSSION

The data used in the case study came from a real-world emissions dataset for 39 items of nonroad heavy duty diesel construction equipment. This dataset was developed by researchers at North Carolina State University from 2005-2009 (Frey et al 2010). It includes over 168 hours of quality assured, second-by-second fuel use, emissions, and engine activity data. In-use average emissions rates were determined for HC, NO_x, CO, and PM. These data were collected by a portable emissions measurement system (PEMS) that was deployed on the equipment as it performed typical construction duty cycles on actual jobsites. For the purposes of this case study, four motor graders were selected from the dataset, including a Tier 0, Tier 1, Tier 2, and Tier 3; Tier 4 emissions standards had not yet been implemented at the time the data were collected. The basic equipment attributes for each motor grader are summarized in Table 2.

Table 2. Summary of Motor Grader Attributes

Motor Grader	Engine Tier	Horsepower	Model Year
Motor Grader A	0	167	1990
Motor Grader B	1	195	2001
Motor Grader C	2	195	2004
Motor Grader D	3	198	2007

Motor Grader A was the oldest item of equipment in the case study fleet, being over 10 years older than the next oldest. As a result, Motor Grader A was not required to conform to any of the EPA emissions standards and is therefore referred to as Tier 0. Motor Grader A also had the smallest rated horsepower of the four motor graders. Motor Graders B, C, and D all had similar horsepower ratings. Even though these three motor graders were similar in age and power, Motor Graders B, C, and D represented EPA emissions standards Tier 1, 2, and 3, respectively.

Table 3 summarizes the average engine loads for the case study motor graders. Engine load represents the fraction (or percentage) of available horsepower from the engine. Diesel engines in construction equipment seldom operate for long periods at maximum engine load (100%), but typically operate intermittently at various engine loads during their duty cycles over the course of a workday. Furthermore, it is common for heavy duty diesel construction equipment to idle for long periods; thus, the overall average engine load for the equipment engine is lowered by long idling episodes. A load factor of 59% is often used as a benchmark value for motor graders (EPA 2010). For the case study motor graders, the average engine load ranged from a minimum of 10% to a maximum of 53%; thus, all of the motor graders operated at an average engine load lower than the stated benchmark.

Table 3 also summarizes the mass per time (grams per hour) emissions rates for HC, CO, NO_x, and PM. Mass per time emissions rates are highly correlated with engine load. For example, equipment that operates under a high average engine load will have a higher rate of emissions for a given unit of time than it would operating at a lower engine load. For NO_x and PM emissions versus engine load, the mass per time emissions rates had Pearson correlation coefficients of $r = 0.52$ and $r = 0.87$, respectively; thus, these emissions rates were moderately-to-highly correlated with engine load. For HC and CO emissions, however, there was little-to-no correlation with engine load. This confounding evidence may be attributed to the fact that each motor grader had different EPA emissions standards, which were developed with the intention of reducing emissions; therefore, engine load alone is not the only variable to impact pollutant emissions.

Table 3. Summary of Average Engine Loads and Emissions Rates

Motor Grader	Load (%)	HC (g/hr)	CO (g/hr)	NO_x (g/hr)	PM (g/hr)
MG A (T0)	27	95	141	596	2.3
MG B (T1)	53	53	67	643	4.9
MG C (T2)	10	50	48	192	1.0
MG D (T3)	38	21	17	163	1.8

Figure 2 assesses the impact of EPA engine tier standards. Note that the values in Table 3 were normalized to the maximum emission rate for each pollutant by dividing each value by the pollutant's maximum emission rate. This was done for the convenience of showing all pollutants on one graph. For HC and CO, emissions rates were reduced with each successive engine tier. For NO_x and PM, however, there was an increase from Tier 0 to Tier 1, although the values for each tier were quantitatively similar. There was a significant reduction for Tier 2 and Tier 3, compared to Tier 0 and Tier 1, for both NO_x and PM. Of course, the reported emissions rates for all pollutants are affected by their respective engine load. The purpose of EPA engine tiers was to reduce the overall quantity of pollutants being emitted. Based on the information in Table 3 and Figure 2, it is apparent that EPA emissions standards have been successful in reducing emissions.

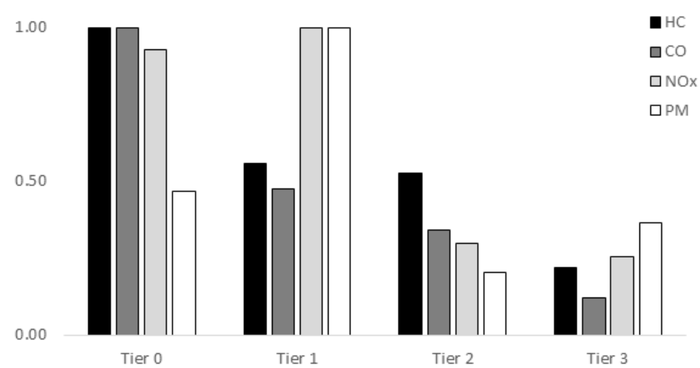

Figure 2. Summary of Normalized Emissions Rates

Another way of evaluating the efficacy of EPA emissions standards is to compare the real-world emissions rates measured in the field to the EPA engine tier standards themselves. Table 4 completes this task for the Tier 1, 2, and 3 motor graders. The Tier 0 motor grader was not included because there were no emissions standards for Tier 0. The emissions rates in Table 3 were converted to a grams per horsepower-hour basis by dividing the grams per hour emission rate by the horsepower rating and average engine load of the motor grader. Of all the values in Table 4, only once did the field measured emission rate exceed the EPA emission standard rate – the Tier 2 Motor Grader C field rate for HC + NO_x was higher than the EPA emission standard. Based on these comparisons, it appears that the EPA emissions standards have been effective in reducing emissions rates for nonroad diesel equipment.

Although the field values in Table 4 are adequate for general comparisons, they should not be considered for regulatory use. When agencies such as EPA conduct regulatory testing, they typically require that specific instrumentation and protocols be utilized under certain conditions (EPA 2020b). The PEMS unit used to collect the data in Tables 3 and 4 did not adhere to any particular set of testing specifications or protocols aimed at collecting data for a specific purpose; however, the values in Tables 3 and 4 are quite reliable for comparing emissions from one item of equipment to another, or making comparisons of one dataset to another.

Table 4. Comparison of Real-World (Field) Emissions Rates vs. EPA Emissions Standards

	HC (g/hp-hr)		$HC+NO_x$ (g/hp-hr)		CO (g/hp-hr)		NO_x (g/hp-hr)		PM (g/hp-hr)	
	EPA	Field	EPA	Field	EPA	Field	EPA	Field	EPA	Field
MG B (T1)	1.0	0.5			8.5	0.6	6.9	6.2	0.40	0.05
MG C (T2)			4.9	12	2.6	2.5			0.15	0.05
MG D (T3)			3.0	2.4	2.6	0.2			0.15	0.02

CONCLUSIONS AND RECOMMENDATIONS

Given the negative attention that onroad diesel vehicles received in the mainstream media, especially Dieselgate, an investigation to determine whether or not nonroad vehicles were violating emissions standards seemed worth the effort. The authors addressed this issue by performing a cursory review of an existing emissions dataset for nonroad heavy duty diesel construction equipment. By examining emissions rates for motor graders with three different EPA emissions standards (Tier 1, 2, and 3), the authors concluded that EPA emissions standards have been effective in reducing emissions from nonroad vehicles; however, there are other issues that need to be considered.

Although this case study concluded that EPA engine tier standards have had a positive impact on reducing emissions from diesel-powered construction equipment, the results are based on a limited analysis of limited data. Additional research needs to be performed. For example, not only do more motor graders need to be examined, but other equipment types should be investigated as well. Other candidate equipment includes backhoes, bulldozers, excavators, nonroad trucks, wheel loaders, skid steer loaders, and track loaders. Introducing more equipment types into the analysis will not only improve diversity in the research but it also will increase statistical robustness, ultimately leading to statistically significant results. The existing dataset used for the case study should be updated to include Tier 4 equipment as well.

Comparing mass per time emissions rates among different items of equipment may become convoluted due to variability in engine loads. Mass per time emissions rates are positively correlated with engine load – as engine load increases, emissions per unit of time increase; thus, it is possible that equipment with a more stringent engine tier and high engine load could actually have a higher mass per time emission rate than equipment with a less stringent EPA engine tier and lower average engine load. In order to offset the impact of variability in engine loads, an analysis based on mass per fuel consumed (grams per gallon) should be conducted. Grams per gallon emissions rates are much less susceptible to variability in engine load, therefore, providing a more consistent comparison among EPA engine tiers.

The most definitive way to determine whether or not nonroad diesel equipment is exceeding EPA emissions standards is by direct testing. Although the results in the database used for this case study were collected by direct testing, the methodologies did not match the requirements of testing protocols used for regulatory purposes. In order to obtain the most accurate field emissions rates possible and compare them to EPA emissions standards, equipment must be tested using the specified instrumentation with the specified approach. It is possible to design experiments that capture real-world emission rates, even in controlled environments.

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Frequency and Magnitude of Cost Growth in Public Works Contracts

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ABSTRACT

Cost overruns are a persistent issue in the construction industry. This paper investigates factors that may drive cost growth on public works contracts. The study collected data on 1,043 public works projects completed over a three year period. The analysis examined the impact of four factors on cost overruns: (1) Project type, (2) Contract size, (3) Contract duration, and (4) Construction placement (value per day). The data were analyzed using a combination of basic descriptive statistics along with statistical hypothesis testing of means for various factors affecting cost growth. Cost growth was found to vary significantly by project type, contract size, duration, and construction placement. The project types with the largest contribution to cost growth are New Construction, Building Repair, Utility and Paving. Further analysis of the cost growth investigated the frequency and magnitude of cost growth for different project factors. The results identify different levels of risk of cost growth for different project type and sizes. The findings can assist in the development of strategies to better anticipate or mitigate cost growth of different projects.

Keywords: Project Cost, Cost Growth, Public Contracts

George Fulton has a MS degree in Civil Engineering from San Diego State University. His graduate work focused on cost growth on public projects.

Dr. **Panagiotis Mitropoulos** is an Associate Professor at the Department of Civil, Construction and Environmental Engineering, at San Diego State University.

INTRODUCTION

In 2019, construction industry spending in the United States, was estimated at over $1.3 trillion with approximately 24% of that being public spending (Census 2020). Cost and schedule overruns are a consistent problem in the construction industry. Similar to the private sector, public works contracts experience cost and schedule growth. Time and cost overruns in public construction projects are a global phenomenon, with no reduction in the last 70 years (Larsen et al 2015, França and Haddad 2018, Famiyeh et al 2017, Arditi et al 1985, Adam et al 2017).

The term "cost growth" is often referred to as a budget increase, cost increase, or cost overrun (Plebankiewicz 2018). Hinze et al. (1992), and Zeitoun and Oberlander (1993), suggested that cost overrun is the difference between the original contract value and the cost at completion. Flyvbjerg et al. (2002) and Odeck (2004) defined a cost overrun as the difference between forecasted and actual construction costs. Cantarelli et. al (2010) define cost overrun as the difference between the cost at project completion and the estimated cost at the time of the decision to build. In this study, the cost growth is defined and calculated as the difference between the final contract value and the original contract value.

The objective of this study is to investigate project factors that affect cost growth on public works contracts. If such factors are identified, it may be possible to develop strategies to control the drivers of cost growth, or better anticipate cost growth for different contracts and make project budgets more predictable. Specific aims of the study of this study are: (1) to provide additional data on the frequency and magnitude of cost and schedule overruns in public work projects, and (2) to determine the difference in the magnitude of overruns based on project type, project size, construction duration, and construction completion time.

BACKGROUND

Cost overruns in construction projects are a significant challenge across the world. In a study of 420 road construction projects, Odeck (2004) found a mean cost overrun of 7.9% with a range of -59% to 183%. For bridges and tunnels, Skamris and Flyvbjerg (1997) found the cost estimates from the decision to build to actual completion experienced a cost overrun of 50 to 100%. Merewitz (1973) reported that the average overrun of infrastructure projects is over 50 percent. The US Government Accountability Office (GAO) found that cost growth occurs on many major highway and bridge projects (GAO 2003). For example, on 23 of 30 projects over $100 million, GAO reported increases ranging from 2 to 211 percent. On about half these projects, the costs increased 25 percent or more. Love et al. (2013) analyzed cost overruns from 276 construction and engineering projects. Using the contract award as the reference point, the research revealed a mean cost increase of of 12.22%.

The problem of cost overruns is recognized in the literature but the causes are still ambiguous, as overruns have been attributed to many different reasons. Factors contributing to overruns include material and labor shortages, price inflation, rework, change orders, site access, unexpected site conditions, and unforeseen events (Arditi et al. 1985; Semple et al. 1994; Chang 2002; Knight and Fayak 2002; Gkritza and Labi 2008, Love et al. 2013, Plebankiewicz 2018). Vidalis and Najafi (2002) investigated causes for cost and schedule overruns in 708 highway projects for the Florida Department of Transportation, constructed between 1999 and 2001 with a combined original contract amount of over $1.9 billion. They found that 39% of the projects' cost overruns were due to plans and modifications in the projects. Lee (2008) reported the following causes of overruns in Korean transportation projects: changes in scope, delays in construction, inaccurate estimates, and adjustment of project costs. Perkins (2009) indicated that there are more owner-requested changes in design–build projects. A UK study found that primary causes for cost overruns include design changes, uncertainties, inaccurate estimates of project duration, complexities and non-performance of subcontractors (Olawale and Sun 2010). Johnson and Babu (2020) found that the top five causes of cost overrun in the UAE are design variation, poor cost estimation, delay in client's decision-making, financial constraints of client and inappropriate procurement method. Senouci et al (2017) emphasized the impact of change orders on cost overruns in projects in Qatar.

Based on a survey of contractors in the Gaza strip, Enshassi et al (2010) found that the contractors attributed the primary causes of cost overruns to environmental factors, such as material availability and prices and the instability of economic and political situation. The use of effective cost estimating and cost management practices such as Earned Value was found to mitigate cost overruns (Alolote and Dimkpa 2020, El Sawalhi and Enshassi 2004). Sinesilassie et al (2018) indicated that the competency of project participants and the extent of conflict between participants are critical factors for the success of public construction projects in Ethiopia.

Research has suggested that the likelihood of a cost overrun increases with contract size and complexity (Hinze et al. 1992). Jahren and Ashe's (1990) examination of 1,576 Naval facility projects found that a cost overrun rate of 1 to 11% is more likely to occur on larger projects. Asiedu et al. (2017) surveyed 321 completed educational projects and found five variables that influenced cost overruns—the initial contract value, gross floor area, number of floors, source of funds and contractors' financial classification. Shrestha et al (2013) analyzed 363 public works projects and reported that large, long-duration projects had significantly higher cost and schedule overruns than smaller, short-duration projects. Heravi and Mohammadian's (2019) study of urban construction projects in Iran found that large projects had higher cost overruns, while renovation projects had higher cost overruns than new-build projects. Also, the cost performance of road projects was better than building projects. On the other hand, Odeck (2004) found that larger overruns were experienced in smaller projects. In their study of 276 construction and engineering projects, Love et al. (2013) found no significant differences for cost overruns were found among procurement method, project type and contract size.

METHODS

To investigate the cost growth on public works contracts, the study analyzed contract data from 16 public agency offices in the Southwest United States, as shown in Table 1. This focus on public projects was less due to the research design, and more due to the access of information to a large number of public projects. The study included projects within a period of three years. The study included projects with the following characteristics: (1) the contract value was over $100,000; and (2) the project had achieved substantial completion during the study period. Cost growth was calculated as a percentage of the original contract value—thus, the difference between the final and the original contract value was divided by the original contract value. Contracts with cost growth over 100% were considered extreme outliers and excluded. The result was 1,043 contracts included in the analysis, with a total award value of $3,012,610,917. Sources of information and data (such as projects) were anonymized to maintain confidentiality of information.

Table 1. Sources of information for projects in the study

Office	No of projects	% of projects	Value of projects
1	42	4%	$62,930,174
2	22	2%	$111,301,919
3	20	2%	$101,497,120
4	22	2%	$80,297,154
5	104	10%	$357,517,530
6	21	2%	$19,680,745
7	53	5%	$192,827,189
8	50	5%	$52,991,660
9	61	6%	$95,655,211
10	85	8%	$271,161,731
11	190	18%	$1,368,147,809
12	32	3%	$32,504,937
13	35	3%	$35,645,866
14	48	5%	$48,883,553
15	125	12%	$117,303,401
16	133	13%	$64,264,918
Total	1,043	100%	$3,012,610,917

Factors investigated and hypotheses

The study focused on the effect of four project factors on cost growth. These factors were selected because they were believed to impact cost growth, and include the following: (1) Project type, (2) Contract size, (3) Duration of contract, and (4) Construction placement.

Project Type

The contracts were grouped in 12 categories that represent the major types of construction projects that the public agencies encounter. The 12 categories are: New Construction, Building Repair, Civil, Demolition, Equipment installation, Fencing, Fire Protection, HVAC, Paint and Carpet, Paving, Roofing, and Utility. Projects classified as Environmental and abatement work were excluded because they tend to be cost plus contracts. *New Construction* typically includes larger projects. *Building Repair* is a general category that typically includes multiple trades doing building renovations.

Construction projects include a wide variety of work types and uncertainties—a roofing project may encounter problems due to weather, a utility project due to unforeseen underground conditions, or building repair due to coordination with the building occupants. This factor was chosen in order to examine which project types experience the greatest cost growth. Thus, it is hypothesized that *Building Repair* projects may have the largest amount of cost growth due to the number of trades involved, the coordination with building occupants, and the uncertainty of existing building conditions. It is also hypothesized that *Utility* projects will have significant cost growth due to uncertainty of underground conditions and coordination with building utilities.

Hypothesis 1: Cost growth means of the different project types will have statistically significant differences, with *Building Repair*, and *Utility* having the highest cost growth.

1. *Project Size*

The *Project Size* factor is indicated by the contract award value and is divided into five categories:

- Category 1: $100K - $500K
- Category 2: $500K - $1M
- Category 3: $1M - $5M
- Category 4: $5M - $15M
- Category 5: Over $15M

The data set does not include contracts smaller than $100K. The categories were chosen in order to create populations that were large enough to analyze. The largest projects were over $100 million, but there were only six and were not a large enough population to analyze as a separate category. Within each size category there are projects of all types, but it seems logical that the larger the project the more potential exists to include more trades and be more complex, which can introduce more cost growth. On the other hand, smaller projects may receive less attention, and any change may have a greater impact on cost growth. For these reasons, it was hypothesized that projects in the smaller and larger categories may have the largest amount of cost growth.

Hypothesis 2: Cost growth means of different project size categories will have statistically significant differences, with the projects in categories 1 and 5 having the largest cost growth.

2. *Duration of Contract*

The shortest duration was 21 days and the longest was 1826 days. The *Duration* factor was divided into four categories, chosen to roughly balance the size of the populations and to correspond to commonly awarded contract durations; 120 days, 180 days, 365 days.

- Category 1: 20 - 120 Days
- Category 2: 120 - 180 Days
- Category 3: 180 - 365 Days
- Category 4: Over 365 Days

Contract duration is another factor related to the complexity of the project, as projects with greater complexity may requiring more time to complete.

Hypothesis 3: Cost growth means of different duration categories will have statistically significant differences, with projects in categories 1 and 4 having the greatest cost growth.

3. *Construction Placement*

The *Construction Placement* reflects the 'intensity' of work on the project which is calculated by dividing the contract value over the duration—the unit of measurement is dollars/day. The contracts were divided into 4 populations chosen to roughly balance their size.

- Category 1: Less than $1,200 /Day
- Category 2: $1,200 /Day - $2,400 /Day
- Category 3: $2,400 /Day - $5,000 /Day
- Category 4: Over $5,000 /Day

It was expected that the potential for complications that can result in cost growth increases as the intensity of the work increases.

Hypothesis 4: Cost growth means of different construction placement categories will have statistically significant differences, with contracts in the greater than 5,000 $/day having the greatest cost growth.

Data analysis

The data were analyzed using a combination of descriptive statistics and charts and by performing hypothesis testing to search for significant differences in mean cost growth, as driven by different factors. The different types of analysis included the following:

- *Descriptive Statistics*, for means, variances, histograms, etc.
- *One Way ANOVA*, as the parametric analysis method, which also included the *Fisher Least Significant Difference (LSD) test.*
- *Comparing Multiple Independent Samples (Kruskal-Wallis ANOVA, Median Test)*, as the nonparametric analysis method.
- *Rank Correlations (Spearman/Pearson)*, analysis method used to search for correlations.

Hypothesis testing was performed using parametric and nonparametric tests. Parametric tests can be used when the data follows a normal distribution, as well as for continuous data that are non-normally distributed, if the sample size is larger than 20. Parametric tests analyze the differences in populations means using measures of central tendency. Nonparametric tests do not assume a normal distribution, but the values for analysis are ranked from 1 to N, where N is the number of values. The analysis is then completed based upon the relative ranks of the data. In order to utilize a parametric test a factor needs to meet three conditions: (1) The populations within each factor must be independent; their outcomes do not affect each other. (2) The different populations must have roughly equal variance. (3) The data must have a normal distribution, or they are non-normal continuous data with large sample size (larger than 20). Table 1 shows whether each factor met the criteria needed to complete a parametric hypothesis testing, and indicates what analysis was performed.

Table 2. Suitability for hypothesis testing and analysis type completed, by factor.

Factor	Independent?	Equal Variances?	ND or large N?	Analysis Used	Correlation Analysis
Project Type	Yes	N/A	N/A	Non-Parametric	No
Project Size	Yes	Yes	Yes	Parametric	Yes
Duration	Yes	Yes	Yes	Parametric	Yes
Placement	Yes	Yes	Yes	Parametric	Yes

Project type was the only factor that did not qualify for parametric hypothesis testing due to unequal variances and not being able to assume a normal distribution for their populations. For this factor non-parametric analysis was performed.

The One Way ANOVA tests looked for significant differences in the mean cost growth of the different factor populations. The test produces a 'P-value', or probability, that is compared to the selected confidence interval of 1%. If this p-value is smaller than the desired confidence interval, then it can be said there a greater than 99% confidence that the test shows a significant difference among the means. A 1% confidence interval was selected in order to decrease the probability of getting 'false positives' due the number of factors being tested. The *Project Type* factor utilized non-parametric analysis. The Kruskal-Wallis test performed the same function as the One Way ANOVA test and with the same 1% confidence interval. If the ANOVA test result showed a significant difference in the means for a factor, the Fisher LSD test was then used to perform pairwise comparisons between the different populations to determine if significant differences existed between them, also with the same confidence interval.

The analysis also completed Spearman and Pearson correlation tests for three factors: *Project Size, Duration* and *Placement*, as discussed in the next section., For these factors, the analysis utilized the raw data, individual award values and contract durations, in order to better identify any possible correlations. Correlation analysis was not performed on P*roject Type* because it is a nominal variable, and is unsuitable for correlation analysis.

RESULTS

Overview of hypothesis testing results

Table 2 summarizes the cost growth statistics. The mean cost growth across all contracts was 6.2%.

Table 3. Cost growth distribution

Cost growth category	Number of contracts	% of contracts
Less or equal to 0%	648	62%
0 – 5%	122	12%
Over 5%	273	26%
Total	**1,043**	**100%**

Table 3 summarizes the parametric and nonparametric hypothesis testing results for the methods described previously. Pairwise comparisons for each factor are described in later tables. Both types of hypothesis testing searched for significant differences in the means. The result was considered significant if the P-value returned was less than 1%. If the P-value was less than 0.1%, the result was considered Very Significant (**), and if the P-value returned was less than 0.01% the result was considered Extremely Significant (***). As shown in Table 3, all four factors analyzed (*Project Size, Project Type, Project Duration,* and *Construction Placement)* were found to have statistically significant differences among the mean cost growth of their populations. The following sections discuss the findings for each factor in more detail and present both the descriptive statistics and the results of hypothesis testing.

Table 4. Hypothesis testing results

Factor	Alpha Value	ANOVA P-Value	Significant Difference in the Means?	Alpha Value	KW P-Value	Significant Difference in the Means?
Project Type				1%	0.0001%***	Yes
Size	1%	0.0000%***	Yes	1%	0.0000%***	Yes
Duration	1%	0.0000%***	Yes	1%	0.0000%***	Yes
Placement	1%	0.0000%***	Yes	1%	0.0000%***	Yes

P-Value < 0.01% = Extremely significant***

P-Value: 0.01% to 0.1% = Very Significant**

P-Value: 0.1% to 1% = Significant

P-Value ≥ 1% = Not significant

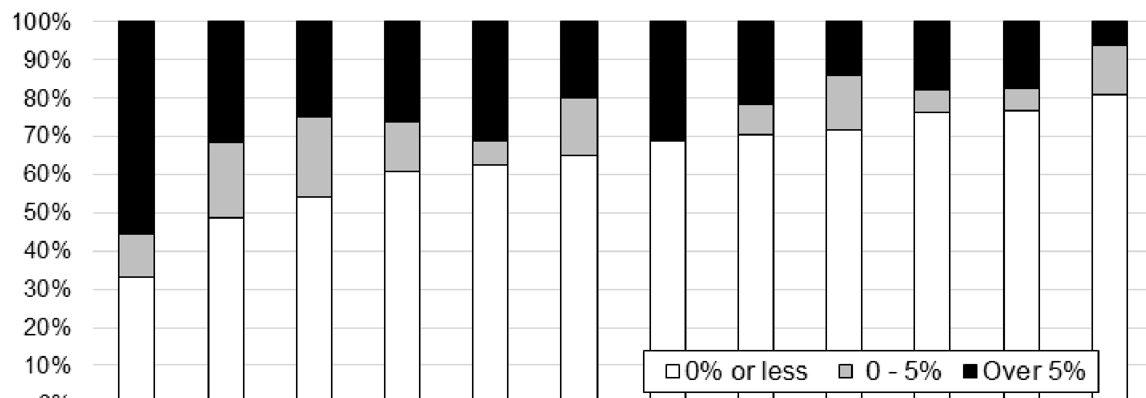
Effect of project type on cost growth

Table 4 shows the descriptive summary statistics for the 12 project types. The total contract award for the period examined was over $3 Billion, with two categories—*New Construction* and *Building Repair* account for 83% of the total value. *Building Repair* is the largest category of projects (34% of total) and accounts for 14.6% of the total value awarded. *New Construction* includes 9% of the total projects and accounts for 68% of the total award value. Project types with most frequent cost growth over 0% are New Construction (67%), Utility (51%), Fire Protection (46%), Building Repair (39%) and Demolition (38%).

Table 5. Summary statistics by project type

Type	Total projects	% total projects	Total Award Value (in $M)	% total value	Mean Award Value	Mean Cost growth
New Construction	99	9.5%	$2,054,663,373	68.2%	$20,754,175	11.7%
Bldg Repair	358	34.3%	$440,669,119	14.6%	$1,230,919	7.6%
Paving	175	16.8%	$167,487,269	5.6%	$957,070	7.0%
Utility	123	11.8%	$165,637,796	5.5%	$1,346,649	6.6%
HVAC	77	7.4%	$53,534,456	1.8%	$695,253	6.4%
Roofing	67	6.4%	$34,407,328	1.1%	$513,542	6.1%
Fire Protection	24	2.3%	$33,045,261	1.1%	$1,376,886	5.4%
Civil	16	1.5%	$17,413,781	0.6%	$1,088,361	4.8%
Paint & Carpet	37	3.5%	$16,322,552	0.5%	$441,150	4.2%
Equipment	31	3.0%	$12,797,846	0.4%	$412,834	3.8%
Demolition	16	1.5%	$11,546,213	0.4%	$721,638	3.2%
Fencing	20	1.9%	$5,085,923	0.2%	$254,296	1.1%
Total	1,043	100%	$3,012,610,917	100%	$2,888,409	**6.2%**

Figure 1 shows the percent of contracts with cost growth for each project type. Projects were categorized in three cost growth groups: (1) zero or negative cost growth, (2) cost growth between 0 and 5%, and (3) cost growth over 5%.



	New Construction	Utility	Fire Protection	Bldg Repair	Demolition	Fencing	Civil	Paint & Carpet	HVAC	Roofing	Paving	Equipment
Over 5%	56%	32%	25%	27%	31%	20%	31%	22%	14%	18%	18%	6%
0 - 5%	11%	20%	21%	13%	6%	15%	0%	8%	14%	6%	6%	13%
0% or less	33%	49%	54%	61%	63%	65%	69%	70%	71%	76%	77%	81%

Figure 1. Percent of contracts with cost growth by project type.

In addition to the mean cost growth for each project type, the study examined the Frequency and the Magnitude of cost growth,

- The Frequency indicates the percent of project with cost growth over 0%.
- The Magnitude is calculated as the average cost growth but only for those projects with positive cost growth. It indicates how "severe" was the overrun on those projects.

The analysis of frequency and magnitude provides useful information regarding the probability and severity of cost overrun risk for the different project types. This is illustrated in Figure 2. The size of the circles reflects the total dollar value of awards of each project type. The mean cost growth frequency for all projects was 38% and the mean magnitude was 17%. Project types with most frequent cost growth are: New Construction (67% of projects had cost growth over 0%), Utility (51%), Fire Protection (46%), Building Repair (39%) and Demolition (38%). *Civil* projects have low frequency (31%) of cost growth, but high magnitude (25%). Thus, only one out of three civil projects have cost growth, but the cost growth on those projects is high (25% on average). They also have large award value. On the other hand, *Utility* projects have lower total award value, high frequency of cost growth (over 50%) but lower magnitude (14%) of cost growth.

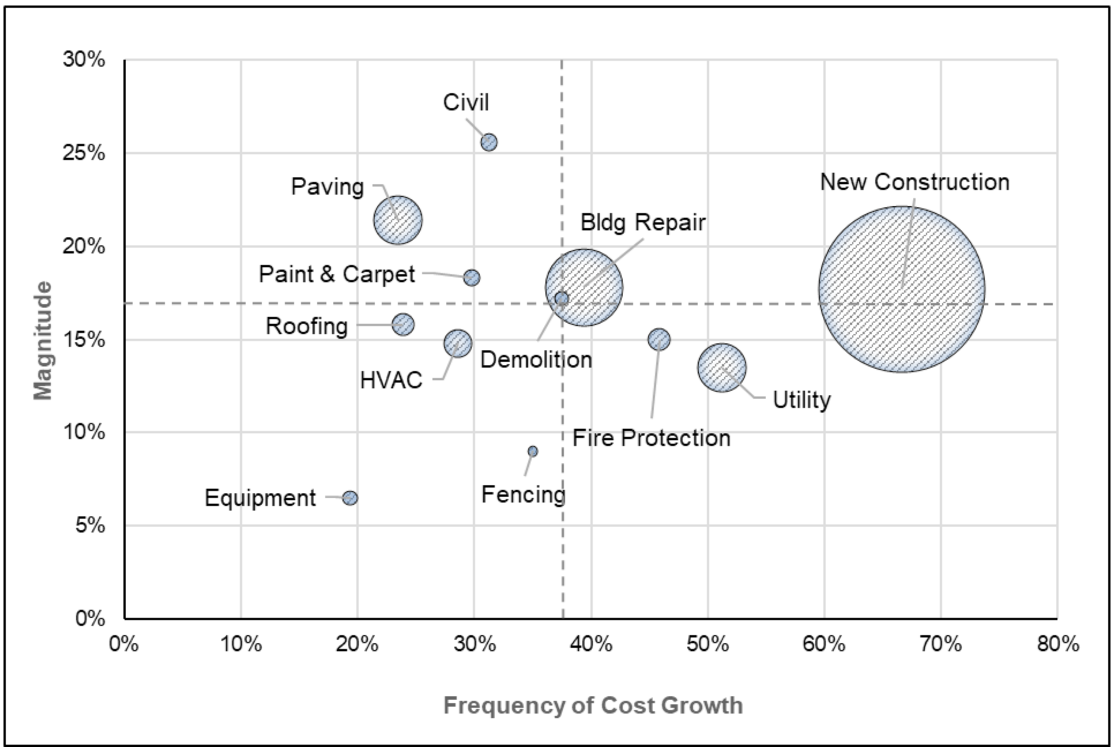


Figure 2. Frequency and magnitude of cost growth by project type.

Results of Testing Hypothesis 1

Hypothesis 1 expected that cost growth means of the different project types will have statistically significant differences. The non-parametric hypothesis testing indicated that there is an extremely significant statistical difference of the cost growth means among the different project types. This means that we can be very confident that when projects are separated into these types there will be a difference in the mean cost growth.

Effect of contract size on cost growth

Hypothesis 2 proposed that different contract size categories will have statistically significant differences of cost growth means, with categories 1 and 5 having the largest cost growth. Table

6 shows the distribution of the contracts into the different size categories, and the mean cost growth in each category.

Table 6. Summary statistics by project size

Size category	No of projects	Mean cost growth
1: $100K - $500K	642	4.0%
2: $500K – $1M	147	6.0%
3: $1M - $5M	160	11.5%
4: $5M - $15M	61	13.2%
5: Over $15M	33	17.2%
Total	**1,043**	**6.2%**

Figure 3 shows the percentage of contracts in the three cost growth categories for each size category.

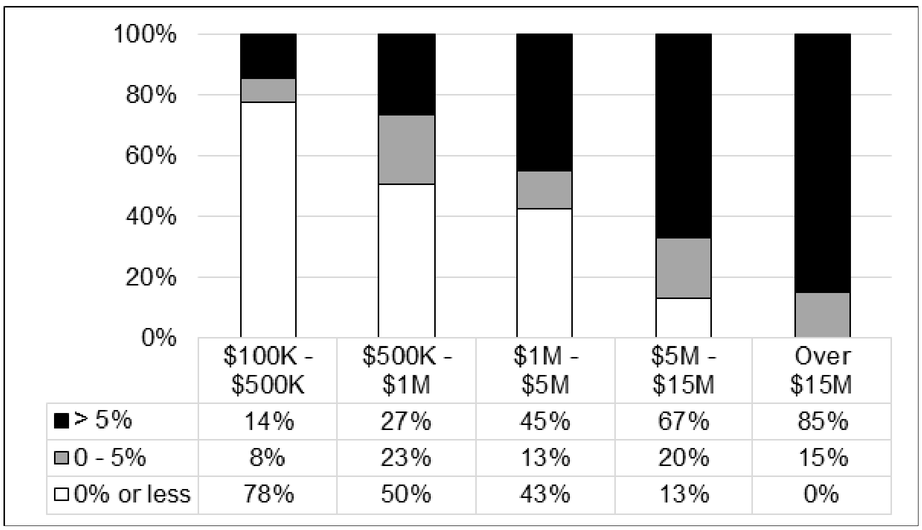


Figure 3. Percent of contracts with cost growth for different size categories.

Results of testing hypothesis 2

Cost growth means were found to have extremely significant statistical differences between the categories created. Table 7 shows the pairwise comparisons with significant differences in the means. Looking at the results, there is a clear split between the projects under $1M (which show mean cost growth under 6%) and those over (which show mean cost growth over 10%). The results supported that category 5 had the largest cost growth, but did not support the expectation that the category 1 projects would have high cost growth.

Table 7. P-Value and significance of pairwise comparisons of size categories.

	$100K - $500K	$500K - $1M	$1M - $5M	$5M - $15M	Over $15M
$100K - $500K	X	8.5826% Not significant	0.0000%*** Extremely significant	0.0000%*** Extremely significant	0.0000%*** Significant
$500K - $1M		X	0.0357%** Very significant	0.0322%** Very significant	0.0010%** Very significant
$1M - $5M			X	36.7120% Not significant	2.0041% Not significant
$5M - $15M				X	14.7982% Not significant
Over $15M					X

Figure 4 illustrates the frequency and magnitude of cost growth for the different size categories. The Figure shows how the frequency of cost growth directly increases with project size, but the mean magnitude of cost growth remains stable. In category 1 ($100K - $500K) only 22% of the projects had positive cost growth, while in category 5 (over $15M) 100% of the projects experienced positive cost growth. The mean magnitude across all projects with positive cost growth is 17%.

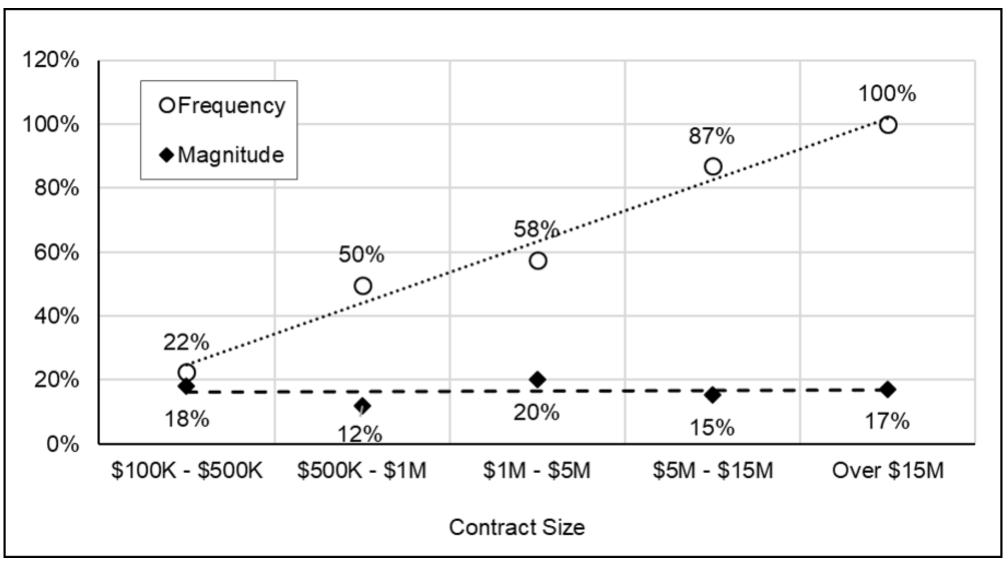


Figure 4. Frequency and magnitude of cost growth by contract size

Effect of Project Duration on Cost Growth

Hypothesis 3 proposed that different project duration categories will have statistically significant differences of cost growth means, with projects over 365 days having the greatest cost growth.

Table 8 shows the distribution of the contracts into the different size categories, and the mean cost growth in each category. One can observe significant differences in the mean values between the categories. Projects with durations greater than 365 days had the largest average cost growth, at 12.6%, which was twice that of projects in the 180-365 day category.

Table 8. Project Duration population sizes and means

Duration Category	No of projects	Mean cost growth
21 – 120 d	264	4.4%
121 – 180 d	252	2.5%
181 – 365 d	320	6.3%
Over 365 d	207	12.6%
Total	**1,043**	**6.2%**

Figure 5 shows the percentage of contracts in the three cost growth categories for each duration category.

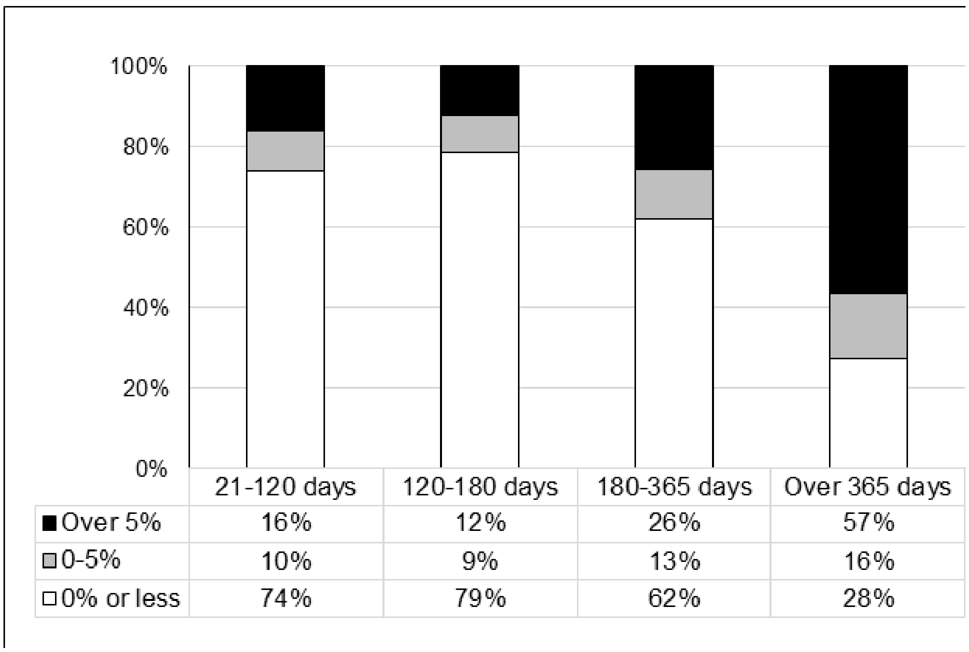


Figure 5. Percent of contracts with cost growth for different duration categories.

Results of Testing Hypothesis 3

Cost growth means were found to have extremely significant statistical differences between the duration categories. Table 9 shows the pairwise comparisons of duration categories. There is a significant difference in the means between projects over 365 days and all other project sizes, but also between projects that run between 120 to 180 days and 180 to 365 days. The difference between the categories “20-120” and “120-180” is not significant.

Table 9. P-Value and significance of pairwise comparisons of duration categories

	20 - 120	120 - 180	180 - 365	Over 365
20 - 120	X	9.5780% Not significant	9.2747% Not significant	0.0000%*** Extremely significant
120 - 180		X	0.063%** Very significant	0.0000*** Extremely significant
180 - 365			X	0.0000*** Extremely significant
Over 365				X

Figure 6 illustrates the frequency and magnitude of cost growth for the different duration categories. In a relationship similar to the project size, the frequency of cost growth directly increases with duration, while the magnitude remains stable. In categories 1 and 2 (20 –180 days) only 26 % and 21% of the projects had positive cost growth, while in category 3 (180-365 days) it was 38% of the projects and in category 4 (over 365 days) 72% of the projects experienced positive cost growth. The magnitude of cost growth does not have significant differences across the duration categories.

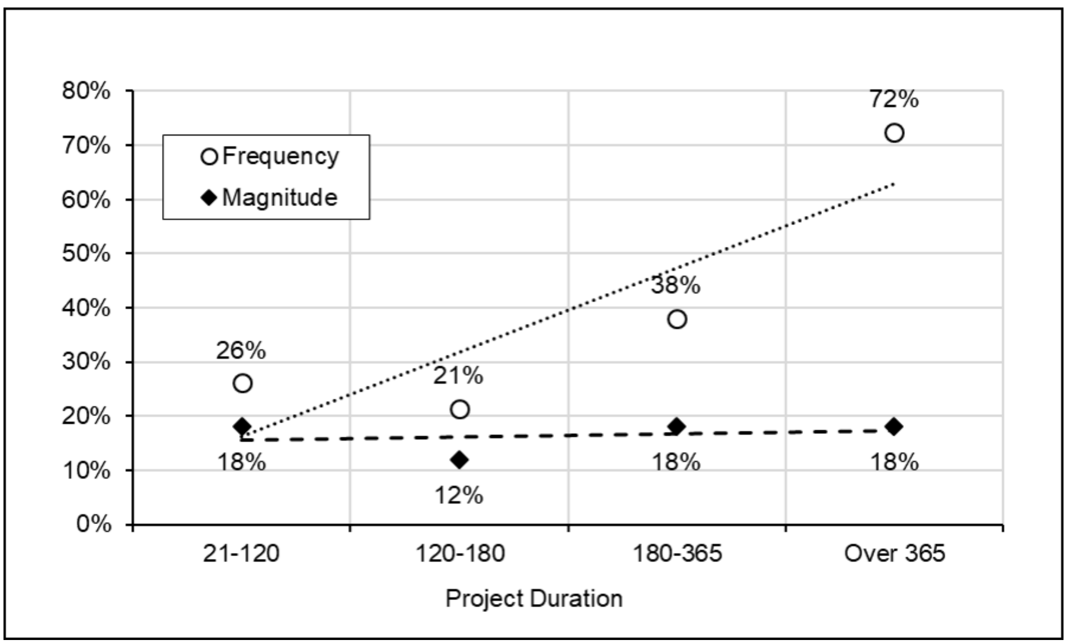


Figure 6. Frequency and magnitude of cost growth by contract duration

Effect of construction placement on cost growth

Hypothesis 4 proposed that cost growth means of different construction placement categories will have statistically significant differences, with contracts in the greater than 5,000 $/day having the greatest cost growth. Table 10 shows the distribution of the contracts into the different placement categories, and the mean cost growth in each category.

Table 10. Construction Placement factor sample size and means

Placement Category	No of projects	Mean cost growth
0 - $1,200	234	4.0%
$1,200 - $2,400/d	304	3.3%
$2,400 - $5,000/d	267	6.6%
Over $5,000 /d	238	11.5%
Total	**1,043**	**6.2%**

As shown in Figure 7, there is a significant difference between the placement categories with regards to the frequency of cost growth.

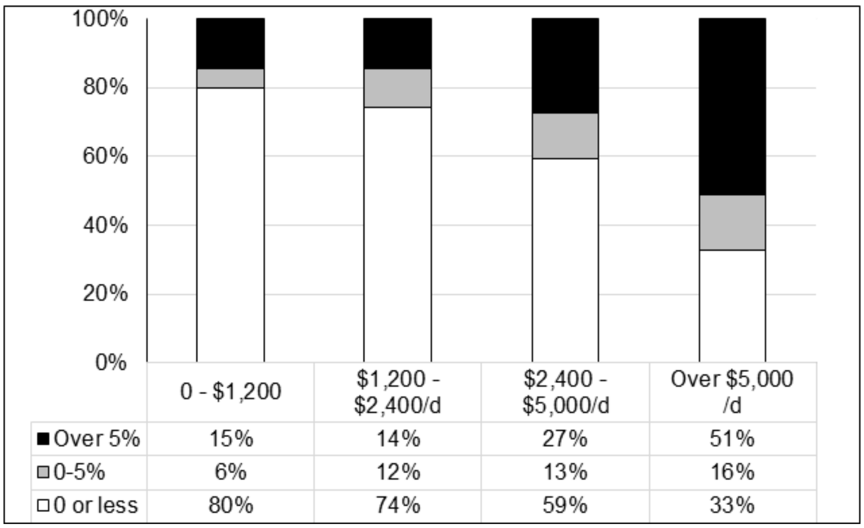


Figure 7. Percent of contracts with cost growth for different placement categories.

Results of Testing Hypothesis 4

The analysis found statistically significant differences between the construction placement categories. Table 11 shows pairwise comparisons with significant differences in the means. As hypothesized, the category of greater than 5,000 $/day had the largest average cost growth at 11.4%, and was almost twice as much as the 2,400 to 5,000 $/day category which had 6.6% average cost growth.

Table 11. P-Value and Significance of Construction Placement pairwise comparisons

	0- $1,200/d	$1,200 - $2,400/d	$2,400 - $5,000	Over $5,000/d
0- $1,200/d	X	54.9773% Not significant	3.0177% Not significant	0.0000%*** Extremely significant
$1,200 - $2,400/d		X	0.3367% Significant	0.0000*** Extremely significant
$2,400 - $5,000			X	0.0076** Very significant
Over $5,000/d				X

Figure 8 shows that the frequency of cost growth increases with placement, but the magnitude of cost growth remains stable. This appears similar to the contract size and duration. These factor are related—as project size increases, project duration as well as placement also increase.

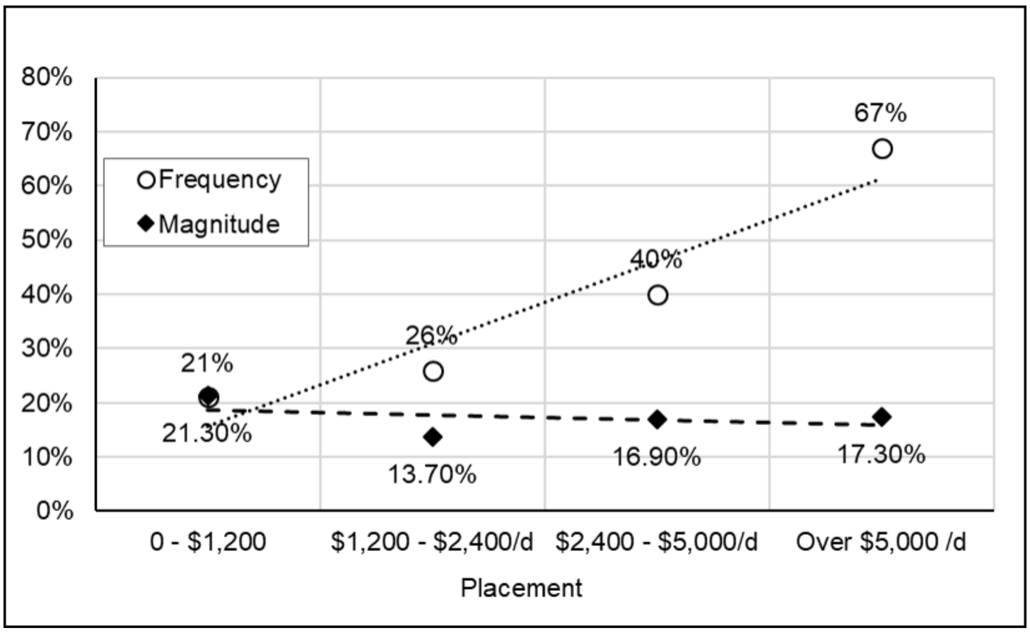


Figure 8. Frequency and magnitude of cost growth by construction placement

Correlation analysis

Table 12 shows the summary of correlation coefficients for the different factors tested. The correlation analysis was not done on *Project Type* factor because it is a nominal variable, neither continuous nor ordinal variables, making it unsuitable for a correlation analysis.

Low values were returned for the Pearson coefficient, with *Project Duration* having the highest value at 19.9%, meaning that 19.9% of the cost growth distribution can be explained by a linear relationship with contract duration.

Table 12. Project Factors and their Correlation Coefficients

Factor	Pearson Coefficient (Linear)	Spearman Coefficient (Monotonic)
Project Size	10.7%	35.4%
Project Duration	19.9%	31.3%
Construction Placement	11.6%	30.7%

Interestingly, all three factors returned similar values ranging from 30.7% to 35.4% for the Spearman coefficient, which measures the monotonic relationship. It is still only a minor correlation, but this does indicate some sort of positive correlation between these three factors and positive cost growth. As they increase, so does cost growth. The relationship between project size, duration and placement is more obvious on the larger contracts. All contracts over $15 M, also have duration over 360 days and placement

over $8,000/d (with one exception).

Analysis of Selected Contract Categories

Based on the above findings, one more step was added in the analysis. The four project types with the largest cost growth (*New Construction, Building Repair, Utility and Paving*) were divided in three size categories: (1) Less than $1 million, (2) $1 - $5 million and (3) over $5 million. For these categories, we examined the frequency of "significant" cost growth (over 5%) and the magnitude of cost growth for those contracts with significant cost overruns.

Figure 9 shows the results, where one can identify roughly three clusters of projects: In cluster 1, *New Construction* and *Paving* contracts over $5M have very high probability of cost growth as 80% or more of the contracts have more than 5% cost growth, and the expected magnitude of the cost growth is about 20%. In cluster 2, about 47% of *Building Repair* and *Utility* projects over $1M experience significant cost growth. The average cost growth for those contracts is 19%. Cluster 3 has low probability of cost growth (only 20% of the contracts), and magnitude of 24%. Finally, New Construction less than $1M very rarely has significant cost growth but those few contracts who do, have extensive overruns (46%).

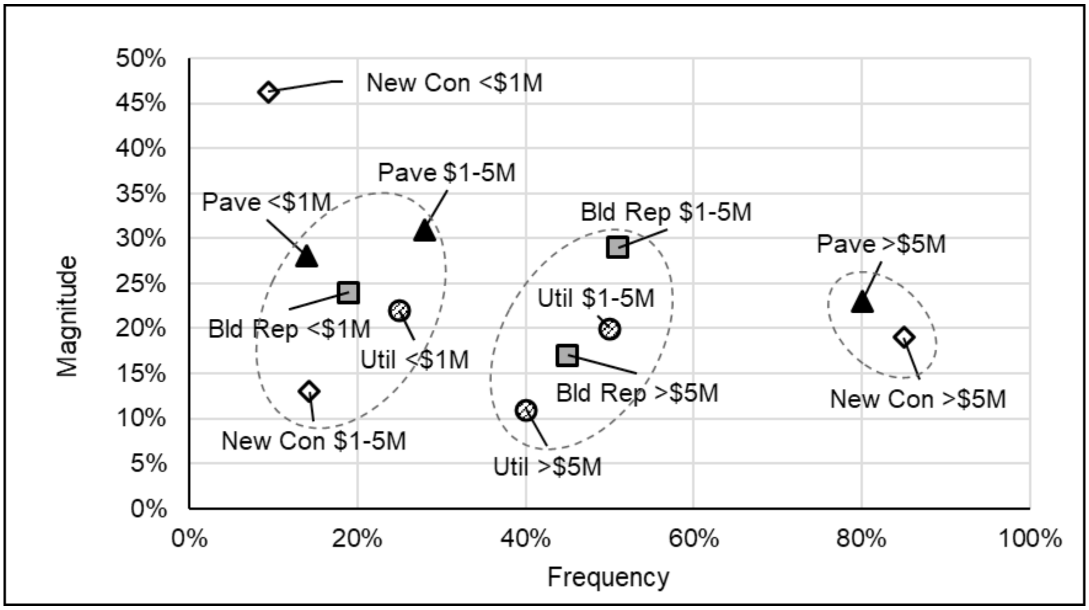


Figure 9. Frequency and magnitude of cost growth over 5% for selected project types

CONCLUSIONS AND IMPLICATIONS

This study analyzed 1,043 public works contracts completed over a three-year period. These projects included over $3 billion in project awards and over $350 million in added costs. The average cost growth across all projects was 6.2%. The study investigated the effect of four factors on cost growth: *Project Type, Contract Size, Contract Duration,* and *Construction Placement*. The key findings and implications are discussed below:

- Project type was found to have statistically significant differences in cost growth. *New Construction* projects had the highest mean cost growth of 11.7%, followed by *Civil (*7.6%) and *Fire Protection* (7%,) contracts. In addition, *Building Repair*, *Utility*, *Demo*, and *Paint and Carpet* are above 5% cost growth.
- The mean cost growth of 11.7% for *New Construction* contracts was found to be very close to the mean cost growth for engineering and construction projects found by Love (2013).
- Contract size was found to have statistically significant differences in cost growth. Projects over $5 million had the greatest cost growth.
- Contract duration was found to have statistically significant differences in cost growth. Projects over 365 days has greater frequency of cost growth.
- Contract placement was also found to have statistically significant differences in cost growth. Projects with placement value over $5,000/day had greater frequency of cost growth.
- *Project Size, Duration*, and *Construction Placement* are related factors; as the project size increases, the duration and construction placement often increase as well, and vice versa. Of the 94 projects over $5 million, all except two had duration over 360 days, and all except one had placement greater than $8,000/day. When project size, duration,

and construction placement all have high values, these projects are at a higher risk of experiencing cost growth. Seventy three percent of projects over $5 million experience cost growth over 5%.

Implications

The findings have the following implications. First, the study confirms that cost growth is statistically related to project characteristics. This indicates that different projects have different levels of risk for cost growth.

Second, the findings enable systematic risk management of the different projects. Specifically, the analysis of "mean cost growth" into frequency and magnitude provides information that enables systematic risk management. Figure 9 is essentially a Risk Matrix—the frequency indicates the probability that a project of a particular type will have cost growth, and the magnitude indicates the impact of cost growth when it occurs. Figure 10 shows the same information as Figure 9 in a traditional Risk Matrix format. This information enables managers to anticipate the cost risk of different projects, and use appropriate strategies to reduce the probability, or mitigate the consequences. For example, this information can provide the basis for allocating contingencies and allowances, etc. Obviously, in large projects, the high percentage of cost growth corresponds to higher amounts than smaller projects.

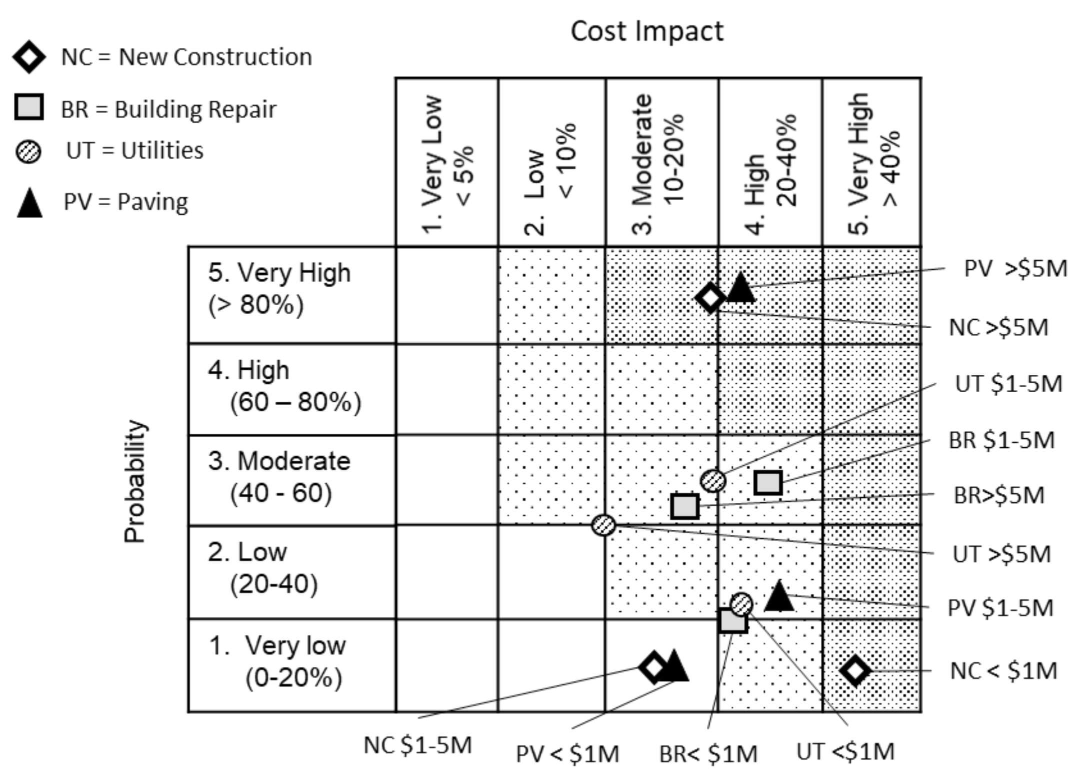


Figure 10. Risk Matrix

Third, the findings identify specific types of projects with high frequency and severity of cost overruns. These findings may be location-specific, as different locations may have different cost growth, but they indicate a general problem with larger contracts. Specifically, *New*

Construction and *Paving* projects over $5M have high probability and impact of cost overruns (80% probability of 20% overrun). Preliminary analysis of the data by location also indicated that locations with a greater component of large projects (over $5M) had higher cost growth.

Finally, the data do not provide information about the causes of cost growth, such as problems with project definition, scope additions, design issues, unexpected project conditions or unforeseen events. However, the data supports the following recommendations:

- Provide appropriate contingencies and allowances for anticipated cost growth depending on the project characteristics.
- Systematically track and analyze the causes of cost growth (such as changes in project scope, design issues, unexpected project conditions or unforeseen events) in order to reduce the frequency and magnitude.
- Improve processes for project definition and front-end planning in order to produce better estimates and reduce modifications after contract award.

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Understanding Sub-Contractor Selection Factors in the Building Construction Industry for the Southeastern United States

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ABSTRACT

The primary entities within building construction industry consists of the owner, the architect / engineer, and the general contractor, that ensure the success of any construction project. On a traditional project, the owner selects and contracts with the general contractor to construct a building designed by the architect. A considerable amount of research has been conducted to understand the owner's selection factors to hire a qualified general contractor. However, the general contractor selected for the project seldom self-performs the entire construction of a building. The general contractor might self-perform some aspects of the actual building construction, but they will typically select and contract with various subcontractors to perform majority of the project scope. Hence, the selection and sub-contractor type selected by the general contractor can significantly impact the actual construction in terms of schedule, quality and cost. With this in mind, this study's main objective is to understand the selection factors that general contractors consider, besides price, when selecting and contracting with subcontractors. A survey was developed and distributed to sixty-five large general contractor companies in the Southeast United States. It was concluded that past performance, experience, financial history, manpower, knowledge of scope and workload were the general contractors' key selection factors.

Key Words: construction, subcontractor, selection criteria

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INTRODUCTION

The primary entities for any building construction project are the owner, the architect / engineer, and the general contractor. These entities form the primary stakeholders for any construction project team. Any project team's goal is to have a collaborative system of stakeholders with diverse experience for project success (Joseph Garcia & Mollaoglu, 2020). The construction industry's complex nature demands multiple participants' involvement in the project delivery system (Ruparathna & Hewage, 2015). Moreover, the collaborative work of the construction projects requires many contracting parties to work together for successful project completion (El-Sayegh et al., 2019).

Among the project delivery team's selection, the selection of the general contractor plays a significant role in ensuring the success of any construction project (Eke et al., 2019). The general contractor is selected to manage the entire project delivery process. This process of general contractor selection is typically carried out by experts in the front-end planning phase of the project (Safa et al., 2016). It is advised that a qualification-based selection must be adopted for selecting general contractors (Alleman et al., 2017). Qualification -based selection takes in consideration the owner's concerns and construction performance of the contractor and encourages contractors to provide a detailed scope specific review and additional input to increase project success (Lines & Ravi Kumar, 2018). Management of the project delivery process includes identifying value engineering, risk reduction, quality assurance metrics, and schedule optimization (Alleman et al., 2017). The general contractor plays a vital role in the overall project performance (Cristóbal & Ramón, 2012) due to the value added to the project team. Therefore, there is no doubt that the general contractor selection process must be managed effectively (Huang, 2011).

However, on any construction project, the general contractor typically contracts with multiple subcontractors to complete the required scope of work (McCord & Gunderson, 2014). Hence, the performance of sub-contractors largely affects the ability of the general contractors to deliver the project on time, keeping in mind the quality and budget (Ramalingam, 2020). The best subcontractor is one that maximizes on high-quality work backed with strong technical skills and a cooperative attitude (Choudhry et al., 2012). Hence, the selection and the type of subcontractor selected by the general contractor can significantly impact the actual construction in terms of managing the project delivery (Ayettey & Danso, 2018). The selection of incompetent subcontractors who do not satisfy the defined performance criteria can affect the successful delivery of projects (El-Abbasy et al., 2013). The selection process should embrace the investigation of a subcontractor's potential to complete the required work (Adamtey, 2020). However, the factors used to select subcontractors can sometimes be subjective and hard to measure, which can cause complications when used in the evaluation (Plebankiewicz & Kubek, 2016).

Despite this complication, defining subcontractor selection should be considered a critical decision-making standard for the general contractor on each construction project (Jato-Espino et al., 2014). Using bid prices as the sole criteria in subcontractor selection is often criticized (Jaskowski et al., 2010). Price should not be the only eligibility criterion for assessing subcontractors to complete work on a project (Lee et al., 2018). Awarding a construction contract to the lowest bidder, without considering other factors, can result in cost overruns, delays, and poor performance (El- khalek et. al., 2019; Wondimu et al., 2020). Moreover, reliance on non-price criteria is shown to be increasing in the United States (Lines et al., 2020; Gajjar et. al. 2018; Gajjar et. al. 2014). Factors like subcontracting strategy, performance improvement, process innovation, information sharing, cooperation, collaboration, standardization of selection, and evaluation feedback are important for better partnerships between general contractor and the sub-contractor (Eom et al., 2015). Evaluation of technical proposals from subcontractors for projects is encouraged since hiring sub-contractors based on price does not guarantee performance (Lines & Miao, 2016).

Previous research on factors for selecting subcontractors have been conducted in other countries such as Australia (Zou and Lim, 2014), Poland (Plebankiewicz, 2010), Turkey (Ulubeyli et al., 2010), Spain (Nieto-Morote & Ruz-Vila, 2012), Egypt (Marzouk et al., 2013) and India (Puri & Tiwari, 2014). However, due to the different laws and industry structure, research outside of the United States cannot be used for the US construction industry. Sub-contractor selection being an important factor and fewer studies conducted within the United States to understand these factors; the objective of this study is to understand the selection factors used by general contractors, besides price, when selecting and contracting with subcontractors for building construction projects, primarily focused in the Southeast United States.

METHODOLOGY

The research methodology for this study is shown in Figure 1.

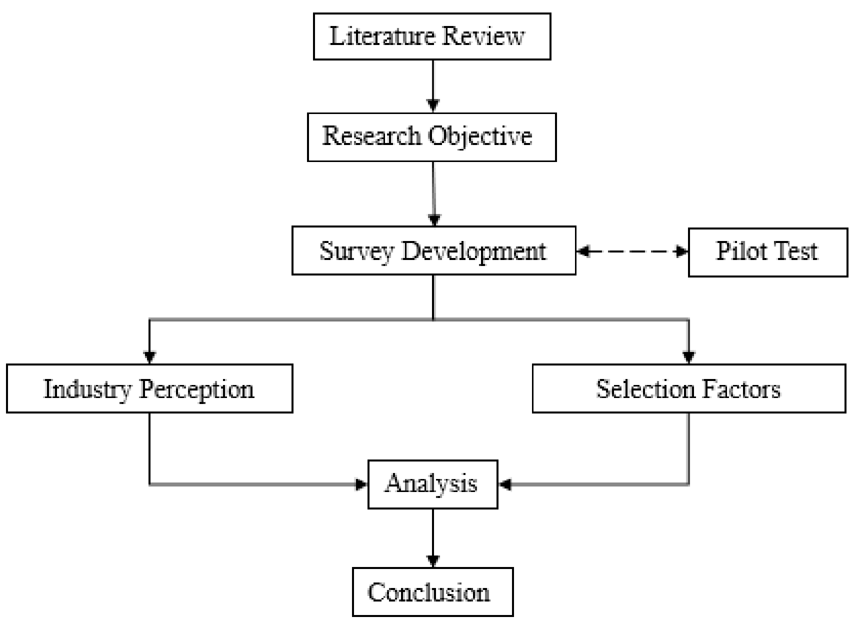

Figure 1. Methodology

Research Objective

The main objective of this study is to understand the selection factors used by general contractors, besides price, when selecting and contracting with subcontractors for building construction projects; primarily focused in the Southeast United States. Further, this study aims to explore the following:

1. The primary method used to collect sub-contractor bid documents.
2. Perception of the industry professionals on current sub-contractor selection.
    a. Need to standardize sub-contractor selection process.
    b. Attendance at a pre-bid meeting and its effect on sub-contractor selection.
3. Understand the various selection factors used for sub-contractors.

Survey Development

To measure the perception of the industry professionals and the sub-contractor selection factors, a survey was developed as shown in Appendix A. The major components of the survey were:

1. Company background information [Q1 to Q7]
2. Industry Perception [Q8 to Q9]
3. Sub-contractor Selection Factors [Q10 to Q13]

Since there are no previous studies in the US for sub-contractor selection factors, the researchers used industry expertise to compile various selection factors on the survey for respondents to select from. With that aim, a pilot study with three major general contracting companies was conducted. A pilot study was also conducted to test the survey instrument's effectiveness and ensure that the data collected aligned with the objectives of the study. The participants had one week to complete the pilot testing of the survey and provide feedback. The survey was updated to include "Other (write-in)" for the selection factors based on the pilot study findings. The feedback from the pilot study also showed that the developed survey was relevant, clear, easy to follow and met the objectives of the study.

The final survey was distributed to sixty-five (65) general contracting companies in the Southeast United States.

Data Collection

Qualtrics, a web-based system, was used to collect survey data for this study. The study achieved a response rate of 45% (twenty-nine general contractor companies out of sixty-five companies). The survey was distributed to senior position employee within each company such as Project Executive, Vice-President, Director, Chief Preconstruction Manager, Chief Estimator, Senior Project Manager and Project Manager that can provide company-wide practices about sub-contractor selection factors. The company background information is provided in Table 1.

Company Background	Data
Total Company Respondents	29
Range of Annual Revenue of Company Respondents	$4 Million - $7 Billion

Table 1. Company Background

ANALYSIS / FINDINGS

The study revealed that all the respondent's utilize electronic platforms such as email and software for receiving subcontractor bids. No contractor indicated requesting subcontractor bids by in-person or mail.

Industry Perception

Figure 2 shows the respondent's perception of statements regarding standardizing the subcontractor selection process and the effect of pre-bid meetings in selection. Participants were asked to rate each statement using a Likert scale of 1 to 5, with 1 being strongly disagree and 5 being strongly agree using the Likert scale.

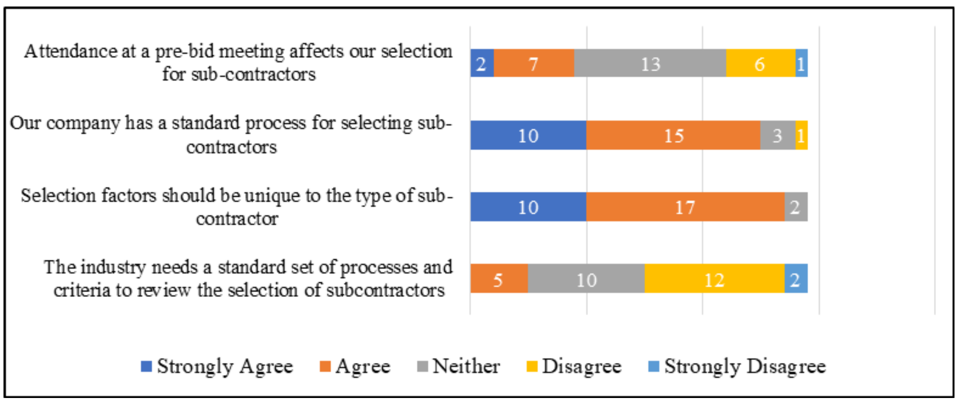

Figure 2. Industry Perception

48% of the survey participants stated that an industry standardized process and criteria are not needed for subcontractor selection. However, 86% of survey respondents agreed that their company has a standard process for selecting subcontractors. This finding aligns with the statement "selection factor should be unique to the type of sub-contractor" that received 93% agreement. Only 31% agreed that attendance at a pre-bid meeting affects their selection of subcontractors.

Selection Factors

Out of the twenty-nine (29) survey respondents, 7% (two respondents) responded that price was the only factor considered when selecting subcontractors. The remaining 93% (twenty-seven respondents) responded that they used other criteria, besides price, for selecting subcontractors. Since two survey respondents stated price is the only selection factor, they were not included in further analysis. The remaining twenty-seven survey respondents were further asked to select all the factors they use to select sub-contractors from the list. There was also an option to manually input any "other" selection factor that was not included on the list. The ranking of the factors based on the responses is shown in Table 2.

Past performance, experience, financial history, and manpower were the top four factors used, whereas technology capability, security access, logistics plan, and equipment availability were the least four factors used.

Out of the twenty-nine survey respondents, 79% (twenty-three respondents) stated that they conduct interviews as part of the subcontractor selection process. Further, an open-ended question was asked to the survey respondents to list all the factors they consider when evaluating sub-contractors during the interview. Since this was an open-ended question the responses received from the survey respondents were further analyzed using thematic coding to identify unique selection factors. Table 3 outlines the individual responses of the participants and the coded selection factor that correlate to the appropriate theme.

#	Factor	Responses	
		#	**% (out of 29)**
1	Past Performance	27	93%
2	Experience	24	83%
3	Financial History	24	83%
4	Manpower	24	83%
5	Reputation	17	59%
6	Schedule	17	59%
7	Safety/EMR Score	16	55%
8	Referrals	15	52%
9	Location	12	41%
10	Lawsuit History	11	38%
11	Risk Management	11	38%
12	Quality Program	10	34%
13	Technology Capability	6	21%
14	Security Access	4	14%
15	Logistics Plan	3	10%
16	Equipment Availability	3	10%

Table 2. Selection Factors

#	Response	Theme(s)
1	Team - Workload - Relevant Experience	Teamwork, Workload, Experience
2	Workload, available manpower, reputation, our past experiences	Workload, Manpower, Reputation, Experience
3	Professionalism, organization, approach to doing business.	Professionalism
4	Collaboration ability. How well are the people in the room willing to collaborate with our team in the room. IT's a specific energy that you will feel when things are connecting, and everyone is focused on delivering a high performing building.	Teamwork
5	Knowledge of Scope and confidence in projected manpower	Knowledge of Scope, Manpower
6	Experience, work, and character.	Experience, Professionalism
7	Financials, manpower, references, workload, etc.	Financials, Manpower, Reputation, Workload
8	competency	Knowledge of Scope
9	How well the subcontractor knows the job and their plan for how they will perform the scope of work	Knowledge of Scope
10	Who is my team (#1 selection criteria)? And then verifying scope.	Teamwork, Knowledge of Scope
11	Safety, Price, Availability, Manpower, Financial Stability, Workload, Risk Assessment, Prequalification's Rating, Bonding Rate	Safety, Price, Workload, Manpower, Financials, Risk Assessment, Bonding
12	Project experience, experience of proposed project team, current project commitments and backlog, available manpower, etc.	Experience, Workload, Manpower
13	Team, Previous Experience, Manpower, Trusted Partner	Teamwork, Experience, Manpower
14	Discuss all the previously referenced criteria, to validate the written information provided with their bids.	None
15	experience	Experience
16	How well they know / have researched the project, what workload at time of work being performed looks like, experience, schedule, price, etc.	Knowledge of Scope, Workload, Experience, Schedule, Price
17	We have a standard process (SPR = Subcontractor Proposal Review) that we perform prior to issuing any subcontractors. This SPR Mtg covers safety, financial status, or sub (bonding requirement), scope, clarifications, schedule, manpower, sub-subcontractors/supplier, etc.	Safety, Financials, Bonding, Knowledge of Scope, Schedule, Manpower, Supplier
18	Our interview is geared to address the following: 1. Subcontractor demonstrated knowledge of the project. 2. Experience of proposed supt. and PM. 3. Ability to identify additional items of value to us and our client. 4. Identify anomalies in subcontractor proposal and discuss exclusions	Knowledge of Scope, Experience
19	reputation, financial strength, manpower, location etc.	Reputation, Financials, Manpower, Location
20	All the items previously listed / checked any addition to the assigned foreman / lead super experience and references	Experience, Reputation
21	Capability/Experience, Available Capacity, Quality/Safety Goals	Experience, Workload, Safety, Quality Program
22	Quality, capacity, price, and safety.	Quality program, Workload, Manpower, Price, Safety
23	The subcontractor will make it to the interview process based on competitive pricing, past performance, and financial status. The subcontractor will be selected after or during the interview based on their understanding of the project and availability to perform the work.	Workload, Manpower, Knowledge of Scope

Table 3. Respondent Responses

To understand the selection factors used for sub-contractor interviews, the total number of unique themes for each response was further recorded and analyzed as shown in Table 4 below.

Response	**Teamwork**	**Workload**	**Experience**	**Manpower**	**Reputation**	**Professionalism**	**Knowledge of Scope**	**Financials**	**Safety**	**Risk Assessment**	**Schedule**	**Supplier**	**Quality**	**Price**
Response #1	X	X	X											
Response #2		X	X	X	X									
Response #3						X								
Response #4	X													
Response #5				X			X							
Response #6			X			X								
Response #7		X		X	X			X						
Response #8							X							
Response #9							X							
Response #10	X						X							
Response #11		X		X				X	X	X				X
Response #12		X	X	X										
Response #13	X		X	X										
Response #14														
Response #15			X											
Response #16		X	X				X				X			X
Response #17				X			X	X	X		X	X		
Response #18			X				X							
Response #19				X	X			X						
Response #20			X		X									
Response #21		X	X						X				X	
Response #22		X		X					X				X	X
Response #23		X		X			X							
Total	**4**	**9**	**10**	**10**	**4**	**2**	**8**	**4**	**4**	**1**	**2**	**1**	**2**	**3**

Table 4. Thematic Coding Analysis

Manpower, experience, workload and knowledge of scope were the top four interview factors used. Risk assessment, supplier relationship, schedule and quality program were the least four factors used during the interview.

CONCLUSION

The main objective of this study was to understand the perception of industry professionals regarding current sub-contractor selection and the selection factors for sub-contractors. Typically, sub-contractor selection is a company-specific operation, and this study explores sub-contractor selection factors from multiple general contracting companies' perspective. This study also fills a literature gap by investigating selection factors for sub-contractors in the US, which is currently missing from the literature body of knowledge.

Based on the survey responses, it was concluded that all the respondents receive sub-contractor bids electronically. The primary methods for collecting bids were either by software portal or email. The study also showed that each construction project and each type of sub-contractor is unique. On that note, only about half of the respondents agree that the industry needs a standardized industry-wide sub-contractor selection process. The majority of the respondents agree that the selection criteria should be unique depending on the sub-contractor.

Moreover, only nine companies out of the twenty-nine surveyed consider attendance at the pre-bid meetings as a sub-contractor selection factor. Typically, a pre-bid meeting is conducted for the sub-contractors to understand the project details, the scope of work, uniqueness, restrictions and potential challenges for the project at hand. Even though attendance at a pre-bid meeting does not affect subcontractor's selection for majority of the respondents, attendance should be highly encouraged for subcontractors to understand the project.

Two out of the twenty-nine respondents reported that price was the only selection factor utilized for sub-contractor selection. Companies that used other factors besides price selected past performance, experience, financial history and manpower as the top four selection factors for sub-contractors. The two factors of experience and manpower were also in the top four factors during the sub-contractor's interview process. Knowledge of scope and workload were the other two factors included in the top four during the interview process. For respondents who conduct interviews, the interview process is used to understand the sub-contractor's in-depth capability and the knowledge of the specific project in hand to perform the required scope of work and evaluate if they have enough manpower available for the project in hand by understanding their current workload. These two factors are critical from the general contractor's perspective to ensure that the project is completed as per the drawings and specifications and on-time with minimum disruptions. In summary, past performance, experience, financial history, manpower, knowledge of scope and workload were the key selection factors utilized by the respondents for sub-contractor selection.

For limitations, this study was conducted among the general contractors in the Southeast United States. Future research needs to be conducted to understand the factors from general contractors in other states and understand the different factors between different regions in the United States. Also, this study focused on the selection factors for an individual project. Further research on the factors that affect sub-contractor pre-qualification to be included in the general contractor bid list needs to be explored.

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The Impact of Climate Change on Building Energy Demands and Mitigation Measures in Florida

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ABSTRACT

Tropical and subtropical parts of the world are projected to be the most vulnerable to the impact of climate change on building energy consumption demand. Few studies, however, focus on all four greenhouse emission scenarios defined by International Panel of Climate Change, which would be useful in assessing the energy demand challenges areas such as Florida. This study applies the most recognized climate change model downscaling approach, the morphing method, to investigate the impact of climate change on the commonly used commercial buildings in Florida's climate zones under all four emission scenarios. It also analyzes the efficacy of various mitigation measures which could be used to adapt to the projected changes in building energy demand. These mitigation measures include thermal insulation R-value of wall systems and roofing systems, visible transmittance (VT) and solar transmittance (ST) of glazing materials. It is found that the mitigation measure VT of glazing material is the least effective in reducing the energy demands while increasing the insulation R-value of both wall and roofing systems is the most effective approach. It is suggested that combination of mitigation measures is certainly more efficient than taking only one mitigation measure. Furthermore, recommended measures are presented for each Florida climate zone, building type, and greenhouse gas emission scenario to best mitigate the impact of climate change and help achieve building energy efficiency.

Keywords: climate change; mitigation measures; building energy efficiency; greenhouse gas emission scenarios; climate zones

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Introduction

The major cause of climate change is the increased emission of greenhouse gases into the atmosphere, which is extremely likely the result of human activities (U.S. National Aeronautics and Space Administration, 2020). Researchers of various fields are investigating the impact of climate change and potential mitigation measures to help address the challenges the global community will face as a result, such as changes in energy demand, especially in tropical and subtropical areas where the impact is projected to be the most notable. The climate of the north and central parts of Florida is humid subtropical while most of south Florida has a tropical climate (Wikipedia.org. https://en.wikipedia.org/wiki/Climate_of_Florida, 2020). According to the U.S. Energy Information Administration (Energy Information Administration. Florida State profile and energy estimate, http://www.eia.gov/state/?sid=FL, 2020), the commercial buildings in Florida account for 23.7% of total energy demand. Building energy consumption associated with space cooling accounts for a significant proportion of commercial building electricity use in Florida (Jiang, et al. 2017)

Studies of climate change impact on building energy consumption usually simulate the future building energy demands based on the predicted future weather data. The simulation tools include HELIOS (Frank, 2005), TRNSYS (Jentsch, Bahaj, and James, 2008, Kikumoto, et al. 2014, Arima, et al., 2016), Visual DOE (Radhi, 2009, Lam, et al. 2010, Wan, et al. 2012), AccuRate (Wang, Chen, and Ren, 2010), BEND (Dirks, et al. 2015), HEED (Sabunas and Kanapickas, 2017), Energy Plus (Dirks, et al. 2015, Xu, et al. 2012, Wang and Chen, 2014, Huang and Gurney, 2016, Shen, 2017, Wang, Liu, and Brown, 2017, Jiang and O'Meara, 2018) and other simulation tools and methods. Among these tools, Energy Plus is widely recognized by academia and industry professionals due to its powerful building energy simulation algorithms.

Most studies focus on climate change impact on residential buildings and office buildings (Frank, 2005, Jentsch, Bahaj, and James, 2008, Kikumoto, et al. 2014, Arima, et al. 2016, Radhi, 2009, Lam, et al. 2010, Wan, et al. 2012, Wang, Chen, and Ren, 2010, Sabunas and Kanapickas, 2017, Wang, Liu, and Brown, 2017, Chan, 2011, Olonscheck, Holsten, and Kropp, 2011, Jentsch, et al, 2013) while only a few investigate building types such as shopping malls (Zhu, et al, 2016), educational buildings (Asimakopoulos, et al. 2012), and other commercial buildings (Xu, et al. 2012, Huang and Gurney, 2016, Shen, 2017). Future weather data is predicted based on climate scenario models developed in a veriety of methods. Frank (2005) projects the trend of future weather in four scenarios: Scenario A: WMO normal, Scenario B: IEA Design Reference Year, Scenario C: Average reference year, Scenario D: Warm reference year. Belcher (Belcher, et al. 2005) and Jentsch (Jentsch, Bahaj, and James, 2008) apply UKCIP02 climate change scenarios to analyze the impact of climate change on multi-story office buildings in the UK. (Kikumoto, et al. 2014) and Arima (2016) use MIROC4h climate models to study the impact of climate change on detached houses in Tokyo, Japan. Zhu (2016), Sabunas and Kanapickas (2017), and Wang (2017) apply scenarios of the Community Earth System Model (CESM) to study the climate change impact on offices, hotels, and shopping malls.

Among these climate scenario models, the assessment reports of Intergovernmental Panel on Climate Change (IPCC), which is widely recognized, projects four greenhouse gas emission scenarios: B1(low), B2 (medium-low), A2 (medium-high), and A1FI (high) in three time slices: the 2020s, 2050s and 2080s. Hadley Centre Coupled Model version 3 (HadCM3) is one of the major models used in the IPCC assessment reports, and has been used by Jentsch and his colleagues (Jentsch, Bahaj, and James, 2008, Jentsch, et al, 2013) to develop a climate change weather file generator tool, CCWorld-WeatherGen, under the A2 greenhouse gas emission scenario using Microsoft Excel. The tool downscales the global climate model HadCM3 to future local climate weather data using a morphing method. It allows individual end users to generate local future weather data according to the A2 greenhouse gas emission scenario in the widely used Typical Meteorological Year (TMY2) and EnergyPlus/ESP-r Weather (EPW) file formats. Subsequently, Sabunas and Kanapickas (2017) and Jiang and O' Meara (2018) used CCWorldWeatherGen to generate future weather data of scenario A2 for the periods of the 2020s, 2050s and 2080s to study the impact of climate change and mitigation measures for the residential buildings in Kaunas, Lithuania, and commercial buildings in Florida, respectively. Other methods of downscaling various global climate models to future local climate weather include the Q-Sin method (Chow and Levermore, 2007), principal component analysis (Lam, et al. 2010), the statistical downscaling dynamic procedure (Xu, et al. 2012), regression modeling (Wan, et al. 2012), the Goodness-of-fit procedure (Dirks, et al. 2015) and the dynamical downscaling method (Kikumoto, et al. 2014, Arima, et al. 2016). Among all these climate change model downscaling approaches, the morphing method is the most widely recognized by researchers (Wang, Chen, and Ren, 2010, Wang and Chen, 2014, Shen, 2017, Wang, Liu, and Brown, 2017, Chan, 2011, Zhu, et al. 2016, Belcher, et al. 2005).

The literature review shows that most research of climate change impact on buildings applies the morphing method to downscale the global climate model, mainly HadCM3, to local future weather data. Then researchers use the predicted local future weather data and building models as inputs to an energy simulation tool, mainly EnergyPlus. However, all these studies either focus on a moderate climate change scenario, such as A2, or a high greenhouse gas emission scenario, such as A1FI. Few research studies all four IPCC greenhouse gas emission scenarios: B1(low), B2 (medium-low), A2 (medium-high), and A1FI (high). This study applies the most recognized climate change model downscaling approach, the morphing method, to investigate the impact of climate change on the most commonly used commercial buildings — high-rise apartment, office, hotel, and school — in humid subtropical and tropical areas under all four scenarios - B1, B2, A2, and A1FI - in time slices of 2020, 2050 and 2080. It also explores the mitigation measures for building energy demand increase to achieve future building energy efficiency.

Methodology

Commercial Building Types and Climate Zones in Florida

Commercial buildings in Florida consume almost one quarter of the state's total energy (Energy Information Administration. Florida State profile and energy estimate, http://www.eia.gov/state/?sid=FL , 2020) and here are nine climate zones in Florida (Figure 1, left) according to Florida Building Code due to its large east-west and north-south geographical span. Accordingly, this study investigates four typical commercial buildings — high-rise apartments, offices, hotels, and secondary schools (Figure 2) — in eight selected cities from the nine climate zones. As reference buildings, these buildings meet the minimum requirements of Florida building energy efficiency code (Jiang and O'Meara, 2018). Their main features are listed in the Table 1 and are modeled to be used in EnergyPlus for energy demand simulation.

Figure 1. (a) Climate zones in Florida

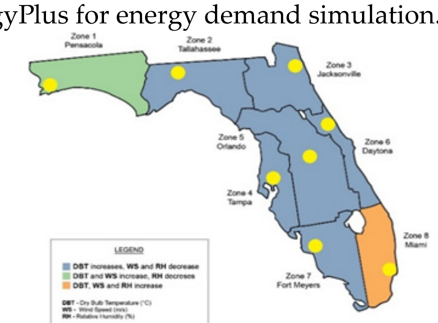
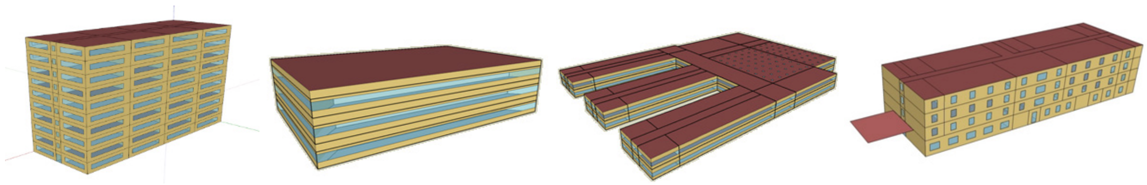


Figure 1. (b) Projected climate change in Florida



(a) (b) (c) (d)

Figure 2. Selected commercial building types: **(a)** high-rise apartment; **(b)** medium office; **(c)** secondary school; **(d)** School Small Hotel.

Table 1. Main features of the commercial buildings

Climate Zone		1	2	3	4	5	6	7	8
Cities		Pensacola	Tallahassee	Jacksonville	Tampa	Orlando	Daytona	Fort Myers	Miami
Total Floor Area	High-rise Apartment	84,360 sf							
	Medium Office	53,600 sf							
	Secondary School	210,900 sf							
	Small Hotel	43,200 sf							
Number of Floors	High-rise Apartment	10							
	Medium Office	3							
	Secondary School	2							
	Small Hotel	4							
Floor to Floor Height	High-rise Apartment	10 ft							
	Medium Office	13 ft							
	Secondary School	13 ft							
	Small Hotel	Ground floor: 11 ft, Upper floors: 9 ft							
Window U-value (Btu / h · ft2 · °F)		0.87	0.87	0.87	0.48	0.48	0.48	0.48	0.48
Window Solar Heat Gain Coefficient		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Window Heat Transfer Coefficient		0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
Exterior Wall Insulation R-value		13	13	13	13	13	13	13	13
Roof Insulation R-value		16	16	16	14	14	14	12	12
Foundation Insulation R-value		0	0	0	0	0	0	0	0
Air Infiltration of fenestration (cfm/lf)		0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Peak infiltration of exterior wall (cfm/lf)		0.2016	0.2016	0.2016	0.2016	0.2016	0.2016	0.2016	0.2016

Table 1. Main features of the commercial buildings (Continued)

Cooling Set Point	High-rise Apartment	75°F
	Medium Office	75°F
	Secondary School	75°F
	Small Hotel	70°F for occupied guest rooms 74°F for vacant guest rooms 75°F for public spaces (lobby, meeting room etc.)
Heating Set Point	High-rise Apartment	70°F
	Medium Office	70°F
	Secondary School	70°F
	Small Hotel	70°F for occupied guest rooms 66°F for vacant guest rooms 70°F for air conditioned public spaces (lobby, meeting room etc.) 45°F heating for stairs and storage rooms
Cooling Set-back Point	High-rise Apartment	None
	Medium Office	80°F
	Secondary School	85°F
	Small Hotel	74°F
Heating Set-back Point	High-rise Apartment	None
	Medium Office	60°F
	Secondary School	60°F
	Small Hotel	66°F

Projected Future Weather

The research team developed a web-based climate change downscaling application Weather Morph: Climate Change Weather File Generator, which could downscale HadCM3 climate change model to local future weather data for all four IPCC greenhouse gas emission scenarios in the early stages of this study (Jiang, et al. 2019). The application assists research and professional communities to conduct further research and sensitivity analysis on climate change impact on not only the building energy demands but also infrastructure, coastal engineering and construction, sustainability analysis of buildings and infrastructure, and land use. This study utilizes the application, which can be accessed at http://139.62.210.131/weatherGen/, to generate local future weather data of the eight selected cities in Florida under all four IPCC emission scenarios; B1, B2, A2, and A1FI. The output of the application is comprised of projected future weather hour by hour datasets, including years 2050 and 2080, in formats TMY2 for general use and EPW for use with Energy Plus, which is the simulation program most widely used in building energy analysis. Table 2 shows the current and year 2080 averages of main weather parameters. Figure 3 and 4 show the comparisons of current and future dry-bulb temperature (°C) and relative humidity (%) in the selected cities under four greenhouse gas emission scenarios. In terms of dry bulb temperature, the trend line of A1FI (high greenhouse gas emission/ fossil fuel intensive scenario) climbs faster along the time line than other trend lines in all selected cities. The trend line of A2 (medium-high greenhouse gas emission) is the second fast-climbing one following the A1FI scenario. Regarding relative humidity, all selected cities are projected to become drier compared to current typical weather except Miami. In other words, Miami will become hotter and more humid while other selected cities will become hotter and drier. Additionally, north Florida (Pensacola, Tallahassee, and Jacksonville) will become windier while the central Florida (Tampa, Orlando, Daytona Beach) and south Florida (Fort Meyer and Miami) are projected to become less windy. The right map in Figure 2 shows projected climate change in various climate zones of Florida.

Table 2. Main Current and Projected Year 2080 Weather Parameters of the Selected Cities

City and Weather Parameters	Current Averages	Averages in Year 2080			
Climate Zone 1 Pensacola	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	19.85	25.278	24.31	22.8	22.91
Relative Humidity (%)	76.03	69.849	70.25	73.51	72.18
Wind Speed (m/s)	3.478	3.598	3.629	3.511	3.532
Climate Zone 2 Tallahassee	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	19.01	24.89	23.84	22.17	22.28
Relative Humidity (%)	74.93	67.245	67.66	71.99	70.49
Wind Speed (m/s)	2.901	2.938	2.951	2.906	2.903
Climate Zone 3 Jacksonville	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	19.8	24.735	23.84	22.54	22.59
Relative Humidity (%)	76.3	73.20	73.29	75.18	74.61
Wind Speed (m/s)	3.283	3.3225	3.345	3.31	3.299
Climate Zone 4 Tampa	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	21.92	26.265	25.45	24.33	24.37
Relative Humidity (%)	73.8	72.309	72.64	73.31	72.97
Wind Speed (m/s)	3.579	3.5639	3.583	3.545	3.549
Climate Zone 5 Orlando	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	21.9	26.252	25.45	24.33	24.35
Relative Humidity (%)	77.1	75.807	75.99	76.63	76.62
Wind Speed (m/s)	3.651	3.6011	3.628	3.605	3.604
Climate Zone 6 Daytona	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	21.3	25.7	24.9	23.7	23.8
Relative Humidity (%)	75.9	74.7	74.8	75.5	75.5
Wind Speed (m/s)	3.396	3.410	3.439	3.411	3.405
Climate Zone 7 Fort Myers	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	23.8	28.1	27.3	26.2	26.2
Relative Humidity (%)	76.5	74.9	75.4	76	75.8
Wind Speed (m/s)	3.040	3.003	3.003	2.952	2.979
Climate Zone 8 Miami	**TMY**	**A1FI**	**A2**	**B1**	**B2**
Dry-bulb Temperature (◦ C)	24.3	28.2	27.5	26.5	26.5
Relative Humidity (%)	72.5	72.88	73.13	72.8	72.96
Wind Speed (m/s)	4.337	4.4343	4.391	4.25	4.299

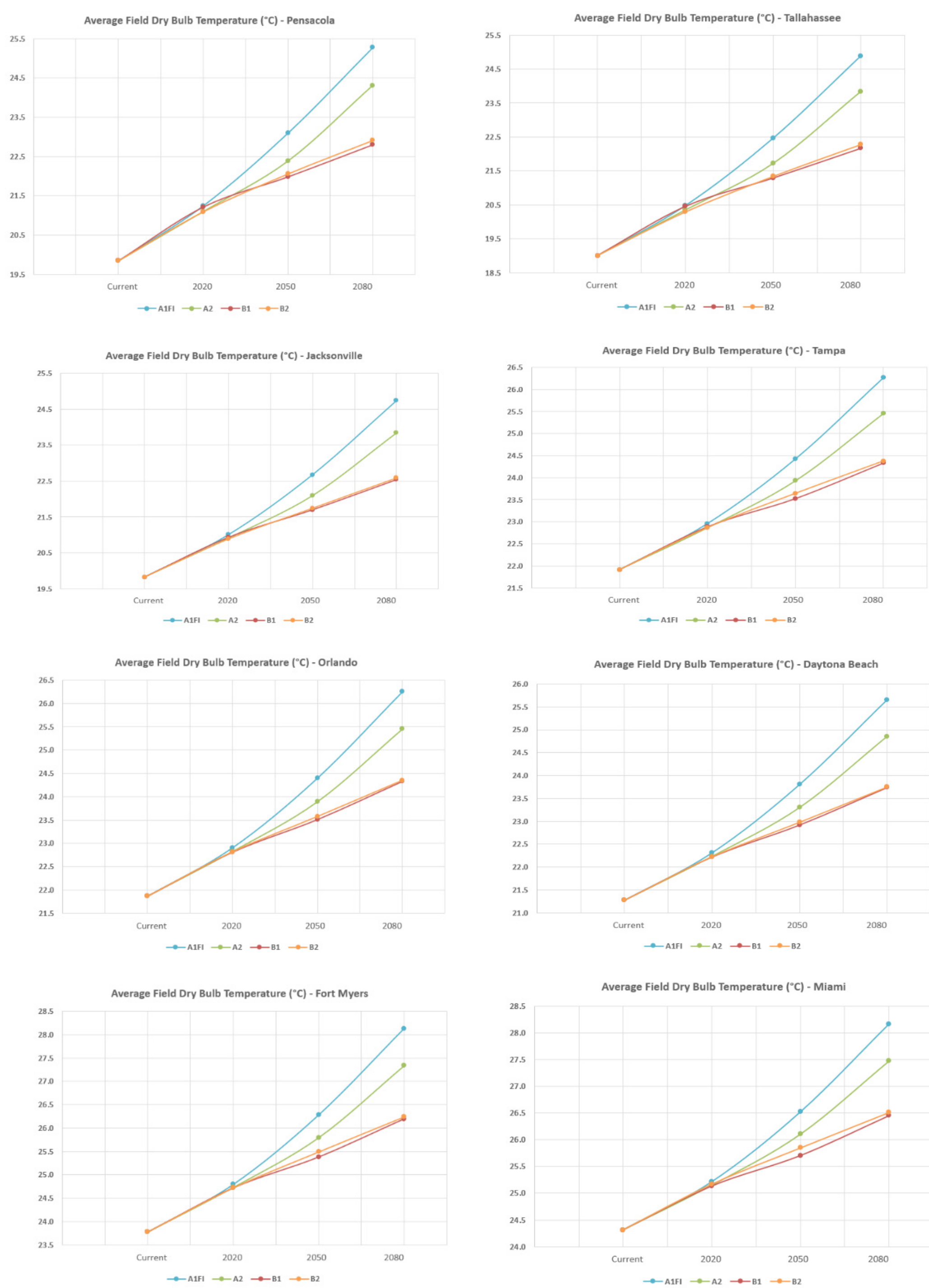


Figure 3. Comparison of current and future dry-bulb temperature (in °C) in the selected cities under four greenhouse gas emission scenarios

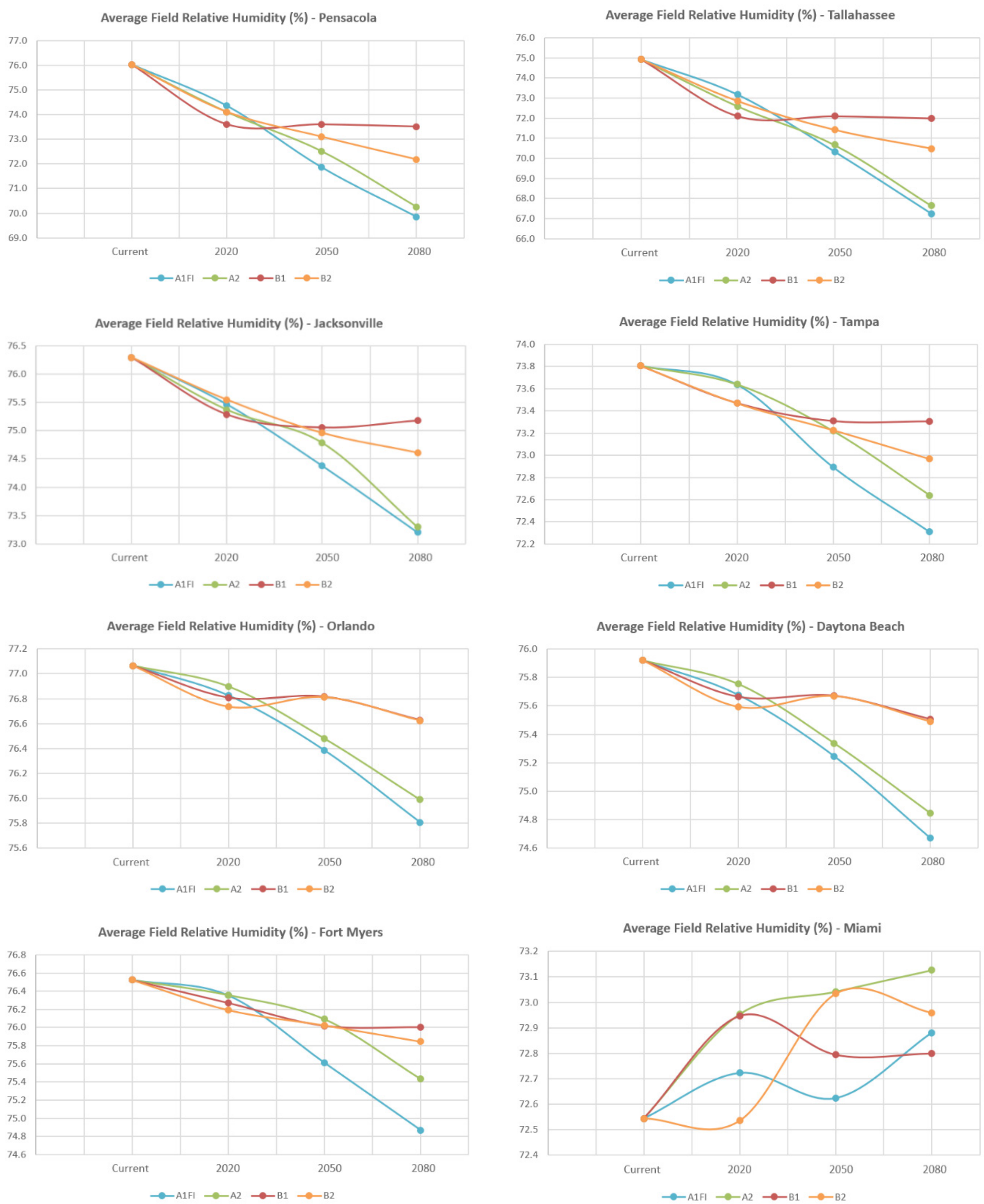


Figure 4. Comparison of current and future relative humidity (in %) of the selected cities under four greenhouse gas emission scenarios

Mitigation Measures for Building Energy Efficiency

Since the dry-bulb temperature, relative humidity, and wind speed are projected to either increase or decrease in all Florida climate zones at varied rates due to the climate change, it is expected that building energy demand will fluctuate significantly in the next few decades. Consequently, the design and construction of energy efficient buildings to accommodate to the impact of the climate change will be an increasing concern for the architecture/engineering/construction (AEC) industry. The current Florida energy efficiency code for commercial buildings will need to be updated accordingly to adapt to the future energy efficiency expectations of clients and occupants alike. The factors that affect building energy demand include, but not limited to, fenestration materials, thermal insulation materials of walls, roofs and ceilings, air infiltration, space heating and cooling systems, ventilation systems, etc. Radhi (2009) pointed out that in Saudi Arabia the thermal insulation and thermal mass are important to cope with global warming; window area and glazing system are beneficial and sensitive to climate change, whereas the shading devices are moderate and insensitive to global warming. Through literature review (Radhi, 2009, Jiang and O'Meara, 2018, Brown, et al. 2014, Wan, Li, and Lam, 2011, Roaf, Crichton, and Nicol, 2005), and in light of the Florida energy efficiency building code and OSHA standards, several mitigation measures have been identified (Table 3):

- Insulation R-value of wall systems
- Insulation R-value of roofing systems
- Insulation R-value of wall and roofing systems
- Visible transmittance (VT) of glazing materials
- Solar transmittance (ST) of glazing materials

Table 3. Commercial Building Code Compliance (extracted from Energy Efficiency in Florida Building Code) and Mitigation Measures.

Wall Type	Florida Building Energy Efficiency Code/Building Model	Mitigation Measures
Metal frame	R-13 (exterior, adjacent, and common)	R-19 and R-20
Built-up roof	Climate zones 1,2, and 3, R-16 Climate zones 4,5, and 6, R-14 Climate zones 7,8, and 9, R-12	R-19 and R-20
Visible transmittance (VT) of glazing materials	0.08-0.898	0.3
Solar transmittance (ST) of glazing materials	0.06-0.831	0.2
Thermal conductivity of windows	0.9	0.3

Using the above projected weather data and building models, this study simulates the energy demands of four types of commercial buildings in eight selected Florida cities in all four greenhouse gas emission scenarios - B1(low), B2 (medium-low), A2 (medium-high), and A1FI (high) - for typical meteorological year (TMY), 2020, 2050, and 2080 projections. The following section shows the analysis of building energy demands due to the climate change and suggested mitigation measures.

Results

This study applies the widely recognized building energy simulation program Energy Plus developed by the Department of Energy to simulate energy consumption in the most common commercial buildings in Florida — apartments, medium-size hotels, medium-size offices, and secondary schools. Figure 5 shows the total percent energy demand change range in all four emission scenarios of four types of buildings. The scenario A1FI (high emission) obviously is the worst scenario in all building types while the scenario B1(low emission) is the best scenario. The total energy demand increase in percentage is as high as 29.4% in Miami schools in scenario A1FI and as low as 3.14% in Jacksonville apartments in scenario B1. All simulation output shows the heating demands will decrease in all areas of Florida. However, the decreased heating energy demand is less than the increased cooling energy demand. This definitely would lead to a total energy demand increase. Therefore, mitigation measures are necessary to achieve building energy efficiency. The following sections show the study results of mitigation measures on the selected four commercial building types.

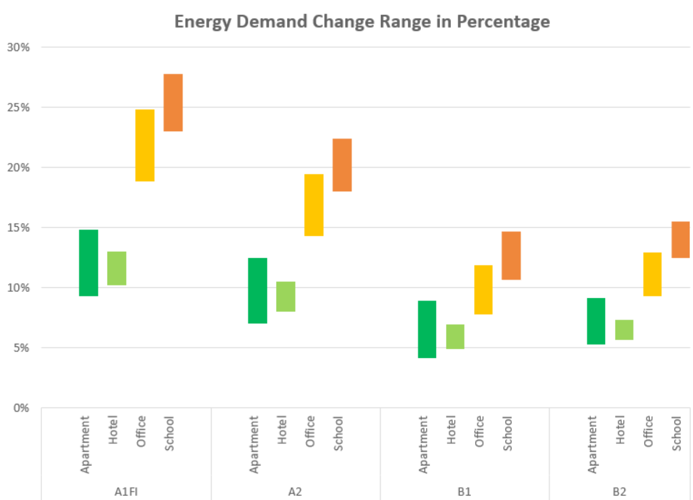


Figure 5. Energy demand changes range in percentage in terms of building types and emission scenarios by comparing the ones in year 2080 with the ones in TMY

Apartment

The high-rise apartments have built-up roofing and steel-frame wall systems. The R values of roofing systems vary in different climate zones. Climate zones 1, 2, and 3 require at least R-16; climate zones 4, 5, and 6 require R-14 or above; while the requirements of climate zones 7, 8, and 9 are at least R-12. Wall and foundation insulation R value are 13 and 0 respectively in all climate zones of Florida (Table 3). The cooling and heating set points of apartment are 75 ^{o}F and 70 ^{o}F respectively. Glazing material's visible transmittance (VT) and solar transmittance (ST) at normal incidence are the amounts of visible light and light respectively that pass through a glazing material. The higher the VT and ST values, the warmer the rooms are. The value ranges of VT and ST of apartment are 0.08–0.0898 and 0.06–0.831 respectively. The mitigation measures include changing the wall and roof insulations to R19, R20, as well as changing the values of VT and ST to 0.3 and 0.2 respectively (see Table 3) to achieve building energy efficiency. The energy demand simulation results of all selected cities under various emission scenarios and mitigation measures are presented in Table 4 and Figure 6:

- Baseline case: the baseline scenario apartment follows the current Florida building codes without mitigation measures. Miami and Fort Myers have the highest energy demands at 15.13 kWh/SF and 15.00 kWh/SF. Without mitigation measures, the cities which have the highest and the lowest energy demands in 2080 in A1FI, A2, B1 and B2 are always Miami (zone 8) and Fort Myers (zone 7), as well as Jacksonville (zone 3), and Tallahassee (zone 2). The second highest and lowest energy demands in 2080 in all four greenhouse gas emission scenarios are Orlando (zone 5) and Tampa (zone 4) as well as Daytona (zone 6) and Pensacola (zone 1). Regarding the energy demand change in percentage, the cities with the highest to the lowest change are always Miami, Fort Myers, Orlando, Daytona, Tampa, Pensacola, Tallahassee, and Jacksonville in all emission scenarios. Miami has the highest increased energy demand change in percentage 14.77% in scenario A1FI while it only has 8.85% increase in scenario B1. Jacksonville has the lowest increased energy demand change 9.29% in scenario A1FI and 4.09% in scenario B1.

- Wall insulation changed to R-19 and R-21: The wall insulation R values of all climate zones are changed to 19 and 21 to mitigate the energy demands in 2080. The simulation results show that Miami which has the highest energy demand increase (from current 15.13 kWh/SF to 17.36 kWh/SF in 2080 in scenario A1FI, 14.77% increase) in the baseline scenario would reduce the energy demand in the A1FI scenario to 17.29 kWh/SF (R-19, 14.31% energy increase) and 17.27 kWh/SF (R-21, 14.14% energy increase). In the meantime, Jacksonville has the lowest energy demand increase in percentage in all emission scenarios in this case — as low as 3.65% and 3.48% respectively when wall R values are 19 and 21 in scenario B1.

- Roof insulation changed to R-19 and R-20: The roof insulation R values of all climate zones are changed to 19 and 21 to mitigate the energy demands in 2080. Comparing to the baseline case, Miami would reduce the energy demand in the A1FI scenario to 17.32 kWh/SF (R-19, 14.52% energy increase) and 17.31 kWh/SF (R-21, 14.44% energy increase) while Jacksonville would again in all emission scenarios have the lowest energy demand increase in percentage — 3.84% in wall R-19 and 3.75% in wall R-21 in scenario B1.

- Both wall and roof insulation changed to R-19 and R-20: When both wall and roof insulation R values are changed to 19s and 20s, the energy demands in Miami would be reduced in the A1FI scenario to 17.25 kWh/SF (both wall and roof R values are 19, 14.06% energy increase) and 17.22 kWh/SF (both wall and roof R values are 21, 13.82% energy increase). In the meantime, the energy demands in Jacksonville would have the least increase in percentage again in this case — as low as 14.78 kWh/SF (both wall and roof R values are 19, 3.39% increase) and 14.74kWh/SF (both wall and roof R values are 21, 3.14% increase) in B1 scenario.

- Glazing material's VT and ST changed to 0.3 and 0.2 respectively: the energy demands in Miami in the A1FI scenario and Jacksonville in the B1 scenario would be reduced to 17.36 kWh/SF and 14.88 kWh/SF respectively (14.77% and 4.09% energy increase) comparing to their current energy demands.

A comparison of these mitigation measures shows that increasing wall insulation values is more efficient than increasing roof insulation values, e.g. the energy demands are 17.27 kWh/SF and 17.31 kWh/SF in Miami in A1FI emission scenario respectively when the wall and roof insulation values are R-21. This impact is attributed to the high aspect ratio of areas of exterior wall to roof. Increasing both wall and insulation values of an apartment building is a better mitigation measure than increasing the insulation values of wall or roof system only. Changing VT to 0.3 and ST to 0.2 is another efficient mitigation measure due to the high aspect ratio of window to exterior wall. The lower a percentage change in energy demand increase, the better a mitigation measure is. The percentage change in energy increase is within the range 3.14% -14.77%. To differentiate the mitigation measures, this study categorizes the mitigation measures in increments of 5% increase in energy demand. For instance, the energy demand increase in percentage are 0% — 5%, 5% — 10%, 10% — 15%, etc. The lower the energy demand increase in percentage, the better a mitigation measure is. Mitigation measures in Table 4 are colored in accordance with this system. For example, the most efficient mitigation measure in Pensacola (climate zone 1) in emission scenario A1FI is to change both wall and roof insulation R values to 21. In the meantime, all mitigation measures (including a scenario without any mitigation measures applied) in Pensacola in emission scenario B1 are efficient due to the modest climate change. Accordingly, not adopting mitigation measures in Pensacola in scenario B1 is more economical. Similarly, Pensacola would not need to adopt mitigation measures in scenario A2 and B2. Figure 7 shows the suggested efficient mitigation measures for apartment buildings in the eight selected cities under all four emission scenarios if the building code officials, designers, and constructors adopt only one mitigation measure among the nine mitigation measures. However, the combination of mitigation measures would certainly be more efficient than adopting one mitigation measures. For instance, the most efficient mitigation measure in Daytona in scenario A2 is to change both wall and roof insulation values R to 21. Under the other three scenarios, it is suggested that Daytona either not adopt any mitigation measures (if only one mitigation measure is permitted) or adopt a combination of mitigation measures (if more than one mitigation measure is needed). This suggestion also applies to Orlando, Fort Myer, and Miami. In other words, the cities located in the climate zones 5, 7, 8 and 9 are advised to adopt more than one mitigation measure while the cities in the climate zones 1, 2, 3, 4 and 6 may adopt one mitigation measure in order to make apartment buildings energy efficient.

Table 4. Energy demand projection of high-rise apartment in 2080

City	Current	Mitigation Measures	Scenario A1FI		Scenario A2		Scenario B1		Scenario B2	
	Energy demand kWh/SF		Energy demand kWh/SF	Change in %	Energy demand kWh/SF	Change in %	Energy demand kWh/SF	Change in %	Energy demand kWh/SF	Change in %
Pensacola	14.48	Without Mitigation	16.07	10.96%	15.71	8.52%	15.19	4.87%	15.4	6.36%
		Wall Insulation R19	16	10.49%	15.65	8.05%	15.12	4.43%	15.33	5.89%
		Roof Insulation R19	16.03	10.69%	15.68	8.26%	15.15	4.62%	15.36	6.09%
		Wall & Roof Insulation R19	15.96	10.22%	15.61	7.78%	15.08	4.17%	15.29	5.62%
		Wall Insulation R21	15.97	10.31%	15.62	7.87%	15.1	4.27%	15.31	5.71%
		Roof Insulation R21	16.02	10.60%	15.66	8.16%	15.14	4.53%	15.35	6.00%
		Wall & Roof Insulation R21	15.92	9.95%	15.57	7.52%	15.05	3.92%	15.26	5.35%
		ST of glazing materials	16.07	10.96%	15.71	8.52%	15.19	4.87%	15.4	6.36%
		VT of glazing materials	16.07	10.96%	15.71	8.52%	15.19	4.87%	15.4	6.36%
Tallahassee	14.29	Without Mitigation	15.8	10.61%	15.41	7.88%	14.88	4.17%	15.1	5.71%
		Wall Insulation R19	15.73	10.12%	15.34	7.40%	14.82	3.72%	15.03	5.22%
		Roof Insulation R19	15.76	10.33%	15.37	7.60%	14.84	3.90%	15.06	5.43%
		Wall & Roof Insulation R19	15.69	9.85%	15.3	7.12%	14.78	3.45%	14.99	4.94%
		Wall Insulation R21	15.71	9.94%	15.32	7.22%	14.79	3.55%	15.01	5.04%
		Roof Insulation R21	15.75	10.24%	15.36	7.51%	14.83	3.82%	15.05	5.34%
		Wall & Roof Insulation R21	15.65	9.57%	15.26	6.85%	14.74	3.19%	14.95	4.67%
		ST of glazing materials	15.8	10.61%	15.41	7.88%	14.88	4.17%	15.1	5.71%
		VT of glazing materials	15.8	10.61%	15.41	7.88%	14.88	4.17%	15.1	5.71%
Jacksonville	14.49	Without Mitigation	15.84	9.29%	15.51	6.99%	15.09	4.09%	15.25	5.22%
		Wall Insulation R19	15.77	8.83%	15.44	6.53%	15.02	3.65%	15.18	4.75%
		Roof Insulation R19	15.8	9.03%	15.47	6.73%	15.05	3.84%	15.21	4.96%
		Wall & Roof Insulation R19	15.73	8.57%	15.4	6.27%	14.98	3.39%	15.14	4.49%
		Wall Insulation R21	15.75	8.65%	15.41	6.36%	15	3.48%	15.16	4.58%
		Roof Insulation R21	15.79	8.94%	15.46	6.65%	15.04	3.75%	15.2	4.87%
		Wall & Roof Insulation R21	15.7	8.31%	15.36	6.02%	14.95	3.14%	15.1	4.22%
		ST of glazing materials	15.84	9.29%	15.51	6.99%	15.09	4.09%	15.25	5.22%
		VT of glazing materials	15.84	9.29%	15.51	6.99%	15.09	4.09%	15.25	5.22%

Table 4. Energy demand projection of high-rise apartment in 2080 (Continued)

Tampa	14.44	Without Mitigation	16.32	13.02%	15.94	10.43%	15.46	7.09%	15.55	7.71%
		Wall Insulation R19	16.25	12.57%	15.88	10.00%	15.4	6.67%	15.49	7.28%
		Roof Insulation R19	16.28	12.77%	15.91	10.18%	15.42	6.85%	15.51	7.47%
		Wall & Roof Insulation R19	16.21	12.32%	15.84	9.75%	15.36	6.43%	15.45	7.04%
		Wall Insulation R21	16.23	12.40%	15.86	9.84%	15.38	6.52%	15.46	7.12%
		Roof Insulation R21	16.27	12.69%	15.89	10.10%	15.41	6.77%	15.5	7.38%
		Wall & Roof Insulation R21	16.18	12.07%	15.81	9.51%	15.33	6.20%	15.42	6.79%
		ST of glazing materials	16.32	13.02%	15.94	10.43%	15.46	7.09%	15.55	7.71%
		VT of glazing materials	16.32	13.02%	15.94	10.43%	15.46	7.09%	15.55	7.71%
Orlando	14.33	Without Mitigation	16.39	14.41%	15.99	11.58%	15.48	8.00%	15.54	8.45%
		Wall Insulation R19	16.33	13.97%	15.93	11.17%	15.42	7.61%	15.48	8.04%
		Roof Insulation R19	16.36	14.16%	15.95	11.35%	15.44	7.77%	15.51	8.21%
		Wall & Roof Insulation R19	16.29	13.72%	15.89	10.93%	15.39	7.37%	15.45	7.80%
		Wall Insulation R21	16.31	13.80%	15.91	11.01%	15.4	7.46%	15.46	7.89%
		Roof Insulation R21	16.35	14.08%	15.94	11.27%	15.43	7.69%	15.49	8.13%
		Wall & Roof Insulation R21	16.26	13.47%	15.86	10.69%	15.35	7.15%	15.41	7.57%
		ST of glazing materials	16.39	14.41%	15.99	11.58%	15.48	8.00%	15.54	8.45%
		VT of glazing materials	16.39	14.41%	15.99	11.58%	15.48	8.00%	15.54	8.45%
Daytona	14.22	Without Mitigation	16.12	13.33%	15.74	10.70%	15.28	7.43%	15.35	7.95%
		Wall Insulation R19	16.05	12.89%	15.68	10.27%	15.22	7.03%	15.29	7.54%
		Roof Insulation R19	16.08	13.08%	15.71	10.45%	15.24	7.20%	15.32	7.71%
		Wall & Roof Insulation R19	16.02	12.65%	15.65	10.03%	15.19	6.80%	15.26	7.30%
		Wall Insulation R21	16.03	12.73%	15.66	10.12%	15.2	6.89%	15.27	7.39%
		Roof Insulation R21	16.07	13.00%	15.7	10.37%	15.23	7.12%	15.31	7.63%
		Wall & Roof Insulation R21	15.98	12.40%	15.61	9.80%	15.16	6.57%	15.22	7.06%
		ST of glazing materials	16.12	13.33%	15.74	10.70%	15.28	7.43%	15.35	7.95%
		VT of glazing materials	16.12	13.33%	15.74	10.70%	15.28	7.43%	15.35	7.95%
Fort Myers	15.00	Without Mitigation	17.18	14.57%	16.79	11.97%	16.27	8.51%	16.29	8.64%
		Wall Insulation R19	17.11	14.10%	16.73	11.53%	16.21	8.10%	16.23	8.22%
		Roof Insulation R19	17.14	14.31%	16.76	11.73%	16.24	8.28%	16.26	8.41%
		Wall & Roof Insulation R19	17.07	13.85%	16.69	11.29%	16.18	7.87%	16.2	7.99%
		Wall Insulation R21	17.09	13.93%	16.7	11.37%	16.19	7.95%	16.21	8.07%
		Roof Insulation R21	17.13	14.23%	16.75	11.65%	16.23	8.20%	16.25	8.33%
		Wall & Roof Insulation R21	17.04	13.59%	16.65	11.05%	16.14	7.64%	16.16	7.76%
		ST of glazing materials	17.18	14.57%	16.79	11.97%	16.27	8.51%	16.29	8.64%
		VT of glazing materials	17.18	14.57%	16.79	11.97%	16.27	8.51%	16.29	8.64%
Miami	15.13	Without Mitigation	17.36	14.77%	17	12.41%	16.47	8.85%	16.5	9.08%
		Wall Insulation R19	17.29	14.31%	16.94	11.98%	16.4	8.45%	16.44	8.68%
		Roof Insulation R19	17.32	14.52%	16.97	12.18%	16.43	8.63%	16.47	8.85%
		Wall & Roof Insulation R19	17.25	14.06%	16.9	11.74%	16.37	8.22%	16.4	8.45%
		Wall Insulation R21	17.27	14.14%	16.91	11.82%	16.38	8.30%	16.42	8.52%
		Roof Insulation R21	17.31	14.44%	16.96	12.10%	16.42	8.56%	16.45	8.78%
		Wall & Roof Insulation R21	17.22	13.82%	16.87	11.51%	16.34	8.00%	16.37	8.22%
		ST of glazing materials	17.36	14.77%	17	12.41%	16.47	8.85%	16.5	9.08%
		VT of glazing materials	17.36	14.77%	17	12.41%	16.47	8.85%	16.5	9.08%

<5%	5%-10%	10%-15%	15%-20%	20%-25%	25%-30%	30%-35%

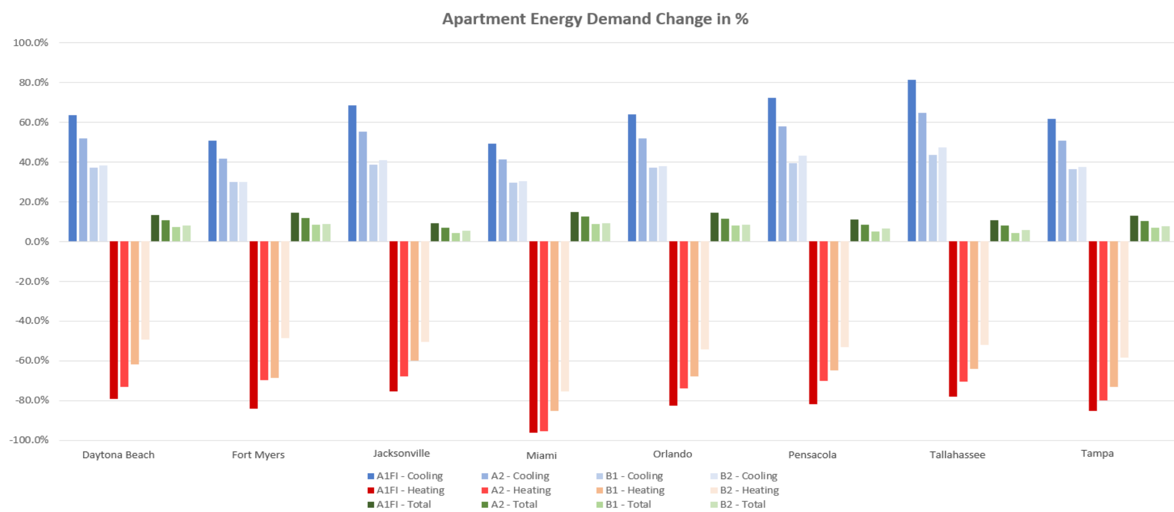


Figure 6. Apartment energy demand changes in percentage by comparing the ones in year 2080 with the ones in TMY

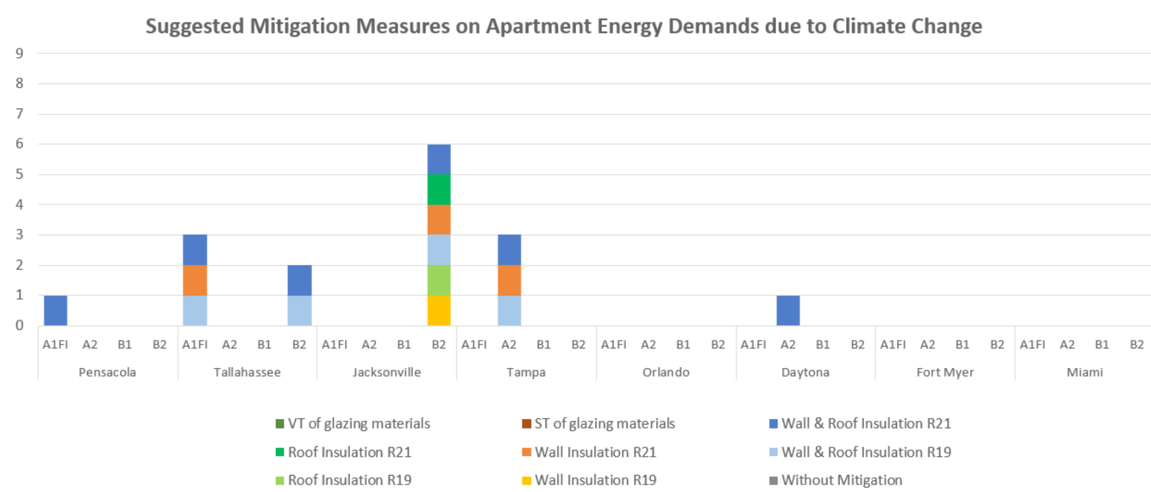


Figure 7. Suggested mitigation measures on apartment energy demands due to climate change

Hotels

Hotels also have built-up roofing and steel-frame wall systems. The main features of hotels can be found in Table 1 and 3 as well as Figure 2. Without mitigation measures (baseline case), the cities which have highest energy demands in 2080 in scenarios A1FI, A2, B1 and B2 are always Miami and Fort Myers while Jacksonville and Tallahassee are the two lowest energy demand cities in all four emission scenarios (Figure 8). The other four cities are in the middle even though their energy demand rankings may vary in the four emission scenarios. When applying the mitigation measures, Fort Myer is consistently projected to have the highest percent energy demand increase in all four emission scenarios. On the other hand, Jacksonville has the lowest energy demand increase in percentage in scenario A1FI, A2, and B2 while Tallahassee has the lowest in scenario B1. Due to the high aspect ratio of area of exterior wall to roof, increasing the wall insulation value is more effective than increasing roof insulation value. VT and ST mitigation measures are not as efficient as they are in the hotel buildings since the hotel's aspect ratio of windows to exterior wall is not as high as that of an apartment building. The mitigation measures (data, which is in the similar format as the apartment building, can be provided per request) are colored based on their capacities in mitigating future increased energy demands due to climate change, and the suggested mitigation measures for hotels is displayed in Figure 7.

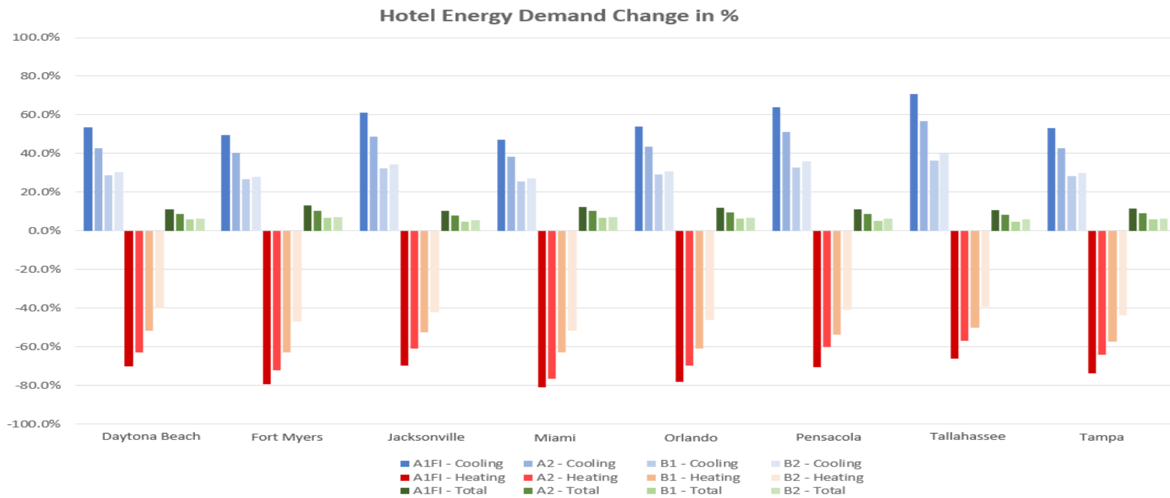


Figure 8 Apartment energy demand changes in percentage by comparing the ones in year 2080 with the ones in TMY

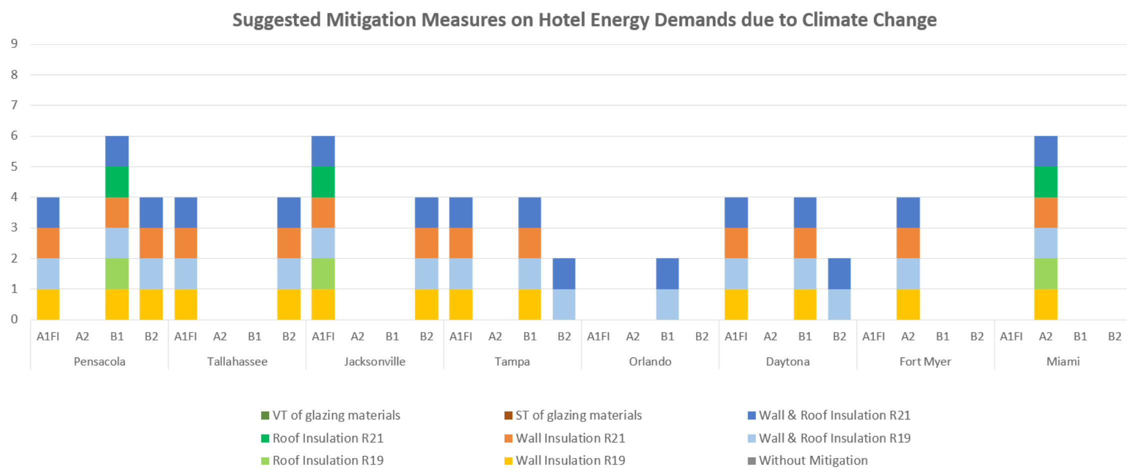


Figure 9 Suggested mitigation measures on hotel energy demands due to climate change

Offices

The built-up roofing and metal wall systems of medium-size office buildings have the same minimal thermal resistance requirements as the above studied buildings according to Energy Efficiency in Florida Building Code. In the baseline case, the cities which have highest energy demands in 2080 in scenarios A1FI, A2, B1 and B2 are always Fort Myers while Jacksonville and Tallahassee take turns to be the lowest energy demand cities in all four emission scenarios (Figure 10). The other four cities' ranks are in the middle in the four emission scenarios. By applying this mitigation measures, Fort Myers still has the highest energy demand increase in percentage in all emission scenarios. In the meantime, Jacksonville has the lowest energy demand increase in percentage in emission scenarios A1FI, A2, and B2 while Tallahassee has the lowest ones in emission scenario B1. In office buildings, increasing the wall insulation value is a more efficient mitigation measure than increasing the roof insulation value due to the high aspect ratio of areas of exterior wall to roof in office buildings. VT and ST mitigation measures are likewise efficient since the office buildings have large curtain wall areas compared to hotels. The suggested mitigation measures for offices are displayed in Figure 11.

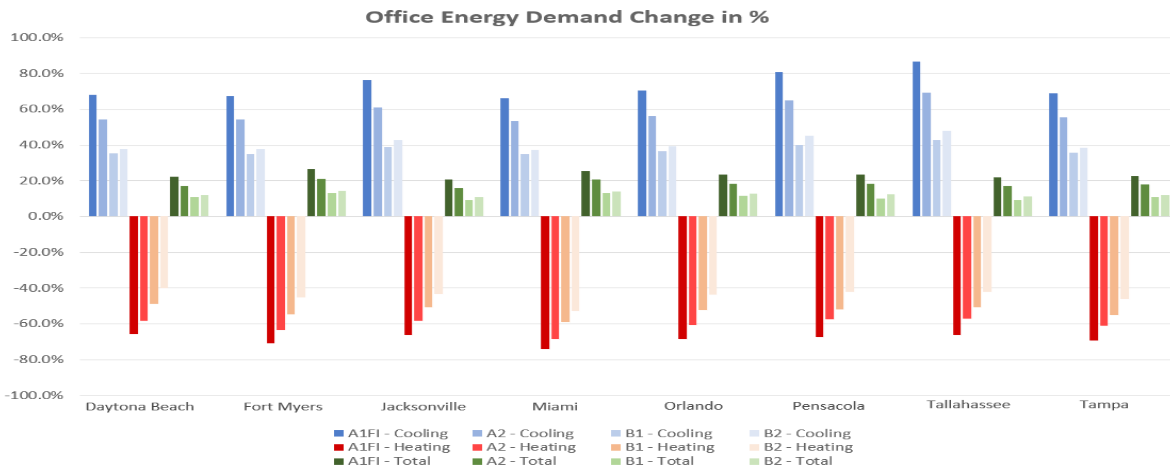


Figure 10 Apartment energy demand changes in percentage by comparing the ones in year 2080 with the ones in TMY

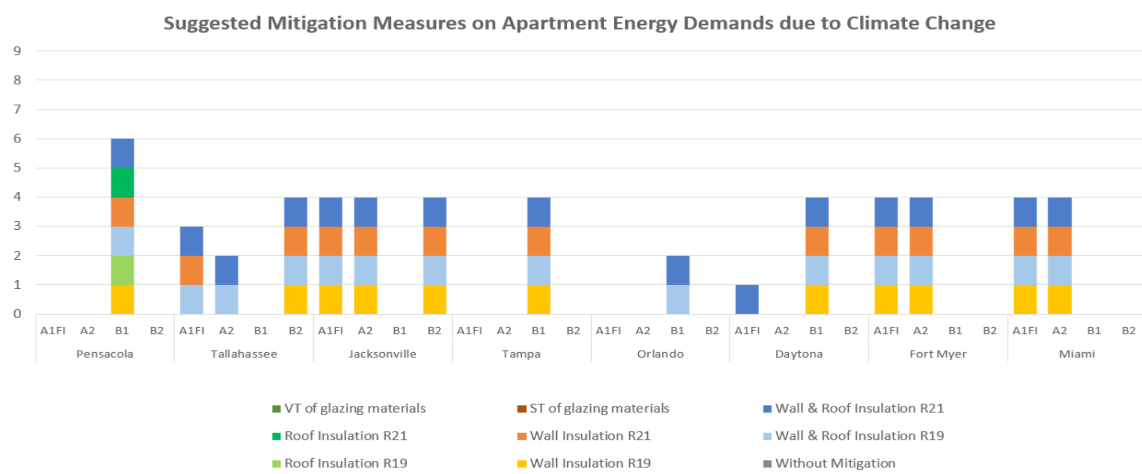


Figure 11 Suggested mitigation measures on office energy demands due to climate change

Secondary Schools

The main features of secondary school buildings have been presented in Table 1 and 3 and Figure 2. Without mitigation measures in the secondary school buildings, the cities which have highest energy demands in 2080 in scenarios A1FI, A2, B1 and B2 are always Miami and Fort Myers while Jacksonville and Tallahassee are the two lowest energy demand cities in all four emission scenarios. The other four cities are in the middle in the four emission scenarios. Figure 12 shows Fort Myers and Miami are projected to have as high as 29.4% and 29.37% increase in A1FI emission scenario while Jacksonville is projected to increase as low as 12% in B1 emission scenario. The energy demand increase in terms of percentage of the other four cities are between 12.38% and 28.1% in all four emission scenarios. By applying the mitigations measures, Miami would have the highest energy demand increases in all four emission scenarios while Jacksonville has the lowest energy demand increases. VT and ST mitigation measures are not as efficient mitigation measures as increasing wall and roof insulation values since the window area is not as much as the ones of roof and exterior wall. The suggested mitigation measures for schools is displayed in Figure 9.

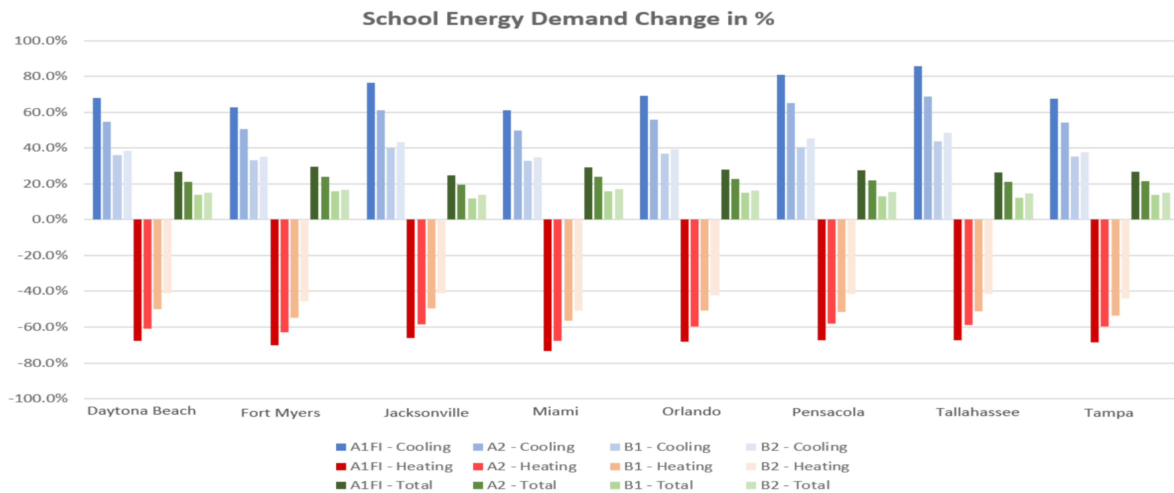


Figure 12 Apartment energy demand changes in percentage by comparing the ones in year 2080 with the ones in TMY

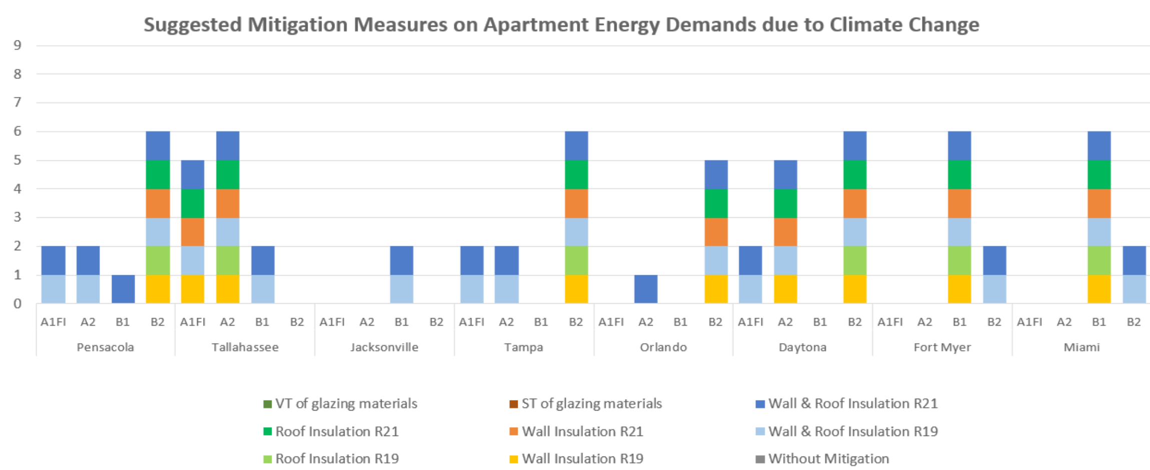


Figure 13 Suggested mitigation measures on school energy demands due to climate change

Conclusions

Tropical and subtropical areas are most vulnerable to the impact of climate change compared to other climate areas. This study applies the most recognized climate change model downscaling approach, the morphing method, to investigate the impact of climate change on the most commonly used commercial buildings — high-rise apartments, offices, hotels, and secondary schools — in Florida which has typical humid subtropical and tropical climates, under all four IPCC greenhouse gas emission scenarios - B1, B2, A2, and A1FI,– and in time slices of 2020, 2050 and 2080. It first uses the application Weather Morph: Climate Change Weather File Generator, which was developed at early stage of this research project series, to downscale HadCM3 climate change model to local future weather data of all four IPCC greenhouse gas emission scenarios. Based on this study's results, Miami is projected to be hotter and more humid while other selected cities will be hotter and drier. In the meantime, north Florida is projected to become windier while central and south Florida would become less windy.

This study then applies the widely recognized building energy simulation program Energy Plus to simulate future building energy demands under various scenarios. It focuses on the building energy demand analysis for the year 2080 to evaluate proposed energy mitigation measures: (1) baseline case with no mitigation measures; (2) Insulation R-value of wall systems is R19 and 20 respectively; (3) Insulation R-value of roofing systems is R19 and 20 respectively; (4) Insulation R-value of both wall and roofing systems is R19 and 20 respectively; (5) Visible transmittance (VT) of glazing materials 0.08–0.0898 to 0.3; (6) Solar transmittance (ST) of glazing materials0.06–0.831 to 0.2. The findings of this study are concluded:

- The total energy demands of each building type would increase while the cooling demand increase is much higher than heating demand decrease in the future in all four emission scenarios in all Florida climate zones due to the climate change.

- The baseline case with no mitigation measures: The energy demand increase ranges in percentage in high-rise apartment, hotel, office, and secondary school are respectively are 4.09% —14.77%, 4.86% —12.96%, 9.14% — 26.67%, and 12% — 29.4%. The cooling demand in the northern cities Tallahassee, Pensacola, and Jacksonville increase (in %) the most while the demand in southern cities Miami and Fort Myers increase (in %) the least.

- The mitigation measure VT of glazing material is the least effective in reducing the energy demands while increasing the insulation R-value of both wall and roofing system is the most effective approach. The combination of mitigation measures is certainly more efficient than taking only one mitigation measure.

- Apartment buildings: in all four types of the studied buildings, apartment buildings require the least mitigation measures. Only the cities located in the climate zones 1, 2, 3, 4 and 6 (north Florida, central east coastal, and central west coastal Florida) need to adopt the proposed mitigation measures. The most effective mitigation measure is using thermal insulation R value 21 for both wall and roofing systems.

- Hotel buildings: the cities located in the climate zones 5 (central Florida excluding the east and west coastal climate zones) requires the least mitigation measures – increasing thermal insulation R value of wall and roofing systems to 19 or 21. All other climate zones require proposed mitigation measures. Among them, the climate zones 4 and 5 (central east and west coastal areas) have the same mitigation measure requirements due to the similar climate change patterns and geographical locations.

- Office buildings: the cities located in the climate zones 5 again (central Florida excluding the east and west coastal climate zones) requires the least mitigation measures – increasing thermal insulation R value of wall and roofing systems to 19 or 21. All other climate zones require proposed mitigation measures. Among them, the climate zones 7 and 8 (south Florida) have the same mitigation measure requirements due to the similar climate change patterns and geographical locations.

- Secondary school buildings: the cities located in the climate zone 3 (northeast Florida) requires the least mitigation measures – increasing thermal insulation R value of wall and roofing systems to 19 or 21. All other climate zones require proposed mitigation measures. Among them, the climate zones 7 and 8 (south Florida) again have the same mitigation measure requirements due to the similar climate change patterns and geographical locations.

The findings of this study provide guidance for needed changes in Florida building energy efficiency codes to address global climate change impacts at the building level. Since Florida has typical subtropical and tropical climates, the findings of this study could be referred by the other areas which have similar climates. The limitation of this study on tropical and subtropical climates leads to further studies in other areas of the United States and world-wide by applying the proposed study method.

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AGC EDUCATION AND RESEARCH FOUNDATION

The **James L. Allhands Essay** was established by the late James L. Allhands, one of the founding members of AGC and a prolific writer of construction related works. The award recognizes a student essay on a specific topic that is deemed to be beneficial to the advancement of technological, educational, or vocational expertise in the construction industry. The competition is open to any senior–level student in a four or five–year ABET or ACCE–accredited university construction management or construction–related engineering program. The First Place essay author receives $1,000. His/her faculty sponsor receives $500. Both the recipient and sponsor are invited as guests of the Foundation to the AGC Annual Convention.

The winner is notified in February and the award is presented at the AGC Annual Convention.

The topic for 2021 was ***"How New, Innovative Technology and Project Execution Tools and Techniques Can be Used to Improve the Construction Process (Including Safety and Efficiency)."*** The essays of the top three finalist are included in the following pages.

1st place - Noah Jackson, Purdue University
2nd place – James L. Craig, Auburn University
3rd place – Rhett Cox, Clemson University

The topic for the 2022 Allhands Essay Competition is "House has COVID-19 affected the construction industry both negatively and positively. What positive things haver we learned that we will carry into the future?" The deadline to apply is November 15, 2021.

For more information, go to the AGC Education and Research Foundation website: https://www.agc.org/about-us/awards-recognition-programs/agc-foundation-awards

How New, Innovative Technology Can Be Implemented to Combat the Construction Industry Labor Shortage

Noah David Jackson, Purdue University

Abstract

This essay addresses the construction industry's need to compensate for the current and projected labor shortage through innovative technologies. In the first portion of this essay, three technologies that are most feasible for implementation – the Internet of Things (IoT), Drones, and Prefabrication – are detailed. The challenges faced are then discussed before the second major portion in which steps for implementation are outlined. These steps include forming partnerships, learning the process, communicating, training, implementing, and adapting and improving. The essay concludes with a discussion of how the AGC organization, and members within, can aid the industry in meeting this goal.

Introduction

The construction industry is in the midst of rapid innovation to compensate for the many years of falling behind the technology revolution. The force driving this is the need to maintain quality production while countering the increasing tradesmen labor shortage. After many years of resisting change, the industry has taken on the dauting challenge of fostering innovation for a prosperous future.

The largest firms are developing innovation departments, investing in new technologies, and testing products on-site. However, they are facing significant hurdles. Companies struggle to determine if the investment of time and capital is worth the efficiency improvement on-site. Additionally, companies face resistance from the tradesmen who perceive some technologies as slower, inefficient, and incapable of adapting to unpredictable site conditions.

Taking this into consideration, three technologies most feasible for implementation have been chosen for discussion. These technologies have high potential to disrupt the industry, have proven their cost effectiveness, and are least intrusive to the tradesmen. The three technologies – the Internet of Things (IoT), Drones, and Prefabrication – will work integrally together to provide a foundation for the future construction jobsite.

Technologies

Internet of Things:

The Internet of Things (IoT) describes a network of devices embedded with sensors for the purpose of connecting and exchanging data. In simpler terms, IoT is a wireless connection of smart devices. This technology is common in the manufacturing industry, however many in the construction industry are yet to understand the potential.

Innovative equipment and tool manufacturers are currently fully invested in incorporating devices linked to IoT. New equipment comes factory-equipped with sensors that can monitor various metrics, and software subscriptions that provide insight to the owner. With this data, owners can make driven decisions that increase efficiency and drive down costs. An example would be data indicating an operator's fuel consumption is significantly above average. The owner could then investigate and resolve the issue, thus saving fuel and lowering project costs. Tool manufacturers are also incorporating IoT into their products. Bosch has created software that connects their tools and gives the owner insight of tool location, battery life, and more (Bosch, 2020). These metrics can all be used by management to save time and money, without intruding on the tradesmen.

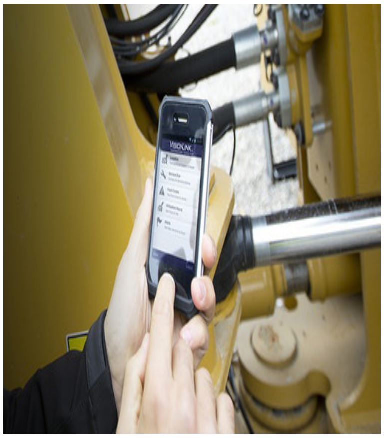

Figure 1. Mobile Software Tracks Fleets Data to Aid in Management Decisions

Tradesmen will appreciate the advanced notice of when equipment or tools will need maintenance, the tracking abilities, and the increased information and predictive analytics IoT provides. Management will appreciate the available data to drive decisions based on the most cost-effective solution. With the tradesmen and management on board, and the financial benefits, IoT is a technology ready for implementation today.

<u>Drones:</u>

Drones' capabilities have been substantially improved in recent years, while their costs have decreased. This has made them more applicable to construction and ready for implementation. On-site, the opportunities for drones are seemingly endless.

Figure 2. Drone Inspects Bridge Condition

Progress tracking and safety monitoring today require management to spend their valuable time walking around the construction site. Not only can drones complete this, but they can also automatically update schedules and documents with the collected data. Managers can then focus on higher-level protocol decisions. Drones are also beneficial for inspecting inaccessible areas to verify conditions as seen in Figure 2. These are just a few of the many tasks drones can complete autonomously on-site (Zucchi, 2016).

Drones will not replace management, rather they will aid staff in focusing less on mundane tasks. With the decreasing costs of drones and increasing costs of management, the financial benefits are clear.

Prefabrication:

Prefabrication provides a more attractive and efficient environment as it transitions tasks previously completed in the field to a controlled location. These controlled manufacturing environments consistently produce worker efficiency of 80-90%, as compared to present levels of on-site construction producing between 30-40%.

With the crippling labor shortage that the industry is experiencing and expecting in the future, focus needs to be set on mass adoption of prefabrication. "In an ideal construction process with a high degree of prefabrication, the work on site… is carried out… so simply that it can be performed by very little specialist labor" (Knaack, 2012). On-site work will then move towards assembly.

Assembly jobsites will require less workers, freeing up space and further increasing efficiency. Implementing prefabrication, in addition to the previously mentioned innovations, will prove to drastically improve the construction industry.

Working Together:

Depicted below is a visual to represent how these three technologies will work integrally on-site. IoT will collect information and deliver data to the office, where decisions will be made. Drones will fly around collecting and analyzing various metrics. Fewer tradesmen will be on-site to complete the assembly of prefabricated modules. The interconnectivity of these technologies will lead to a more efficient site, competing with the production levels of the manufacturing industry.

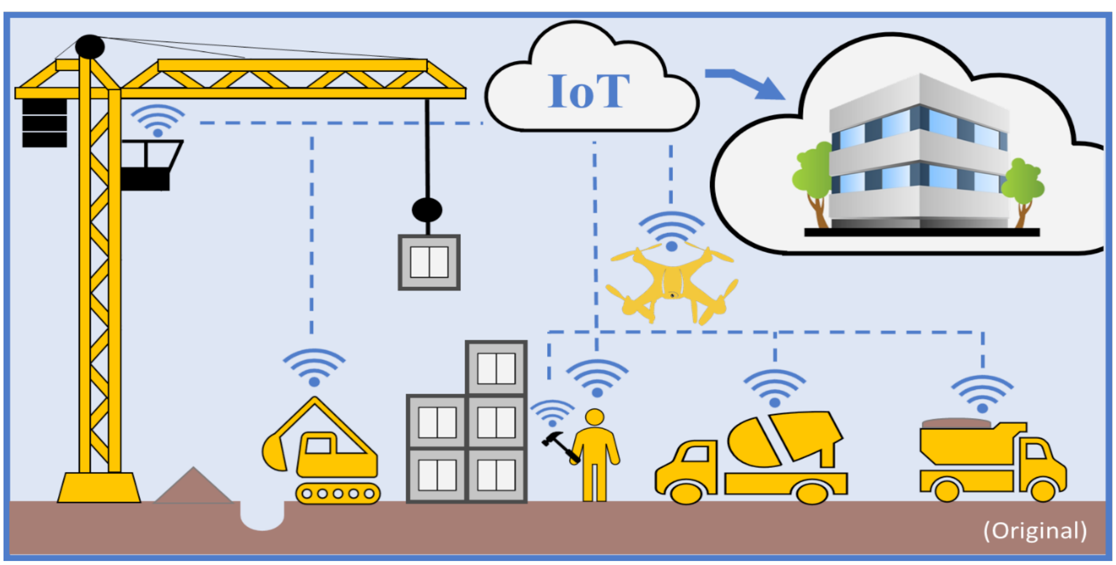

Figure 3 – IoT, Drones, and Prefabrication work integrally together to create an efficient jobsite

Challenges

As great as these technologies are, and as great as futuristic construction sites seem, they will not be possible without methodical implementation. Many new technologies are being implemented too quickly and without enough analysis – they are too expensive or not fully capable. An example of a this is with robots.

Robots are not yet advanced enough to fully take the place of a tradesman. While they have proven their capability to complete repetitive tasks, they struggle to adapt to issues and cannot handle change. They need to be monitored, are expensive, and create logistical issues that occupy a lot of high-salaried management time. The collective cost to implement robots, beyond for repetitive tasks, is presently challenging to defend. Robots may one day run construction sites, but not until they are affordable and fully capable. Therefore, focusing on technologies that can be rapidly implemented today will prove most advantageous.

The tradesmen themselves also need to be seriously considered when evaluating the implementation of a new technology. Many have been successful with their techniques incorporated over their careers and may be resistant to change. Forcing robots or other intrusive technologies into their environment will cause issues with the labor force – issues our industry cannot afford. Proper implementation will take time. To ease the transition, it will be prudent to first introduce technologies that are least intrusive.

IoT, Drones, and Prefabrication were meticulously chosen to detail because of their feasibility and readiness to implement. The final section will outline how general contractors can implement these technologies and foster an excited tradesmen cohort for the future.

Implementation

There are two key factors for the successful implementation of new technologies in the construction industry: acceptance from the tradesmen and cost effectiveness. Forcing technologies into the industry, without tradesmen acceptance, will increase the labor shortage crisis that is already crippling the industry. Therefore, technologies must be phased in the least intrusive manners. More importantly, to promote why every contractor is in business, the technologies must be cost effective. New technologies must directly contribute to lowering costs or increasing efficiency. Of all the innovative technologies, IoT, Drones, and Prefabrication are most aligned today with these critical factors for implementation.

Identifying the technologies to start implementing, however, is only the first step. The hard next steps are conducting the implementation. Below is a graphic to represent how a general contractor can best implement these three innovative technologies:

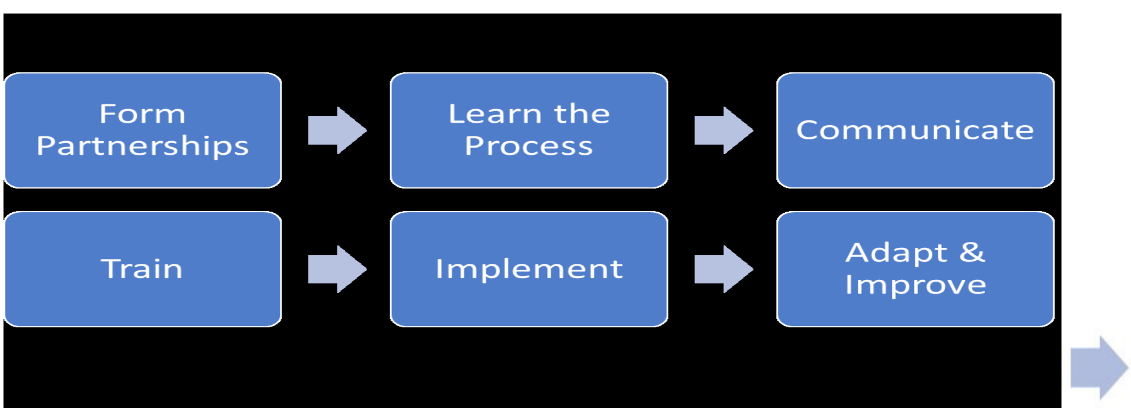

Figure 4 - Steps to successfully implement innovative technologies

1. Form Partnerships:

The first step to implement innovative technologies is to form strategic partnerships. This is a matter of recognizing our expertise in construction, and lack of expertise in areas of technology, manufacturing, and psychology. Efforts in forming partnerships shall be focused on complementing our knowledge with industries that are experts in what they do.

Technology partners will be beneficial in giving insight to current and future products, helping to bridge the gap between an older, tenured generation of executives currently in place in our industry. Manufacturing partners are crucial as they have experience implementing innovative technologies. The construction industry can take lessons learned from manufacturers to increase rates of implementation. Psychology partners will help with planning least intrusive implementation – especially for the tradesmen. As an industry, we can't afford to lose tradesmen due to a lack of consideration for how they feel or what they think about change. Psychology partners will explain how different decisions regarding implementation will affect each stakeholder.

2. Learn the Process:

Learning the process is a matter of general contractors leveraging their newly formed partnerships to understand how these expert perspectives will help.

From the technology partners, general contractors should focus on learning the details of innovative products. They should dive into the depths of how IoT and Drones work, and what their capabilities are. Technology partners will also be able to give realistic estimates of cost of implementation, potential savings, and overall impact.

From the manufacturing partners, prefabrication methods can be observed, as well as how they integrated technology. Many manufacturing industries are incorporating IoT, and general contractors can learn how to include this in prefabrication processes. From the psychology partners, management can learn how best to communicate, train, and implement technologies – while minimizing intrusiveness and motivating the workforce.

3. Communicate:

After learning all aspects from each of the partners, general contractors will need to strategically communicate the plan to their team. This should be conducted early so that the information has time to spread down the management ladder to the tradesmen. Each manager should be given specific guidelines for how to best communicate with his or her team. The goal of the communication step is to inform all stakeholders that change is coming, how that change will work, and why it will be beneficial. The right communication will instill passion in the workforce and create excitement for the future.

4. Train:

Training is necessary for management and tradesmen to learn how to use, and behave around, technology. However, these three technologies chosen will not require the expensive and time-consuming training that many other technologies do. For IoT, management will simply need to be trained on how to utilize software and access data. Tradesmen training will consist of showing how to wear sensors and perform tasks of this nature. Drones will likely be operated by third-party companies or hired operators. Therefore, the training is simple as well. Management will be shown how to access drone data and tradesmen will be taught how to behave around them. Prefabrication will require training in the manufacturing facility, where rooms can be dedicated for this. These three technologies were strategically selected with ease of training in mind. Easier training translates to lower costs and increased tradesmen acceptance – the two crucial factors for technology implementation.

5. Implement:

Timely and effective implementation of these technologies should begin during the training stage. This step requires getting connected devices on site for IoT, software packages to collect and analyze data, hiring or outsourcing a drone operator, and expanding prefabrication. This step would be near impossible without the strategic partnerships developed early on. By this step, the general contractor's relationship with its partners is anticipated to be well-developed and substantially helpful.

6. Adapt & Improve:

The final step, after the job site is up and running with all of the new technology, is to receive feedback and continue to improve. Technology will continue to advance with or without the construction industry. The general contractor must focus on continual improvement – never to become stagnant. Feedback from the tradesmen and management should be collected often. Efficiency, production, and cost reports should be regularly analyzed as well. Most importantly, general contractors should stay connected with their partners and look to the future.

Conclusion

The implementation of IoT, Drones, and Prefabrication will serve as the foundation for rapid innovation in the construction industry. Construction sites will accomplish more with less through strategic implementation of technologies.

The future construction site will have devices collaboratively working together through a network connection. Data points will be collected to track historical data, project progress, and safety metrics. Drones will conduct routine management tasks and automatically update schedules and reports. Buildings will be prefabricated off-site and assembled in the field. The technology of the future is here today; the challenge is implementation. The three technologies detailed throughout this report are most feasible with that in mind.

As an association, AGC can enhance its mission, "to ensure the continued success of the commercial construction industry", by focusing on the technology that can be implemented today. AGC can leverage its network to provide partners for general contractors in the three necessary categories – technology, manufacturing, and psychology. Furthermore, AGC can develop detailed steps for properly implementing innovative technology on-site – focused on minimal intrusiveness and maximum cost effectiveness. AGC's support will provide general contractors the resources they need to start the construction technology revolution.

Each and every industry member has a responsibility to help foster this critical innovation. The two keys for success will be to maintain cost effectiveness and ensure all stakeholders are educated for maximum cooperation. Starting with the foundation of IoT, Drones, and Prefabrication will enable this. The construction industry of tomorrow is here today; it is time to get to work.

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How New, Innovative Technology and Project Execution Tools and Techniques Can Be Used to Improve the Construction Process (Including Safety and Efficiency)

James L Craig, Auburn University

Abstract

Humanity has often sought to utilize tools and technology to make working faster, more efficient, more comfortable, and more accurate. While humans may have started with stone tools, we have since developed complex and sophisticated mechanical and digital technologies. The construction industry has been utilizing construction technology and equipment for these same reasons for generations. While other industries have embraced the use of smart, autonomous technology and robotics, the construction industry has steadily fallen behind in this effort. In this paper, I will discuss current work using these tools and possible applications for future development.

Improving the construction process

Using innovative technologies

Ever since the experiments and work of Charles Babbage, the father of the computer, mankind has been using mechanical and digital computation tools to help create efficiency in all walks of life. In construction, robotics and technology have been primarily limited to office work programs. However, many robotic devices could improve the construction process and make up for the deficiency of a low-skilled labor force in the construction industry (AGC's Construction Hiring and Business Outlook Reports).

There are opportunities for machines that could create a much more efficient and well-documented construction process. One application would be a material-moving system on job sites that utilizes robots. These robots could be programmed to automate deliveries between pre-set drop-off zones within a construction site. This process creates efficiency by allowing skilled construction workers to concentrate on more profitable and complex work. Construction also requires documentation, so another application could be the automation of progress photography and scanning. The material-moving robot could document project progress while recording the last known location of materials using photography and other sensors.

Construction robots

Skibniewski noted in "*Robotic materials handling for automated building construction technology*" that "the robot serves as a [middle-man] between the arrival of individual components and materials and the [worker] requiring them. This handling robot receives material at a pickup point and automatically identifies and inspects it. The robot then stores the material in an appropriate location according to its type or transfers it to a delivery point for immediate transfer to the [worker] or transfers it to a delivery point for the return to the manufacturing facility." (Skibniewski, 12). Robots can take a lot of labor demands off the backs of construction workers. As noted above by Skibniewski, these kinds of robots could help lower the amount of intense labor-related injuries caused by material moving. Making the construction workplace safer helps companies retain employees longer and can also increase the quality of life for laborers in the field. This kind of system also creates all sorts of opportunities to make the job site more efficient.

Robots need many sensors to help them navigate and interact with the world around them. By using these sensors, a robotic material mover could help human workers with tasks that do not require their direct attention. Examples of using such sensors might be using high-resolution video recording and streaming equipment for QR code reading, remote control, and tracking the robot's actions on the job site. Infrared electronic distance measurement sensors could be utilized for collision avoidance and response protocols, as well as drift correction. All of these sensors and devices could also be used to document work.

Automated construction progress documentation

A smaller robotic device could also be used for both virtual job site tours and automated progress photos. Using systems similar to the robotic material mover discussed above, a camera robot could be programmed to follow specified routes for progress photos, laser scans, or taking a client on a pre-routed job site tour. The camera robot could also be programmed to follow a specified individual, by using a QR code printed on a safety vest for job site tours, or could be remote-controlled by the client (with collision avoidance protocols in place to protect the job site and the robot).

At the end of each workday, a robot could be programmed to run a route with a laser scanner attached. This would allow the General Contractor, Architect, and Owner to have a precise reading and images of the daily work. This kind of transparency and accuracy, when automated, would help the entire project run smoothly and keeps all the contracted parties informed about the project's progress. Errors can be immediately seen by all parties and dealt with swiftly to avoid delays to the schedule.

At the end of the project, the images (or a select few of them, given that point cloud models are large) can be layered to give a 3D model as-built with cut through sections to show every stage of the project's structure. Not only does this assist with future maintenance, repair, and renovations to existing structures, but researchers could use that information almost like a snapshot in time to show how the structural elements shift as the building ages. This could help engineers better understand what methods and materials last longer than others.

Undergraduate research – personal experience with robotics for construction

Undergraduate research topic description

As an undergraduate research student, I have been using a small consumer-level AI (Artificial Intelligence) robot to test a proof of concept for a material-moving robot on small scale construction job site layouts. The robot chosen for these experiments is called the Robomaster EP Core. The EP core and its dimensions can be seen in Figure 1.0 below.

Figure 1.0

Figure 2.0

In Figure 1.0, general robot dimensions can be found for the length, width, and height of the robot, as well as the gripper width. This robot uses a specialized wheel system that not only allows it to move and turn like any other vehicle, but also enables it to move in specialized directions/ways. The wheels' motors operate independently of one another, which allows the robot to move directly left or right, like a drone, without rotating. The robot can also rotate itself without moving in any direction. The robotic arm on the robot is fixed in place at the front of the chassis. The robotic arm utilizes two servos which allow it to move up/down and forward/back to position the gripper in the proper location.

I set my experiments up at a 1:10 scale to make the gripper large enough to lift a 3'x 3' pallet—adding to the realism factor of my tests. Another reason the 1:10 scale is best for this research is that it makes a one-lane road about 0.5 meters wide at a smaller scale. At this scale, the robot is similar in size to a commercial truck or a small 100 HP excavator. The Robomaster EP Core is programmed using Scratch 2.0, a graphical coding program. An image of this programming language can be seen above in Figure 2.0.

Latest experimentation update

Using this programming language, I successfully programmed the robot to move from one point to another while delivering materials. In this experiment, the robotic material-mover robot was manually set up and calibrated, then set out to automatically move material from a drop-off zone to a laydown yard, and then navigate back home.

This first attempt was not a proof of concept. I expect to create and utilize a navigational system that uses multiple sensors and sources of information. This includes QR codes, tape lines, IR (infrared) distance sensors, and clap/gesture commands to teach the robot how to go to a point from anywhere on the job site and complete a material-moving tasks in one coding script. This experiment will include functions like collision avoidance and reaction protocols, drift correction, smart object locating and sorting, and other programs to help keep the robotic material mover as intelligent and reactive/interactive as possible.

How the construction industry is addressing the use of robotics and the advantages and disadvantages

Automation in Japan

There is a great deal of automated robot construction in Japan. In fact, "Several leading Japanese construction firms are developing fully automated, self-rising platforms for the construction of high-rise buildings. These automated building construction systems provide an integrated building construction environment for robotized cranes, finishing robots, computer work stations, and other automated construction equipment." (Skibniewski, 1). This emphasis on automated construction has propelled Japan's construction industry to develop some very useful automated construction systems. One area that seems to be lacking in development is an automatic, mobile semi-autonomous material handling system. In this automated building construction system, "components are … trucked to fully automated storage facilities at the building site, where they are stored or transported to the assembly platform by an automated material handling system. The material handling system consists of automated lifts, conveyors, and elevators. When components arrive at the assembly platform, they are carried by an overhead gantry crane, which positions them at their proper location for erection." (Skibniewski, 2).

Advantages and disadvantages

System speed

While the system described above works well for a fully-automated construction process, what about those projects that are being built and managed by people? It could be feasible to have a mobile robotic material-handling system to assist in the construction process and cut down on labor costs for material moving. There can be some drawbacks to an approach like this. For example, “Compared with hard automation, [a multi-purpose robot] is slower in throughput; however, the flexibility offered by [a multi-purpose robot] allows easier integration within the dynamic ABC construction environment. Also, fixed automation may become obsolete when removed from a production site” (Skibniewski 15). The mobile system may also be slower than a human counterpart, but being able to use human assets for complex tasks that a robot is not capable of is another factor of productivity that is important to remember.

Health and safety

Tasks like material moving can cause some severe health problems for an increasingly-aging workforce. Because “robots are primarily developed for the sectors in which poor labor conditions prevail and in which a reduction of the load is possible,” it seems fitting that these automated systems could be used to help lighten the load on construction workers (Bock, 14). “The comparatively high frequency of accidents as well as the high statistics of labor-related sickness and premature retirement in the building industry are an indication of the special requirements.” (Bock, 14). Also, “A positive relationship has been established between physical workload and level of exhaustion.” (Lee 3.) Seeing as it could help decrease injury rates in construction, a mobile semi-autonomous material-moving system could be vital in creating a better work environment for laborers.

Profits and labor costs

Profit margins and costs are always necessary to consider, but it has been stated that “By automation, increased productivity could reduce high labor cost share of 40 or more percent.” (Bock, 1). This large cost saving is the result of several factors. Robots do not require payment or health insurance. They can work all day or all night. If programmed creatively, the robot could aid human workers with set up and close down each day.

Addressing challenges

Current technology

To address the challenges expressed above, I propose to devote more time, energy, and other resources to utilize technology to make up for the deficiency of low skill laborers in the workforce. Creating robots that can perform various tasks or one complex task can pay for itself over time by reducing labor costs – one of the construction industry’s largest cost sectors. Looking back on the undergraduate research section above, I see an opportunity to develop an advanced, full-scale AI material-moving robot. With some added accuracy and innovative software design, such a machine could go beyond the applications studied in my research. A more accurate and intelligent robot could be used for operations like modular building construction by placing the prefabricated elements into their proper position. Smaller versions could also be created as an automated tool cart to help organize and distribute tools to the laborers as they work.

Health and safety

A robot does not have to go home at the end of the day or need to breathe or use light to navigate in the dark, etc. A robot does not have a mandated carry limit like OSHA requires for human workers. “To prevent workers from taking on excessive workloads in material handling jobs, safety professionals’ guidelines limit the weight of materials that workers need to install and carry. In terms of ergonomics, it is better to manage the demands of all tasks through the control of tools, equipment, and the work environment.” (Lee, 10). This benefit to vital in the robot’s success as a real-world option. The robot’s lack of human limitations can be used to maximize its efficiency.

How an organization such as the AGC might play an important role in addressing issues related to this topic

AGC could start addressing the lack of technology in construction by initiating the conversation on construction robotics with students to spur creativity in the academic community. The academic community would advance and find new applications for current technologies, which could then be made feasible and cost-effective by industry professionals.

From a research and development perspective, the goal should be to integrate existing technology into smarter, more automated systems. I see opportunities for fully automated material-moving assistants, as-built laser scan robots, virtual replacements for job site tours, and many more applications that utilize and integrate existing technologies. These efforts toward the application of AI robotics on a more routine basis will surely help to advance smart construction technology on the construction job site.

Summary

Throughout history, mankind has sought to invent new tools and techniques. This overarching goal of our species has taken us from stone tools to advanced autonomous and self-learning AI technology. While advanced technology is being used in the construction industry, for the most part, construction is behind other industries as far as the application and implementation of on-the-job robotics. However, both the academic and business communities are steadily working to close that gap.

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The Adaptative Construction Industry

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Abstract

The construction industry is an industry that always unites to find ways to solve problems. It is very complex and requires considerable organization, hard work, specific skills, and a whole lot of determination. In this paper, I will discuss three ways that the industry is making strides to make construction better and more efficient: (a) increased use of modular construction and prefabrication, (b) use of drones, and (c) Building Information Modeling (BIM) use. With the construction process becoming more and more complex, improving efficiency and safety has gained more attraction, especially when coping with fundamental issues such as labor shortage, resource limitations, and quality/safety assurance.

The Adaptative Construction Industry

We all know there is a shortage of skilled labor in the market right now. The average age of skilled laborers is approximately 41 years old (DataUSA). How are we to keep up with efficiency and quality when there are less people to employ? That is a problem our industry is facing right now.

This shortage of young labor is due to a combination of many things, but I will mention a few that I have seen. Those include college being pushed on all young adults during high school, while opportunities of apprenticeships and things of the like are being discouraged. The uncertainty of location and long and unpredictable working hours are also making it hard for the younger generation to take on the challenges of construction jobs. As the shortage of labor has led to efficiency and safety being harder to obtain, the industry has found certain ways to adapt and improvise.

Personally, I have seen evidence of this labor shortage in my experiences with the industry. One evening at dinner in a conversation focused around faith in construction, I was talking with a gentleman in the home building industry. He told me that the average age of their carpenters was 65 and that they were always looking for more experienced carpenters. During my last internship with Baker Concrete, I saw a shortage of skilled finishing concrete workers. Baker did not have many in-house finishers, so the finishers were stretched thin when we had small and miscellaneous pours. The shortage is evident everywhere you look in the construction industry, and improvements in the efficiency and safety of construction processes would certainly help.

Modular/Prefabrication Construction

One method used for combating the need for greater efficiency and safety in construction is greater use of modular construction and prefabrication. According to an article by The Modular Institute that was published in 2018, only 3% of all new buildings in America were using modular construction. In Japan, a modular home factory can have four employees build one home in a month. Consider that: four employees in a constant, safe, stable environment using the latest technology and having predictable hours and job location (Modular institute). These jobs still require skilled workers who know how to operate the machinery and know the process, but the process would be much easier to learn and master in a constant location and environment.

During my first internship with Miller Electric, I witnessed prefabrication on a large scale. At Miller, they had their apprentices, along with one or two experienced electricians, working in their shop to prefabricate conduit runs for mechanical rooms and for underground runs. What I saw was a mechanical room with the walls, conduit, panel boxes, and everything else prefabricated and made ready to be shipped to the jobsite to be put in. This way of doing work would save the company money and time, and make the job much safer by being performed in a controlled environment. One experienced electrician could teach four or five apprentices how to do the job. Prefabrication and modular construction can take people with no knowledge and teach them how to do something by doing it over and over again, becoming efficient in the process. In a controlled environment, the work will not change. Workers will be able to have a routine that rarely changes, and this is a unique opportunity to maximize safety and efficiency.

Prefabrication and modular construction is a way to make the construction industry appeal more to the next generation and improve efficiency and safety in construction despite a lack of labor. However, there are also some challenges to modular construction. One of the challenges is that a component built in a shop may not fit exactly right when it is delivered to the job site. Another challenge is the assumption among people that a modular-built component is of less quality. Also, with modular and prefabrication, more things will become automated, therefore some jobs will be lost. How will AGC help prevent people from losing jobs? I think they could ensure that even if some tasks become automated, there is still a need for human aid in the process. For example, machines will need human input to control the outputs, so people will still be needed. There may be a decrease in the amount of work done by a person, but the person will always need to be present and working. If managed correctly, modular and prefabrication will not lead to job loses, but will change the nature of the job from an onsite job to a job in a controlled environment.

I think AGC and other organizations can make modular and prefabricated construction more popular and accepted by backing programs and companies that use modular and prefabrication construction. With modular construction, AGC may have to expand its boundaries since modular and prefabrication fall under the umbrella of manufacturing and are not directly related to general contracting. If AGC helped make modular and prefabrication construction more popular, it could really aid in the efficiency and safety of the construction process. I personally think that modular and prefabrication construction could become more popular by having models built that are studied and put through certain conditions to see if the modular and prefabrication components would stand the test of time and the environment.

Drones

The most important goal of construction is safety. Everyone in the construction industry wants employees to go home safely to their loved ones at the end of a job. Safety has improved greatly in the construction industry, but there is always room to improve.

One new technology that is helping address safety in construction, while making the process more efficient, is Unmanned Aerial Vehicles (UAVs) or drones. According to Drone Deploy, drones can improve safety by eliminating the need for a person to go walk a job site for inspection, safety checks, or punch list preparation. Also, eliminating the need for a person to walk on site can give a construction professional more time to get more things done, ultimately making him or her more efficient.

Drones can also help make preconstruction professionals more efficient. According to David Pratt, a manager in preconstruction with Robins and Morton, drones can be used to make estimating much easier, especially with grading. In a presentation to my Emerging Technologies class, Mr. Pratt stated that they can use the information from a drone fly-over on a site to measure how much earth will need to be removed or added for the building. This tool can make these professionals much more efficient with their time and improve the quality of their work.

Inspections for industry professionals can also be made more efficient and safer with drones. A drone can collect thermal information that can be used to see where or if the building has leaks. This process normally takes days to do, but with drones, an inspector can decipher and analyze the building quickly and much more efficiently. Also, a manager on-site can use drones to check on the status of construction and can use the drones to effectively and efficiently find problems with the building that need to be addressed.

There are some challenges with drones. One challenge is the possibility for an accident when a drone is flying a site. If a drone fails and falls out of the sky, it could potentially hit and harm someone. Drones may not be able to be flown in windy conditions, therefore making the drone useless on a windy day. Also, there is some risk when using drones about the privacy of neighboring sites and homes. I predict that these challenges will play out and become less relevant as this new technology progresses and more and more people begin to use it.

AGC and other organizations can mitigate risks by providing employee training to teach industry professionals how to use drones in a correct and proper way. With the correct training, widespread drone use can become more common both to people already in the industry and to people who are entering into the industry. I personally have not used drones in my short time in the construction industry, but as they gain more and more popularity, I am certain I will use them at some point in the future.

Building Information Modeling

The last technology I will cover that will help improve construction efficiency is BIM. BIM is a way for collaboration and coordination to take place in an efficient way. While BIM is a known software, I do not believe it is used to its full potential in the construction industry yet. This could be due to industry resistance, lack of ability for everyone to collaborate early on jobs, and the lack of training on how to use it.

According to Lead Innovation Management's article "4 ways BIM can boost the productivity of your construction business", communication and teamwork are keys to a successful project. With that said, communication and teamwork can be enhanced through BIM platforms like Navisworks, which can greatly improve efficiency on a jobsite. The article also says, "The main culprit in construction delays and mistakes is a lack of proper communication on the work site." So, if we are able to eliminate delays due to someone not getting information or having to wait on someone to provide information, then we can greatly improve efficiency with the amount of labor we have available.

BIM technology makes everything near-real-time. If there is a change to the drawings, the architect can make the change and everyone can see the change almost instantly. This means the professional in the field can see the change and notify coworkers so that they realize the change has been made. Also, an advantage of having 3D technology in the hands of field professionals is that they can visualize and catch problems well before the problems arise.

I have seen BIM technology used, but at a minimum. I have seen where clash detection is used, and it was seen that a sidewalk was drawn to run into the side of our building. This was a quick and easy catch, but if we wouldn't have had the BIM technology, the problem would not have been fixed as fast. I think the overall advantage of BIM use is the decrease in delays, which will in turn make workers and the process more efficient.

As with everything, there are some challenges that restrict the use of BIM. One of these problems is that Design-Bid-Build contracts are still prevalent in the industry today. With a Design-Bid-Build contract there is a limited opportunity for BIM to be used because there is limited true collaboration between the construction manager and the architect and engineers. Without this collaboration, the construction manager cannot catch problems prior to the drawings being submitted. This way of doing work leads to unnecessary change orders and delays, which makes the industry less efficient.

Another problem is the lack of willingness to adopt these new technologies. As stated earlier, the average age of a construction worker is 42 years old, and chances are that this generation does not use technology frequently. If these experienced workers do not embrace the technology, then the knowledge will not be transferred down to the next generation.

I think one way to solve the challenges associated with this technology is to pay bonuses for utilizing technology. We know the extraordinary advantages of using BIM technology, and I think the best way to get the construction industry to buy into and use the technology is providing some kind of incentive for making use of the technology.

I believe AGC and similar organizations, should organize conferences and meetings to discuss the advantages of BIM technology use. These organizations should try to help companies that may be otherwise reluctant to invest in BIM technology explore the impacts it can have on the efficiency of our construction industry. AGC can also help promote more innovative executive/ contractual platforms (e.g., design-build or CM- at- risk) that help with the use of BIM to its full capability.

In conclusion, the labor shortage and the cultural/generational change in our industry are serious, but we will adapt and come up with ways to keep on producing quality buildings. In this paper, I have discussed how modular construction or prefabrication can help improve efficiency to combat the labor shortage. I emphasized how drones can help with safety, inspections, preconstruction, and site progress updates. Lastly, I spoke about how BIM technology can improve efficiency in the industry. I hope that all of these tools will be used to make the construction industry better.

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