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Monte Carlo simulation approach to understand the cost variance for energy retrofit projects: comparative study of Finland and the United States

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Abstract

Energy-efficient building is often characterized with higher construction costs. There is a large variance in energy-efficient building construction costs, especially in retrofit projects. A lack of understanding of cost variance and ambiguity of cost-optimal practices has impeded the adoption of energy retrofit practices globally. To respond to such a knowledge gap, a comparative study was conducted on energy retrofit projects on residential buildings in Finland and the United States. A Monte Carlo simulation was used to determine the coefficient of variation for construction costs and the potential reasons behind the variations. The specific aims of this study are (a) to gain a deeper understanding of construction cost variances in energy retrofit projects, (b) to identify the most influential cost items, and (c) to understand the correlations among different cost items. For this analysis, a database including 10 Finnish buildings and 7 US buildings was created, and actual construction cost data was collected. The results showed the following: (1) US projects had a larger total construction cost variance with highly skewed distribution, and Finnish energy retrofit projects had a cost distribution similar to conventional retrofit projects; (2) the two most significant construction cost factors for both countries were non-energy related cost items and the building envelope, rather than the mechanical system (heating and ventilation) as commonly perceived; and (3) the larger construction cost variance in the United States may be associated with the unfamiliarity of energy-efficient technologies and varied construction methods

in different regions. The insights and suggestions derived from those findings are discussed in the conclusion.

1.0 Background

Energy-efficient building is often associated with higher construction costs. These high construction costs have been rated as the leading barrier to green building advancements during the past decades (Hu 2019). Current energy-efficient building construction cost data are extremely fragmented and untransparent, and there is a lack of understanding about the cost factors contributing to higher costs in difference regions and countries. Hu & Skibniewski (2021) found the United States has the highest energy-efficient building construction cost surcharge, at 7%, compared to 3% in European countries. But the drivers and causes were not identified. An increasing body of literature has focused on economic viability of energy retrofit projects. Multiple drivers have been identified for moving investment in energy retrofits to existing building stocks, including high utility costs (Achtnicht and Madlener 2014); needs for upgrades, renovation and maintenance; the potential for increased indoor environmental quality (Brown et al. 2013); and environmental and climate protection (Nord & Sjøthun 2014). A variety of factors have been recognized as influential to the success of energy retrofitting projects, such as building physical properties (i.e. ages) (Aksoezen et al. 2015), decision and attitude from building owners and tenants (Azar & Menassa, 2012), market-related factors (i.e. financial incentives) (Wang et al, 2015). Alternatively, uncertainty in the payback period, high construction costs and lack of financial resources, and a lack of skills regarding building envelope retrofits have been recognized as major barriers (Hu 2019). Copiello and colleagues compared several retrofit scenarios in public housing projects in Italy, their findings show the retrofit scenario characterized by the lower upfront costs (construction cost) are more likely to have lower life cycle costs with the possibility to achieve a 27% energy saving (Copiello et al., 2017). Neroutsou and Croxford evaluate two energy retrofit options to refurbish the thermal envelope of a residential building in London, they concluded the financial incentives are an important factor to the total cost (Neroutsou and Croxford 2016).

In this study, a definition of differences among refurbishment, renovation and retrofit proposed by Husin et al (2019) was adopted. Refurbishment is a process of returning the building, or its systems, to their original condition. Renovation is a process of taking refurbishment as one step onwards by integrating additional physical changes to buildings. Retrofit is a process of replacing and upgrading systems and technology in existing building to address its environmental needs. Wood described retrofit as a building that has been adapted to a new use, to reduce the operational energy and maximize the enduring benefit of the embodied energy (Wood 2006). Urban land institute described the retrofit as a type of building upgrade of an existing building to improve energy and environmental performance (Urban Land Institute 2009). In general, retrofit is more associated with energy performance improvement than refurbishment and renovation.

The drivers and barriers together have a determining influence on the success of energy retrofit projects. Hu & Milner (2020) identified a combination of three variables that are particularly influential to the success of an energy retrofit project: climate zone, construction costs, and the existing building compact ratio. In this study, we focus on the construction cost variances in two countries. To provide a comparative study, we have focused on multifamily buildings (with similar compact ratios) in cold and very cold climate regions in Finland and the United States, to exclude the impacts of climate zones and building types.

In Finland, residential buildings represent a significant segment of all building stock, and multifamily buildings make up 21% of the total floor area of buildings in Finland (Hirvonen 2019). In the United States, multifamily buildings comprise 12% of the total building stock (EIA). The similarities between American and Finnish multifamily building stocks made the two countries comparable: both have an aging building stock—more 54% of Finnish residential units were built before 1980 (Statistics Finland 2014), and 61.5% of American units were built before 1980. Consequently, these buildings are more than 30 years old and require major renovations or upgrades in the near future; this type of housing renovation represents a great potential in energy saving and carbon emissions reduction. In this study, cold and very cold climate regions were defined using heating degree days (HDD), average temperature, and precipitation data (EIA, Office of Energy Efficiency & Renewable Energy).

Due to the difference in economic status, financial structure, and purchasing power, focusing on the construction cost amount in the two countries will not provide useful information on the cost variances of the energy retrofit projects. Rather, investigating the coefficient of variation (CV) in construction costs in different countries will provide a better understanding of the common and unique risks and uncertainty associated with multifamily energy retrofit projects. The CV represents the ratio of the standard deviation to the mean calculated by Equation 1; it is a useful statistic for comparing the degree of variation from one data set to another, even if the means are dramatically different from one another (Investopedia). In this project, a Monte Carlo simulation was chosen to study the CV and cost factors. The reasoning is explained in the following section.

$$CV = \frac{\sigma}{\mu} \qquad \text{Equation 1}$$

Where σ the standard variation of studied population, μ is the mean of the studied population.

2.0 Literature review: Monte Carlo simulation for green construction costs

Monte Carlo methods have been utilized to manage the risk and uncertainty in project costs and schedules for more than a couple decades. Vose (2000) pointed out the advantages of a Monte Carlo simulation in risk management: the model elements can be correlated for more realistic and reliable scenarios but do not require sophisticated mathematical knowledge, hence more professionals can access the simulation. Clark (2011) used actual costs from 19 completed projects in the United States and China to demonstrate the effectiveness of a Monte Carlo method in identifying project risk or opportunity elements and in quantifying contingency. Nabawy and Khodeir (2020) conducted a systematic review on quantitative analysis of mega construction projects worldwide between 2013 and 2018, and they concluded that a Monte Carlo method was successful in supporting project managers allocate risk in mega projects. Despite the acceptance and adoption of Monte Carlo methods in the project and risk management field, the use of them in energy retrofit projects is limited, and very few studies can be found in literature.

The following examples are published literature relevant to our study. Togashi (2018) investigated the risk involved in an energy-saving investment by calculating the probability distribution for energy reduction using a Monte Carlo method. This demonstrates a Monte Carlo method can be used as a decision support tool for energy retrofit projects. Garshasbi et al. (2016) employed a hybrid genetic algorithm and Monte Carlo simulation approach to simulate the energy performance of a cluster of net zero energy buildings. The cluster of buildings were 10,000 hypothetic detached residential buildings. However, the details of the hypothetic building data and resources were not specified; therefore, even with the validated hybrid approach, the simulated results cannot be used to draw a conclusion for real energy-efficient building practices.

There are a few studies directly related to energy-efficient building costs or building component costs. Mahdiyar et al. (2016) used a Monte Carlo approach to study the cost-benefit analysis of green roofs in Malaysia using one case building. Pant & Srinivas (2019) analyzed the cost of a residential building in India using a Monte Carlo simulation with software called @Risk. Their study demonstrated that historical data could be used for a Monte Carlo simulation; however, they focused on method validation instead of result analysis.

In general, although a Monte Carlo simulation is documented as a useful method for project management applications, including cost and schedule management, it has not been used much by project managers in real-world situations (Kwak & Ingall 2007); most literature found has been research-based exploration. Particularly for building construction projects, using a Monte Carlo method as a risk management method has been proposed, but the conditions to determine the input parameters are rarely discussed (Peleskei et al. 2015). In reviewed literature, the subjective opinions from experts in the industry were commonly used as the common source of cost input parameters. Analysis and use of historical data do exist, but only rudimental information (Peleskei et al. 2015). As for energy-efficient buildings, to date there is no commonly accepted construction cost definition or comprehensive description of the components that should be included in the construction cost estimation (Dwaiku & Ali 2016, Hwang et al. 2017).

Currently, the cost estimation of energy-efficient buildings is conducted in the same way as for conventional buildings. No proposed risk or uncertainty management method can be found in the literature for energy-efficient project construction cost control. The disadvantage of a conventional approach to energy-efficient building is that the input of cost parameters largely depends on an expert's subjective opinion. When experts lack experience and knowledge regarding energy-efficient building systems and advanced technology, the cost estimation can lead to either over- or underestimation. For an objective data input, RSMeans is the most widely used building construction cost database in the United States. It includes a section on green commercial/industrial/institutional building cost data. Since the data sources are not explained, it is not possible to conclude whether RSMeans uses actual building cost data, expert opinions, or simulated data. In summary, there is a very large knowledge gap, and opportunities exist to apply a Monte Carlo method in studying the **construction cost variances** in energy retrofit projects.

3.0 Research method and materials

Three dominant cost analysis methods are used in the building industry: deterministic methods, probabilistic methods, and modern mathematical methods (Bakhshi & Touran 2014). Probabilistic methods can be used to account for uncertainties and risks that can occur during the project construction, which are not included in conventional deterministic methods (Tan & Makwasha 2010). Energy-efficient retrofit projects have higher uncertainties and risks compared to conventional renovation projects because of the complexity of the building system, the unknown existing building condition, and unfamiliarity with energy efficiency related practices. Consequently, in this study the probabilistic method was chosen. A probabilistic approach requires a large dataset; however, as explained in Section 2.0, the historical construction cost data are limited, especially for energy-efficient retrofit projects. The issue can be solved by using simulations like Monte Carlo (Peleskei et al. 2015). In a simulation-based cost estimation, risk and contingency allowance is determined by two factors: the probability of risks occurring and their impact. There is uncertainty as the input of analysis can be quantified as a range of numbers; typically, we use minimal cost to maximum cost, while the impact of risk as the output from a Monte Carlo simulation can be portrayed by a probability distribution (Wang et al. 2021).

Simulation-based cost analysis requires two sets of data: the marginal distribution of the individual cost elements and the correlation matrix consisting of the correlation coefficients between the different cost items (Yang 2005). Both sets of data can be estimated in two ways: (a) using historical data from previous projects and (b) subjective judgements or input from experts in the industry (Yang 2005). In this study, the first method was employed: a historical dataset was created based on built projects in Finland and in the United States (cold and very cold climates). Figure 1 illustrates the research method composed of five steps: (1) data inquiries and historical dataset collection, (2) a definition of the construction costs included in this study, (3) a test of fitness of the data, (4) a determined correlation between cost items, (5) a Monte Carlo simulation, and (6) a sensitivity analysis. Each step is explained in the following section.

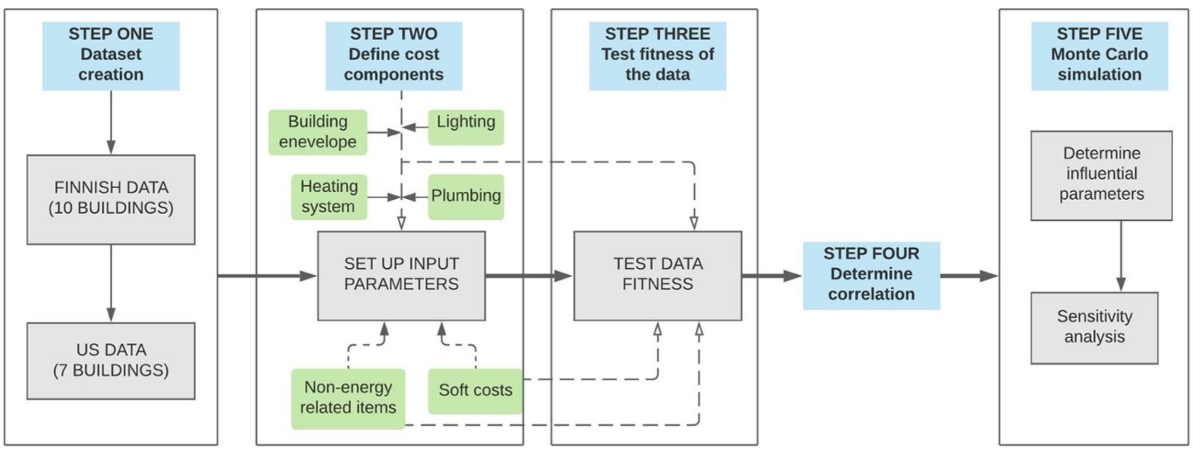


Figure 1 Research flow

3.1 Construction cost data collection

For the Finnish data, the research team reached out to city officials, construction companies, academic researchers, the Finish Green Building Council (FGBC), and The Housing Finance and Development Centre of Finland (ARA); available detailed data were eventually provided by ARA. Altogether, ten renovated multifamily projects, total 1092 units, and 60,763 m^2 of floor space are included in the Finish database. The buildings were originally built between 1960 and 1970 and renovated from 2012 to 2019. The gross floor areas of the buildings are between 3389 and 14,190 m^2, and the building heights range from 1 story to 5 stories (refer to Figure 2 for sample building).

Figure 2 Sample building (left: Finnish project; Right: US project)

For the United States data, there were two main sources: the New Buildings Institute (NBI) database and the Team Zero database. The research team first drew the project list from the largest net zero energy building library in the United States (online library), which is created and managed by the NBI. There are two multifamily projects located in cold and very cold climates in the NBI database. NBI does not collect cost information; therefore, the research team searched for the cost information of the extracted projects from a variety of online resources, including project websites, contractor websites, and design team websites. Then the research team reached out to Team Zero, a non-profit organization formally known as the Net Zero Energy Coalition. Team Zero has been collecting net zero residential building data from the United States and Canada since 2015. From their dataset, 12 multifamily retrofit buildings were found in cold and very cold climates. Team Zero did not have cost data, so the research team searched the project site and reached out to the project team to acquire construction cost data, which resulted in five buildings with detailed construction cost data. Altogether, seven built and verified multifamily buildings, around 404 units, and 31,298 m^2 of space are included in the US database. The buildings were originally built between 1914 and 1980 and renovated from 2011 to 2020. The gross floor area of the buildings is between 565 and 13,006 m^2. All buildings range from two stories to seven stories (refer to Figure 2 for sample project). The sample is assumed to be sufficient to minimize possible sampling errors for Monte Carlo simulation and is considered a reasonable representation of the building type (multifamily building) in a specific climate zone. The cost per square meter is used to eliminate the complexity and problems of project size or scale.

3.2 Definition of the total construction cost (TCC) and cost components

The total construction cost in this study is defined as the sum of all materials, labor and related equipment costs related to the retrofit. The retrofit activities include the items that directly contribute to energy efficiency improvement, such as adding additional insulation to the building envelope or replacing and upgrading the heating and ventilation (HVAC) system. However, retrofit buildings often include renovation items that do not directly contribute to energy efficiency. Those non-energy related retrofit activities are either induced by deferred maintenance or needs for modernization and upgrades. For example, kitchen or bathroom upgrades are common in residential building renovations. Modernized appliances and fixtures can contribute to energy efficiency; however, they represent only a small fraction of the entire kitchen and bathroom renovation cost. In addition, for townhouse style multifamily housing, landscape upgrades are also common in the United States. Therefore, in the cost input parameters listed in Table 1, we separate non-energy related cost items from the energy-related cost items. In this research project, non-energy related cost items include the cost of structural renovation and repair, and the cost of fire protection system, the cost of interior finish. We further break down the energy-related cost items into four main categories as illustrated in Table 1 and Table 2: the building envelope, heating and ventilation system, lighting system, and plumbing system. We have also included soft costs, which are not directly related to the physical construction of the buildings but are necessary for the administration of a building project (Zahirah et al. 2013). Soft costs included in this study are administration fees, design fees, project planning and management fee. The total construction cost is measured per square meter, and the gross floor areas of the buildings are used as the common measurement for area.

Table 1 Monte Carlo setup for Finnish dataset for total construction costs

Cost Input Parameters	**Baseline**	**Min.**	**Most Likely**	**Max.**
Building envelope (€/m2)	656	428	709	1146
Heating & ventilation (€/m2)	178	116	281	991
Lighting (€/m2)	115	0	145	495
Non-energy-related renovation (€/m2)	260	34	369	1,610
Plumbing (€/m2)	260	34	191	495
Soft costs (€/m2)	461	214	547	1,517
Total cost (€/m2)	**2,712**	**1,260**	**3,279**	**8,924**

Soft costs include administration fees, design fees, project planning and management fee

Table 2 Monte Carlo setup for United States dataset for total construction costs

Cost Input Parameters	**Baseline**	**Min.**	**Most Likely**	**Max.**
Building envelope (€/m2)	453	64	453	866
Heating & ventilation (€/m2)	299	50	299	527
Lighting (€/m2)	166	53	166	548
Non-energy-related renovation (€/m2)	350	81	350	4,746
Plumbing (€/m2)	23	0	23	264
Soft costs (€/m2)	153	41	153	160
Total cost (€/m2)	**1,444**	**759**	**1,444**	**7,112**

3.3 Goodness of fit test

It is important to specify the probability distribution best fit of cost input data. Touran & Wiser (1992) suggest a lognormal distribution as best for historic construction cost data. Kim et al. (2009) recommend using beta distribution for cost estimation. Normal and triangular distribution are also commonly used in construction cost analysis (Chau 1995, Heidari et al. 2020). In this project, the fitting of the probability distribution of each cost input parameter was tested using the @RISK built-in distribution fitting tool. The Anderson-Darling test, commonly used as a test for normality, was employed to rank the best fit for each cost item. The statistics of the fitness data are demonstrated in Table 4 and explained in Section 4.3 Results of goodness of fit test."

3.4 Monte Carlo simulation

The Monte Carlo simulation encompasses technique of statistical sampling employed to approximate solutions to quantitative problems (Kwak & Ingall, 2007). The principle of using Monte Carlo simulation in this study involves breaking down the construction of a project into sub-components (i.e. building façade, heating system, lighting system) that are random and variable to each projects. The variability of each sub-components in individual projects are affected by many factors, such as existing building condition, building size, etc. With a small set of accurate collected project cost data, the Monte Carlo method simulates the potential project cost many times (thousands of times) based on the probability distribution function of the value of each sub-components (Kwak and Ingall, 2007). The use of a Monte Carlo simulation in TCC allows for the input factors of the cost using a range of values, rather than the deterministic single point number that is typically used in the traditional construction cost estimation model. The output of the Monte Carlo simulation results takes into consideration uncertainties and risks that are not accounted for sufficiently in the traditional method. In addition, the Monte Carlo simulation output can consider various scenarios related to future events, such as an increase or decrease of the unit price of building materials. Theoretically, the simulation model's credibility is determined by the number of iterations used to generate the outcome (Wang et al. 2012). In general, one to five thousand iterations are sufficient to reach an acceptable answer for most complex models (Gladwin 2006).

3.4.1 Cost input parameters of the model

The input cost parameters in the simulation are the different retrofit cost items (refer to Table 1 and Table 2); they are the key factors that have an impact on TCC. A three-point probability distribution function is defined for each input variable based on the collected historical data (described in Section 3.1): minimal, mostly likely (mean), and maximum. For a three-point distribution, the most likely cost is used to express a value around which most of the cost possibilities could be expected to occur (Wang et al. 2012).

3.4.2 Correlation between cost input parameters and scenario setup

In the traditional deterministic cost analysis model, the cost input parameters are treated independently of each other. However, ignoring the interdependency and correlations might result in a significant underestimation of the cost. Therefore, we set up two scenarios to avoid this problem. Scenario one represents the condition where the cost items are independent of each other; in scenario two, the cost items are correlated with each other. We first use StaTools to rank the (Spearman) correlation coefficient to determine the degree of correlation between different cost input parameters (refer to Equation 2). Then we manually input the determined correlation coefficient value in the Monte Carlo model. The Spearman correlation coefficient was chosen to account for the potentially unnormal distribution of the cost item variables. The advantage of the Spearman correlation coefficient is that it can be used in the study where among the variables there is non-linear relationship (Peleskei et al., 2015):

$$r_{xy} = 1 - \frac{6\sum_{i=1}^{n} d_1^2}{\mathrm{n}(n^2 - 1)}, \qquad \text{Equation 2}$$

Where r_{xy} is the coefficient between two variables (i.e. (*x)* building envelope cost and *(y)* heating system cost), *d* is the difference between the ranks of the corresponding *x* and *y*. The coefficients range between -1 and +1. +1 represents a perfect positive relation, and -1 represents a perfect negative one. *n* is the number of the variables included, in this study, variables are the sub-components (i.e. building envelope)

3.4.3 Simulation tool and setup

In this study, the Monte Carlo simulation was conducted using the software @RISK. Two sets of 5,000 iterations were performed for two scenarios for each country (Finland and the US): one incorporating correlated data and the second assuming all cost items are independent of each other. In all, four Monte Carlo simulations (a total of 20,000 iterations) were conducted, and four scenarios were generated, with the results explained in Section 4.0 Findings." In this study, the beta distribution (PERT) was determined to be the best fit for the TCC (with each cost item having its own fitted distribution). PERT uses a weighted average—where more weight is given to the most likely scenario—a commonly used method for project managers. After the four simulations, a sensitivity analysis was used to study how changes of most influential cost variables impacted the total construction cost. The sensitivity analysis was set up to simulate the impact of cost fluctuation, either increase or decrease by 20% from the current mean value (base value). In the @Risk software, method was chosen as "% Change from Base Value", base value is mean value. Min. and Max Change (%) was set up as -20% and 20%. Number of steps for simulation was set up as 7 (for each direction, increase or decrease). Together 14 simulations, a total of 70,000 iterations, were conducted, with the results explained in Section 4.6 Sensitivity analysis.

4.0 Findings

4.1 Overall coefficient of variation (CV) of total construction cost

Compared to the US scenarios, the Finnish retrofit project total construction cost has a smaller CV, less skewed distribution, and less standard deviation (Std Dev) in both scenarios (refer to Table 3). When looking at the coefficient of variation, the higher it is, the greater the level of dispersion around the mean. A greater dispersion means a larger construction cost variance among the projects. Both US scenarios have larger CVs (0.337 and 0.351) than those of the Finnish projects (0.161 and 0.302). Due to the higher Std Dev and CV, we can conclude that US projects have a larger total construction cost variance compared to Finnish projects. The potential causal factors are (a) the construction means and method; (b) the competition among products and services; (c) the skill sets and working experience of the project team; and (d) the maturity of the technologies and supply chain, especially those for energy retrofit projects. Those factors are further discussed in Section 5.1. The higher skewness of the US projects is caused by a couple of projects with extremely high costs; more details are explained in Section 5.3.

Table 3 Monte Carlo simulation summary

	Mean (€/m^2)	**Median (€/m^2)**	**Mode (€/m^2)**	**Skewness**	**Std Dev**	**CV**
Finnish Scenario 1 (independent parameters)	2,674	2,658	2608	0.24	430.52	0.161
Finnish Scenario 2 (dependent parameters)	2,674	2,614	2,644	0.38	807.97	0.302
US Scenario 1 (independent parameters)	2,195	2,053	1847	0.86	740.72	0.337
US Scenario 2 (dependent parameters)	2,195	2,034	1640	0.91	771.40	0.351

Figure 3 shows the two scenarios of the US projects (above). Both scenarios demonstrated the TCC in the US is more skewed toward the right (positive-skewed), as the mean cost is higher than the median. Figure 3 also shows the two scenarios of the Finnish projects. Unlike the US projects, Finnish scenario 1's distribution is similar to that of a conventional retrofit project, where the cost parameters are treated independent of each other. In addition, compared to scenario two of the US projects, the correlations among the cost parameters have bigger impact on the overall cost distribution in scenario two of the Finish projects. As demonstrated in Figure 3, Finnish scenario two has a much wider distribution than scenario one. In scenario one, 90% total cost of projects range from €1,990/m^2 to €3,420/m^2 2, while in scenario two, 90% project cost range between €1,453/m^2 to €4,130/m^2. Both Finnish scenarios have a nearly normal distribution. The normal distribution is an indication that the maturity of energy retrofit projects. Such maturity can be explained by that fact Finland launched state subsidy program for housing cooperation around year 1979, and such subsidy directly contributed to the adoption and implementation of energy retrofit technologies in housing market. After more 30 years practice, renovation with energy retrofit technologies has become normal practice in Finland; therefore, the cost variance distribution is comparable to that of conventional projects. Potential reasons for such a maturity are explained in Section 5.1 Implications of cost variance**.**"

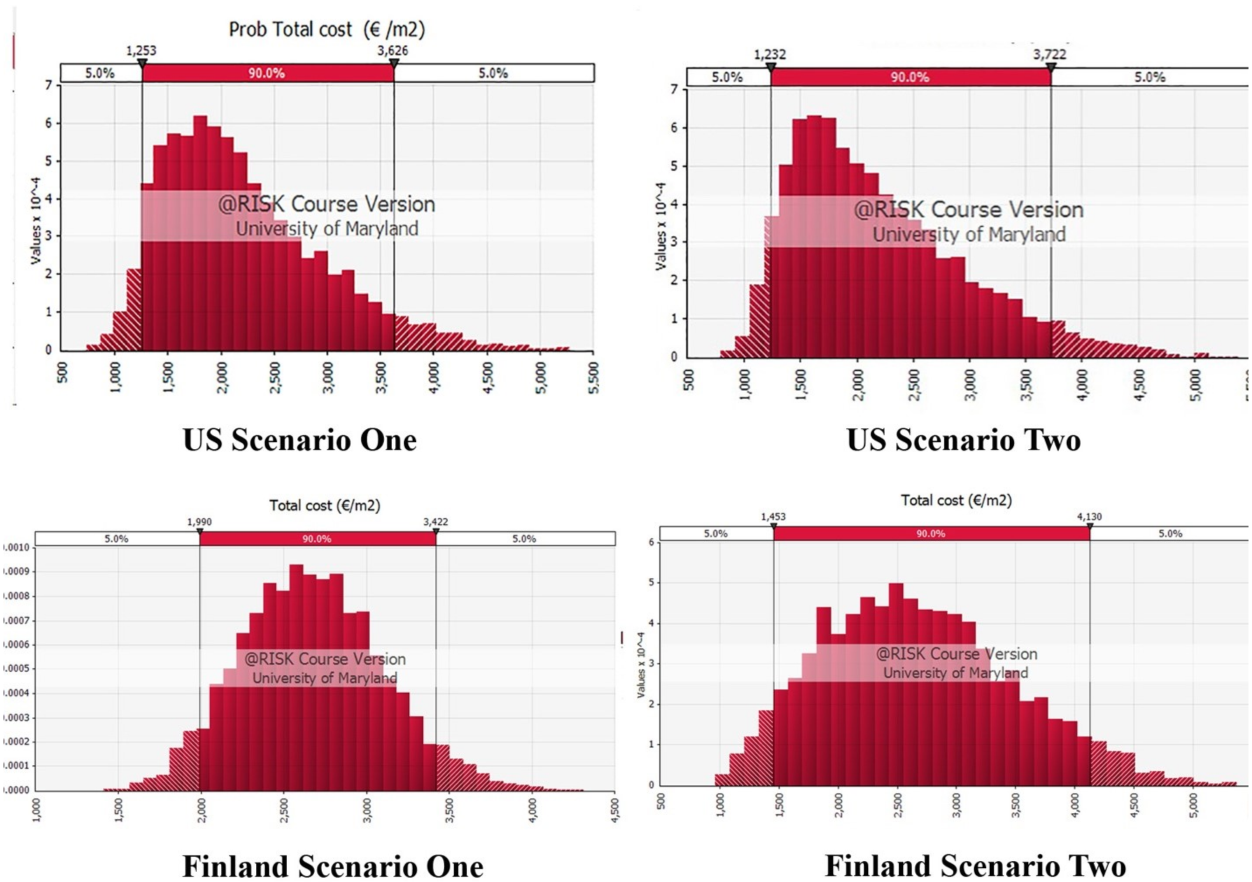
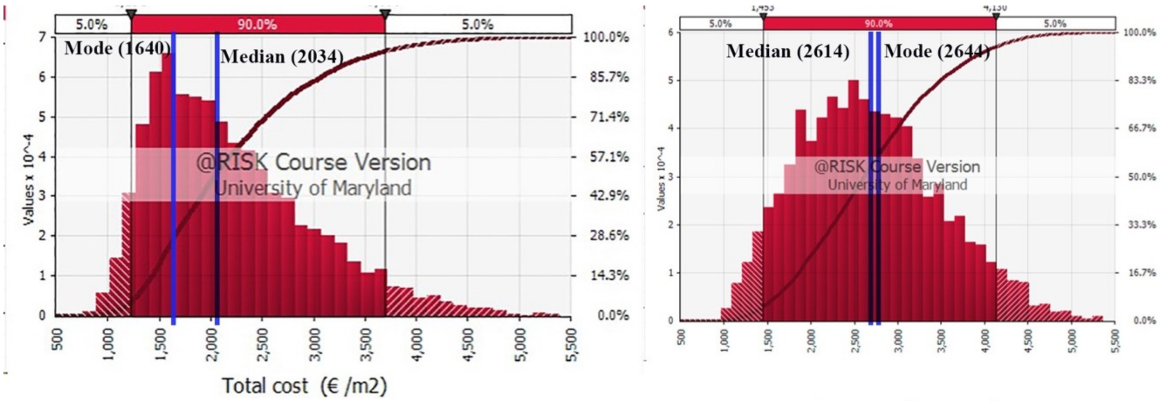


Figure 3 United States and Finnish Monte Carlo simulation results: cost variance distribution (image downloaded from @ Risk)

4.2 Mode value and probability of future project costs

It is quite possible that the construction cost input variables are correlated; for instance, with an improved building envelope, the required mechanical system can be smaller and thus cost less. Consequently, we examined the mode value for both the US and Finnish scenario two, where the cost input variables are correlated. Table 3 shows when incorporating the correlation of cost items, US scenario two has a lower mode value (€1,640/m^2) than in scenario one (€1,847/m^2). Finnish scenario two has a higher mode value (€2,644/m^2) than in scenario one (€2,608/m^2). Both numbers for the US and Finnish scenario two are within the expected range. Statistically, the mode is the value that presents the highest probability, so the mode values in scenario two for both countries can potentially represent a reasonable construction cost for energy retrofit projects with a similar scope of work in the two countries. Next, we examined the possibility of whether future projects could fall into the reasonable construction cost range.

Figure 4 shows that the probability of completing the energy retrofit project beyond a budget of €2,644/m^2 (mode value in Finland) is exceedingly small, and it is expected that construction costs of similar energy retrofit projects in Finland can be reasonably estimated and managed. The graph shows that the probability of completing US projects within €1,640/m^2 (mode value in the US) has a more gradual change, representing a higher probability that US projects will have higher construction costs than the mode value.



US Scenario Two **Finland Scenario Two**

Figure 4 Simulation results of the total project cost, showing location of mode and median

4.3 Results of goodness of fit test for cost input variables

The test results show the best fitting distribution for each cost input variable is different: the building envelope is normal, heating and ventilation is lognormal, and the rest of the cost items are loglogistic. And all cost input variables have a mean that is greater than the median, as illustrated in Figure 5, the distribution curve are all right-skewed, that is defined as positive skewness. The positive skewness of the distributions is consistent with studies on conventional building costs. The tails of the distribution of cost input variables on the right are longer than that on the left, which indicates that a major portion of the cost falls below the average, but a few expensive projects exceed the average cost.

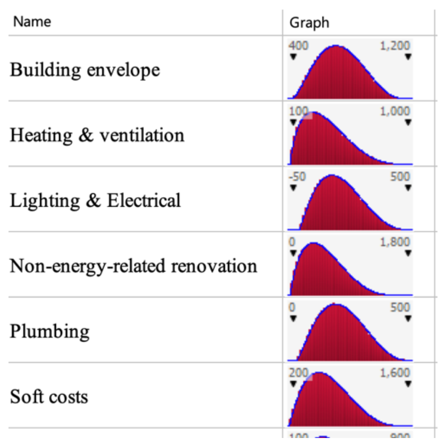


Figure 5 Distribution curve of input variables

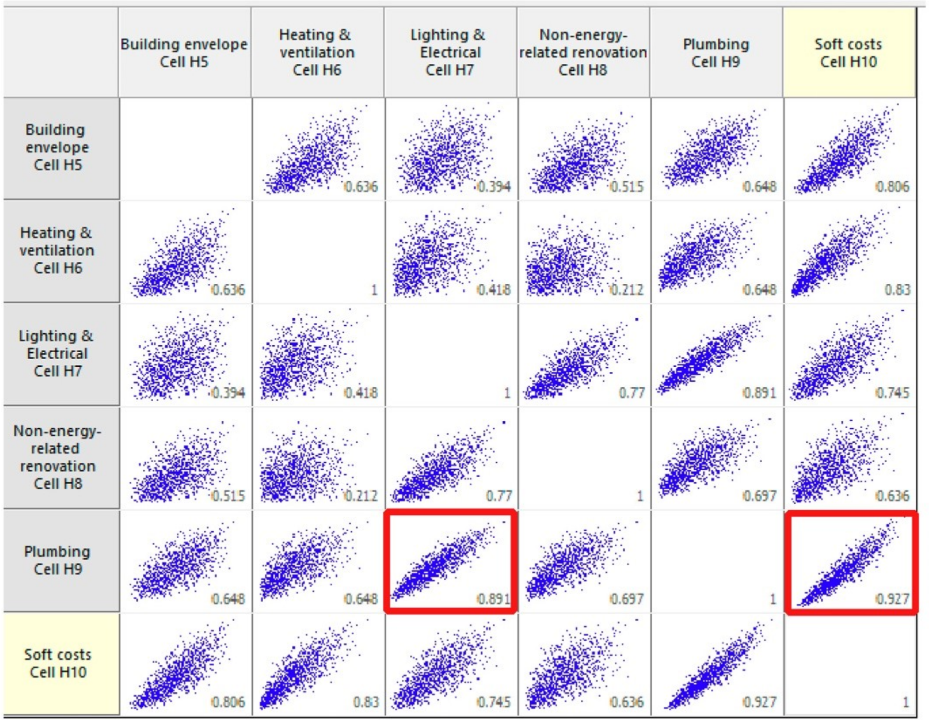
The second finding from the distribution fitting is that all distributions have a Kurtosis value higher than three (refer to Table 4). A Kurtosis measures how heavily the tails of a distribution differ from the tails of normal distribution. A Kurtosis larger than 3 is associated with a high level of uncertainty and risk and indicates a high probability of extremely high costs (on the right side). A higher Kurtosis and skewness together indicate that the cost items in a retrofit project might have a higher peak compared to a normal distribution. This can be explained by the extreme deviation from the mean in each cost category, which is much higher than that in a conventional retrofit project**.** It is worth noting that the extreme deviation in the non-energy related category is 7.07, which could be one of the main drivers for a large cost variation in retrofit projects (refer to Section 5.2 Consideration of non-energy related ").

Table 4 Anderson-Darling goodness of fit test results

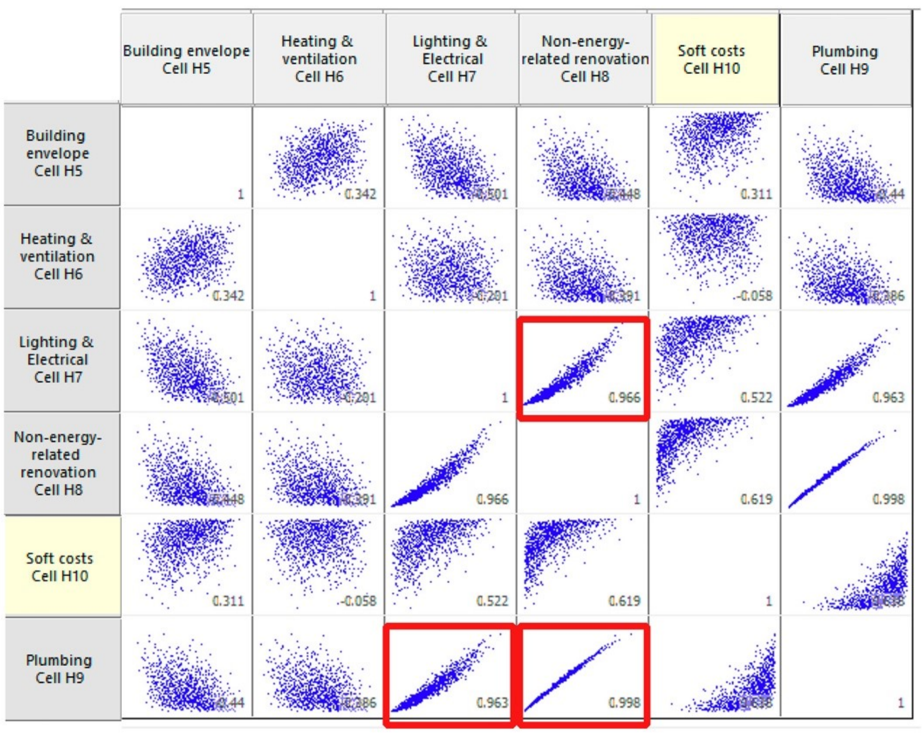
Item	**Building envelope**	**Heating system**	**Non-energy**	**Soft cost**
A-D Ranking	**0.57**	**0.28**	**0.92**	**0.38**
Kurtosis	2.33	4.42	7.07	3.9
Skewness	0.02	0.88	2.15	0.71

4.4 Correlation among cost input variables

Figure 6 illustrates the correlation among the different cost input variables. For Finnish energy retrofit projects, lighting and plumbing have a clear positive linear correlation (=0.891), and soft costs and plumbing have a clear positive linear correlation (=0.927). Unlike the results of the Finnish projects, in the US energy retrofit projects, non-energy related items and lighting (=0.996) and plumbing (=0.998) have a clear positive linear correlation. Lighting and plumbing also have a clear positive linear correlation (=0.963). Other cost input variables do not show a clear correlation.



Finland Correlation



US Correlation

Figure 6 Cost input variable correlations

4.5 Significant cost items

As demonstrated in Figure 7, simulation results show in both countries non-energy related retrofit cost items have the highest impact on the total construction cost. In the United States, non-energy related costs are the leading factor followed by the building envelope, while in Finland, non-energy related items and the soft cost ranked as the first and second influencing factors. In both countries, heating and ventilation are not the highest-ranking factor, which differs from the common perception of the heating system being the most influential construction cost parameter for energy retrofit projects.

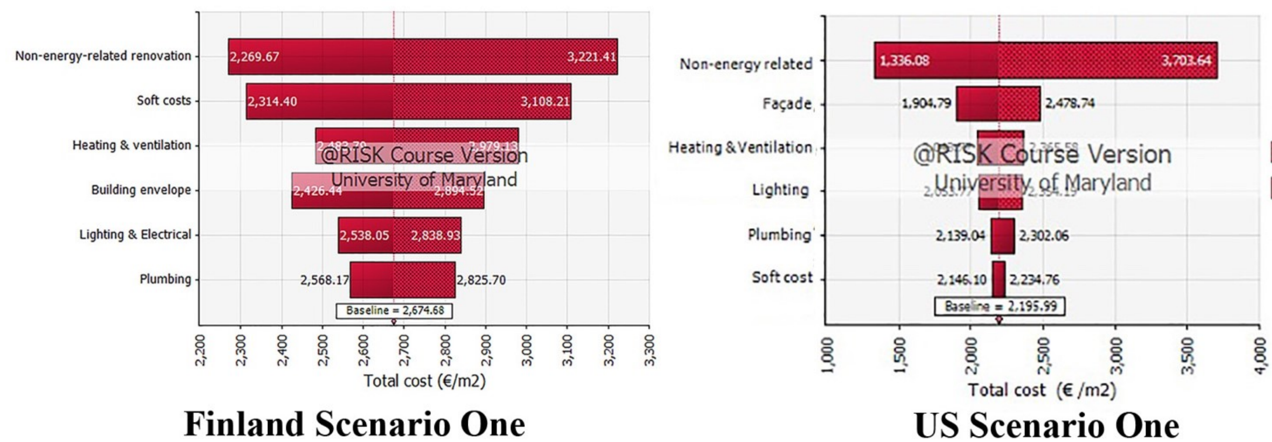


Figure 7 Inputs ranked by effect on output cost

Non-energy related items are the most influential cost variable. The non-energy related retrofit cost is mainly derived from the two categories in Finland: deferred maintenance and upgrades to meet the current code requirement. For example, for Finnish apartment buildings, natural ventilation was dominant before the 1970s, but mechanical exhaust ventilation become most common for buildings built after the 1970s (Litiu 2012). Therefore, when retrofitting the buildings built before the 1970s, mechanical ventilation systems must be integrated (National Building Code of Finland).

The non-energy related renovation items in the US vary significantly from project to project. Certain high-cost items may be customized for a client's particular requirement or for future resale potential. For instance, for the most expensive project in the US database, the building owner installed a ventilation system that has 5-7 air changes per hour, which significantly exceeds the code requirement of 0.35 air changes per hour in United States(ASHRAE 62.2). Another high-cost item is kitchen and bathroom renovation and upgrades. Compared to Finland, renovations for kitchens and bathrooms in medium to high-end apartment buildings are more extensive in the United States. Besides upgrading the appliances with more energy-efficient versions, in the United States, investments in kitchen and bathroom renovations can reach up to 26% of the total unit value (HomeGuide), and over 56% of the total retrofit construction cost (HomeAdvisor). Many upgrades can be considered as cosmetic but beneficial to increase the resale value; for instance, installing a marble kitchen countertop and using high-end cabinets and floor tiles. The reasons for the high costs of non-energy related items in the United States are discussed in Section 5.2.

As for the interpretation of the correlation between cost parameters to the total construction cost. Correlation is not equal to causal effect. The correlation demonstrates that two items typically occur together in a consistent pattern, while the two items do not necessarily have a causal relation.

However, since the total construction cost is the sum of all cost parameters, hence from the strong correlation between individual parameter to the total construction cost, we can speculate that individual parameter such as non-energy related items can be a primary driver driving the retrofit project total construction cost.

5.0 Discussion

5.1 Implications of cost variance

Simulation results show the United States has a larger coefficient variance in total construction cost than that in Finland. Further, in the US, there is extreme deviation in the total construction cost. We first examine the cost variance induced by energy-related cost items. There are two potential causes: ***first,*** familiarity or unfamiliarity of energy efficiency-related technologies, and ***second,*** the construction method.

The first cause refers specifically to the heat pump system. All projects included in the Finnish database have been retrofit with an energy-efficient heat pump system, using either a ground source or air source. The main benefits of a heat pump system are realized when the heat demand is high (such as in cold climates), which makes the heat pump system preferable as a highly energy-efficient heating system. Heat pump technologies have been utilized in Finland for several decades, and design and construction teams are equipped with the necessary knowledge to retrofit buildings with more energy-efficient systems. There have been many studies in Finland supporting the rapid adoption of the heat pump system. It was suggested that Finnish nearly zero energy buildings can be achieved more cost-efficiently from utilizing heat pumps rather than district heating (Häkämies et al. 2015).

However, in the United States, the majority of residential buildings depend on a central furnace for heating. Warm air is circulated through the buildings through ducts, thus it is often called a forced air system. It can be powered by electricity, natural gas, or fuel oil (Smart House). The heat pump system, especially newer ground source heat pump systems, is not well known in the US building and construction industry. For buildings with high heating energy consumption, a ground source heat pump's energy-saving potential is larger than that of an air source heat pump (Häkämies et al. 2015). When a ground source heat pump system needs to be integrated with other building systems, the US contractors are less familiar with such system installation compared to the Finnish contractors. However, the air source heat pump is gaining rapid adoption in renovation projects in some regions in the US. For example, as of 2018, it was estimated that over twenty thousand New England homes and businesses installed air source heat pumps using incentive programs (Cape Light Compact 2020) . This lack of knowledge and experience of ground source heat pumps is directly linked to an increase in risk and uncertainty, consequently contributing to higher construction costs, a higher probability of cost overrun, and a higher probability of project schedule overrun.

The second potential cause for a larger cost variance in the United States is associated with the existing building exterior wall construction type. For building façade renovation, adding external insulation is a preferable method, compared to internal insulation, due to its practicality and decreased risk of mold (Häkkinen 2012). Normally, the additional insulation and new façade cladding are attached directly to the load bearing system of existing walls. In Finland, close to 50% of apartment buildings have concrete panel walls; brick walls account for 33% and brick panel walls represent the majority, with the remaining being wood construction (Paiho et al. 2015). As illustrated in Figure 8, a typical existing exterior concrete panel wall is made of an outer concrete panel with finish, thermal insulation, and an interior material (such as plaster) (Niemela 2017). Attaching additional prefabricated wall panels to an existing building allows for quick installation and improved insulation, wind resistance, and overall quality control. In addition, the panelized exterior wall erection time can be shortened by 75%, in contrast to conventionally built walls (Lindow & Jasinski 2003). Compared to Finland, prefabricated panels in the United States are infrequently applied in residential buildings (Steinhardt & Manley 2016). The United States multifamily residential building typically use wet brick and mortar exterior wall systems, that is more labor-intense and time-consuming, and the wall system is also constrained by weather conditions. Consequently, there is higher risk and more uncertainty related to the renovation, which might leads to larger construction cost variance among projects. Another point related to the construction method is that the Finnish construction method and quality is more consistent across regions, while there is a wider difference between individual states in the United States. Such consistencies and inconsistencies can contribute to the smaller construction cost variance in Finland and larger variance in the United States for a building envelope retrofit.

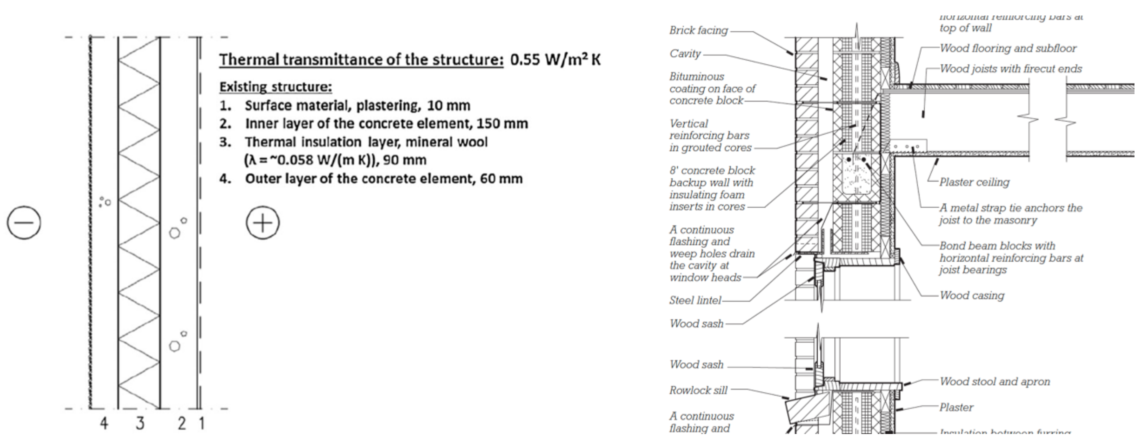


Figure 8 Typical existing concrete building wall section detail in Finland (left) and in the US (right) (Allen & Iano 2019)

5.2 Consideration of non-energy related construction costs

As illustrated in Figure 7, in both countries, the non-energy related costs are the most influential factor to the total construction cost. Some non-energy related renovations are necessary due to deferred maintenance and requirements for meeting the building code, while others are not necessary and merely cosmetic. For example, in one of the US projects included in the study, the owner spent $94,800 (€81,727) on an HVAC system replacement, while spending $63,000 (€54,312)on a fresh coat of paint, $16,695(€14,392) on customized stone tiling, and $74,049 on new hardwood floors. The expenses for non-energy related renovation—the paint, tiling, and floor— are altogether 1.5 times more than renovating the HVAC system. In one of Finnish project which has been recognized with historical significance, €2,796,030 was spent on HVAC system, while €1,048,511 was spent on yard and landscape, €7,514,333 was spent on historical preservation and restoration. In addition, findings from the sensitivity analysis showed both the Finnish and US projects' total construction costs are sensitive to changes in non-energy related costs, with the impact on Finnish projects being higher. Cosmetic upgrades are not uncommon in most renovation projects; it is practical and economical for the client and contractors to perform energy-related and non-energy related work at the same time. Such findings about non-energy related costs driving up the total energy retrofit project construction cost cannot be ignored, since higher costs have been the leading barrier to promoting energy retrofits, especially in residential sectors. The public's perception about energy-efficient buildings having higher construction costs has remained the top obstacle for the past decades. According to Dodge Data Analytics SmartMarket report (World Green Building Council), close to 49% of people think building green is more expensive than conventional building. To date, despite the widespread perception of energy-efficient building as being expensive, empirical studies and evidence needed to support this claim are inadequate, and the issue of a higher first construction cost for an energy retrofit is still debatable (Hu 2019). The findings from this study further elaborate that the non-energy related items drive the construction cost variances rather than the energy-efficient items, and there is no obvious correlation between the heating and ventilation system and the total construction cost. On the other hand, the cost directly contributing to the energy efficiency, such as heating system only ranks as the third most influential factor to the total construction cost in both countries. Such findings do not support the perceptions people have for the expense of building sustainable buildings. In some case projects, the cost of heating and ventilation system renovation is smaller than other non-energy related renovation costs. Those energy-related cost are likely to have a stronger effect on reducing operational costs (lower energy consumption) than non-energy related costs. Such relatively small "additional" cost of achieving energy saving can be seen as a positive thing, since most older buildings requires extensive renovation regardless of the energy performance goal, with a small additional cost allocated to energy -related systems, i.e., the conventional existing upgrades and renovation can achieve a higher energy performance standard in a economical and practical way.

5.3 Contributions and limitations of this study

The contributions of this study can be discussed in two aspects: the findings and method. To the authors' knowledge, there are no previous studies focusing on energy retrofit project construction costs, nor are there previous studies comparing the construction cost variances between different countries. This study provided three informative findings that give new insights into the energy retrofit project construction costs.

First, the larger construction cost variance in the United States was found to be potentially associated with the unfamiliarity of energy-efficient technologies and the varied construction methods in different regions. A less-skilled workforce include contractors and designer, and such deficiency can start from the design stage. For example, due to the lack of experience and knowledge, designers are less familiar with energy efficient technologies, such as ground source heat pump, consequently, the contractors have less opportunities to gain experience in installation and implementation. Further workforce training on those advanced building technologies and the modular exterior wall construction method can help to reduce the overall construction cost and control the uncertainty and risk during construction. ***Second***, besides technologies, materials, and labor, the construction cost economic system (structure) is another important factor in the total construction cost. This study provides a first look into the different construction cost structures in the United States and Finland. For example, a lump sum VAT is included in the Finnish projects but not in the US projects, which can have a direct influence on what design decision will be made in the retrofit projects to control the budget. ***Third,*** similarities were found between the two countries: the non-energy related items contributed largely to the construction cost variance in both countries. Since non-energy related items actually contribute largely to the overall construction cost, more in-depth analysis and more transparent data on those cost items can help to change people's perceptions of energy-efficient building being expensive. This study's contribution, from a methodological perspective, proved that a Monte Carlo method can be used in analyzing construction cost variance between regions and countries. The method can help to identify the trends and patterns of construction cost variances and determine the influential cost variables. The parallel comparison between the United States and Finland demonstrates the proposed analysis process can be applied in different countries and to different building types.

This study has four main limitations related to data collected for this study. The first is related to collected data. Due to difficulties in accessing actual construction costs, the Finnish data were mainly from one primary source while the US data were collected from various sources; the difference in sources may have impacted the accuracy of the research data. For both Finnish and US data, we were not able to verify the data with the project team. Therefore, the data accuracy was not verified. The second limitation is related to a lack of granular data. For example, under non-energy related cost items, there was no breakdown into subcategories for most projects, so we used aggregated data. The research team was not able to thoroughly analyze which non-energy related cost items contributed the most to the total construction cost and why they were needed. The third limitation is that this study mainly focused on the technical factors, such as the construction method and heating system used. The influence of the availability of skilled workers was not fully explored or explained, nor was the maturity of supply chains examined well. These limitations can be the next research steps taken. The fourth limitation is that solely focusing on initial cost data can limit our understanding of the life cycle cost benefit of energy retrofit projects; a cost and benefit analysis will be helpful to gain a comprehensive picture. As for the limitation of the simulation and analysis. The research team did not include the risk and uncertainty assessment when comparing the cost variance of US and Finnish projects. As discussed in Section 5.1, lack of experience and experience in certain technologies can be linked to increased uncertain and risk, consequently, leads to higher cost variance, further research integrating risk assessment can provide further understanding of those cost variances.

6.0 Conclusion

Despite existing perceptions and speculations about energy-efficient building being expensive, due to the difficulty of acquiring actual construction cost data, there are still limited studies in this area. In order to fill this knowledge gap, a comparative study was conducted on energy-efficient retrofit multifamily projects in Finland and in the United States (cold climate regions). For this study, a database including 17 multifamily units was created, and actual construction cost data was collected. The findings showed (1) the Finnish projects had a smaller construction cost variance with less skewed distribution; (2) the two most significant construction cost factors for both countries were non-energy related cost items and the building envelope, rather than the mechanical system (heating and ventilation) as commonly perceived; (3) Finnish retrofit projects have a high probability of having construction costs within in the normal range measured by the mode value; and (4) Finnish project construction costs are more sensitive to changes in price of non-energy related cost variables and the building envelope cost.

Important conclusions can be derived from these findings. First, unfamiliarity of energy efficiency-related technologies and varied construction methods might contribute to the large construction cost variance in US projects. Therefore, workforce training on advanced technologies and modular construction can be an effective way to drive down construction costs. Second, unlike the conventional perception of the heating and ventilation system being the most important factor of energy retrofit projects, non-energy related costs not only contribute to a large portion of the total construction cost but are also the most influential factor in determining cost variances. Such knowledge can help to combat the public's misperception about energy-efficient building costs and demand more construction cost data to be made available to decision makers and policy makers. Looking from the other side, the energy-related items are less influential and take up a relatively lower percentage of the total construction cost. With relatively small "additional" cost, the renovation project can achieve high energy efficiency; such cost-benefit relation can be viewed as a positive thing that can incentivize future energy retrofit movement. The next steps to continue this research entails collecting more construction data, studying other building types, and interviewing the project teams and building owners to gain a deeper understanding of the influential cost items.

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