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A Framework for Building Performance Analysis: Investment Return Approach for Energy Savings on Building Product Installation

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Abstract. *Product installation during the construction process impacts the overall performance and durability of a building. However, when the building construction industry fails to address installation quality the product performance is affected. This research explores the importance of optimized product installation and how it affects product performance. During the installation period, standard product performance can be affected by the information known about the product and the amount of time put into the assembly of the product. The building products can vary from insulation, A/C units, water heaters, etc. An installers' workmanship can impact standard product performance if they have limited knowledge about the product and its operational functionality. The products' prescribed functionality could be altered due to less than standardized installation practices. Improper installation of a product can lead to major deviations in performance that can increase maintenance costs over the lifetime of the product in addition to adverse effects of the product during its normal life cycle. Labor sensitivity is an underrepresented aspect of building construction that contributes to the problem of energy inefficiency. The goal of this work is to develop a metric that can quantify how relatively sensitive a building product and overall building performance is to the efforts of time and knowledge, specifically during the installation process. From this metric, the impact of installation on performance for different products can be compared through numerical values, highlighting products that require special care during the installation process to ensure desired performance.*

Keywords: *Building Performance, Sustainability, Product Installation, Installation Cost.*

1 Introduction

In terms of product performance there are theoretical and practical benchmarks in place to evaluate standard operation and procedures. Manufacturers design a product with certain achievement expectations in mind during the product development process. Before production begins, prototypes are designed with the goal of meeting this desired performance set forth by the manufacturer. As Murthy and Rausand (2008) has classified that the prototype specifications are manipulated and changed until the desired performance is reached by the product. Essentially, the performance set by the manufacturer becomes the expected level of performance the product should reach after its usage. A perspective to consider when analyzing overall building performance, "achieving the expected performance requires that the factors
that the design concept is based on fulfils certain standards and are within expected ranges. Hagentoft (2017) suggest that these factors could for instance be workmanship, interior and exterior climate, maintenance and/or material properties.

There are several factors that contribute to inefficient building performance, we intend to focus on the impact of workmanship during the installation process. Individual product performance and energy usages contribute to the overall performance and efficiency of the building. Considering this approach to building performance leads us to focus on individual products and how their performances measure on smaller scales within the performance gap. Frei (2017) considers the term “Performance Gap” used to denote deviations between a buildings’ planned and actual performances. Comparatively so, the previous definition of a building performance gap is the framework for the gap between the actual and individual product performances; the expected performance would not be met if it varies from the actual performance. In this paper we focused on building products that are extremely sensitive to performance issues that occurred during the installation process as a result of workmanship.

Most specialized products and their installation within a building is dependent upon the workmanship of skilled laborers. Some of the products include HVAC systems and heat pumps, which are particularly susceptible to poor performance due to installation errors. Residential heat pump installations and the vocational education of technicians have a dynamic impact on the successfulness of the job completed by the installer. As Gleeson (2016) stated, the lack of broader educational content and deficiencies in engineering knowledge will have profound negative impacts on both the performance and market acceptance of heat pumps. Domanski (2014) conducted a sensitivity analysis on heap pump installation faults and its skewed performance as a result in five different climatic zones. Simulations were run for faults including duct leakage and refrigerant undercharge to determine the effects on energy performance. The study concluded that installation faults could be responsible for a 30% increase in energy usage. The findings in this study can be further validated by the energy reports from the American Council for Energy Efficient Economy. According to the ACEEE (2018), energy savings from high efficiency air conditioners and heat pumps can be negated by a 20-40% loss in energy efficiency due to poor installation. Additional performances of other building products were reviewed to contribute to the argument of unsatisfactory workmanship affecting standard functionality. According to Langmans (2017), the insulation installed in building cavity walls provides a thermal barrier for reducing energy consumption. A performance analysis of these building components illustrated that the thermal performance of especially rigid board insulated cavity walls were highly depending on the installation quality of the insulation layer.

The product used as an example throughout this framework is building insulation. Zero Carbon Hub (2014) acknowledged that faulty installation of insulation is the main contributor to the building performance gap. In their study, two groups of houses were constructed to simulate good and bad workmanship to measure the impacts. Some of the test houses were constructed carefully in a manner that could be described as good workmanship while others were constructed in such a way as to mimic poor workmanship…features associated with poor workmanship could in some cases cause the U-value to rise by as much as 310%. Other investigations related to similar issues performed by Doran (2008) included a thermographic test and visual inspection which found that the quality of installation of insulation can be very important. Essentially areas where insulation is poorly fitted can incur high levels of heat loss. From these results it can be concluded that the poor installation can be a contributor to poor product performance.

2 Methods

The proposed framework emphasizes the effects of installation and its importance for reducing energy consumption. Continual reduction of energy consumption will result in lower cost throughout the lifetime of the product. The overall goal of this paper is to produce a Probabilistic Investment Return (PIR) that includes cost and energy performance of any given product. Consumers can gain an understanding of how the installation cost of a product and its energy savings per year combined can provide information on how it will pay for itself over a span of time. The PIR is based on the installation and performance aspects of building products. In Figure 1, the development of this end goal is displayed in a concept map.

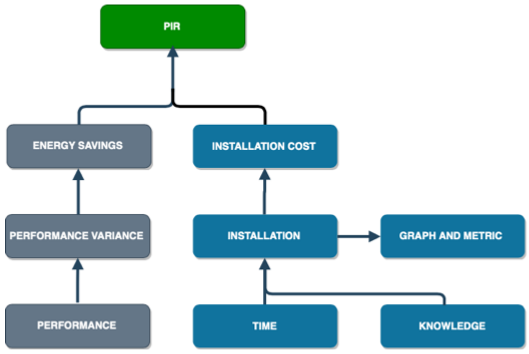

Figure 1. Probabilistic Investment Return Flow Map.

The proposed performance metric is based on the cost of installation and its potential energy savings. The Probabilistic Investment Return value is representative of the return on an investment of any given product in regard to its performance and installation cost. Apart from the installation process, this section will discuss how performance can be used to the estimate the returns on product investments. This figure is a representation of the developmental process and breakdown of each section in the overall framework.

The methods provided in this framework consider the difficulty of installation, variance in product performance, energy consumption as a result of performance, and a resulting probabilistic investment return. A conceptual map reflects the process of how each part within the developmental process of the PIR value was considered in the overall framework. A graphical representation of how an installer's performance is dependent on their contributions of time and knowledge is presented in Graph 1, representing a trade-off between an installer's knowledge and time spent on installation in relation to how a product performs.

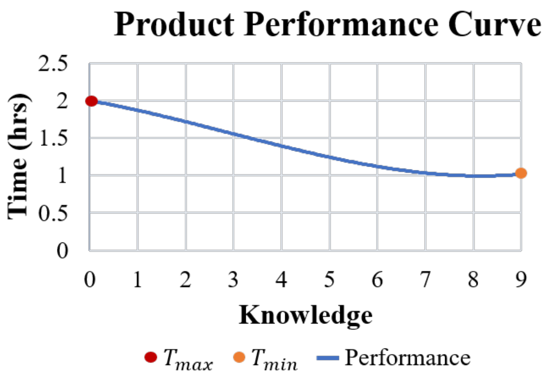

Figure 2. Product Performance Curve.

The above graphic is an example of the performance output of various products throughout a building system. Whether the product is a HVAC unit, heat pump, or roof/wall insulation there are apparent sensitivities to the installation process which require both time and knowledge. The time variable of this analysis was defined to be highly fluctuating due to the innate behavior of the installation process. There is no definite maximum on the time scale to measure the installation time. Depending on the installers' knowledge level different products will require varying time allotments to complete the installation. For this reason, time was treated as a relative variable that could be applied to all products. Knowledge proves to be more difficult to classify when considering unskilled and skilled persons. This framework focuses on the comprehensive ability of an installer based on their knowledge and experience, so it requires a scale to measure that ability. In the UK, the NVQs, or national vocational qualifications, consists of a system for understanding vocational skill sets in terms of a ranking system. Gann and Senker (1998) suggest that different qualification levels can be met through performance-based assessments of vocational skills within specialized fields. A ranking system was developed in **Table 1** for an individual to place themselves on the knowledge scale. Intuitively, an installer would have a better gauge of their experience and to what extent it can be applied. The scale is also a rubric to help categorize and differentiate between areas of workmanship and understanding, which helps defines an individual's competency level.

Knowledge	
• Basic understanding of product and its functions	+1
• Read Installation Manual	+1
• Knowledge of required tools	+1
Training	
• Attended vocational training	+1
• Witnessed an installation/watched instructional video	+1
• Received certification	+1
Experience	
• Installed the product once	+1
• Has installed 50+ units	+1
• Has installed 100+ units	+1
Total Knowledge Score (0-9):	*K*

Table 1. Installer Knowledge Level Conditions.

Guo *et. al*., (2012) determined a knowledge worker's human capital scale to include the dimensions of education, work experience, learning ability, and training. The Knowledge Score (K) represents an individual's knowledge within a product installation context.

3 Installation Metric

The graphical representation presented above provides a visual understanding of the relationship between time, knowledge, and performance, but a metric is desired in order to fully understand the magnitude of the relationships. The metric proposed comes in two parts which together describe the installation effort and the variability in that effort.

$$\text{Metric} = \text{Area under Performance Curve} \tag{1}$$

$$\text{Area} = \frac{T_{max} - T_{min}}{T_{max}} \text{ X } 100\%$$

The first portion is determined from the area underneath the performance curve. Each unique product will have its own curve and therefore its own area. In this case, the area is a combination of time and knowledge which together are a representation of the effort required to reach expected performance. In order to perform the installation, the installer spends the necessary amount of time put forth time during the installation process. This time can be considered a portion of the effort required to install the product. The second contributor to this effort comes from the installer's knowledge level. To have met their current knowledge level, an installer must have invested in their understanding, training, and experience. Products which require the installation be completed by knowledgeable installers are considered effort intensive in terms of its underlying training and experience required to complete the process. The combination of time and knowledge required to perform an installation describe the overall effort of installing the product.

The second portion of the metric intends to describe the variation in time and knowledge across the performance curve. A ratio is created by subtracting the minimum installation time from the maximum installation time and then dividing by the max installation time. This percentage gives an indicator of how much time and knowledge vary in relation to performance. From this percentage we can gain insight on the installation of a product. If this value is high, then the time required for a knowledgeable installer to perform the installation will be significantly less when compared to an unknowledgeable installer. If the percentage is low, then an installer with a high knowledge level will not receive a significant decrease in installation time when compared to unknowledgeable installer. This would indicate that the installation may take a similar amount of ‘effort’ in terms of time for all knowledge levels. This is particularly useful when determining who should install a product. Installers with greater knowledge levels typically have a higher hourly wage due to their experience and skill. An individual may choose to hire an installer with minimum knowledge if they can pay them less money but still have the job done correctly and on time. Generally, this percentage provides a depiction of the shape and steepness of the curve from start to finish. Both values can provide information on the visualization of the graph. For example, the area represents the space under the curve in units of time and knowledge combined (K-hrs). The percentage represents the time differential between the highest and lowest recorded times throughout the data. Both parameters are essential for providing the bounds of the graph. An example is provided below.

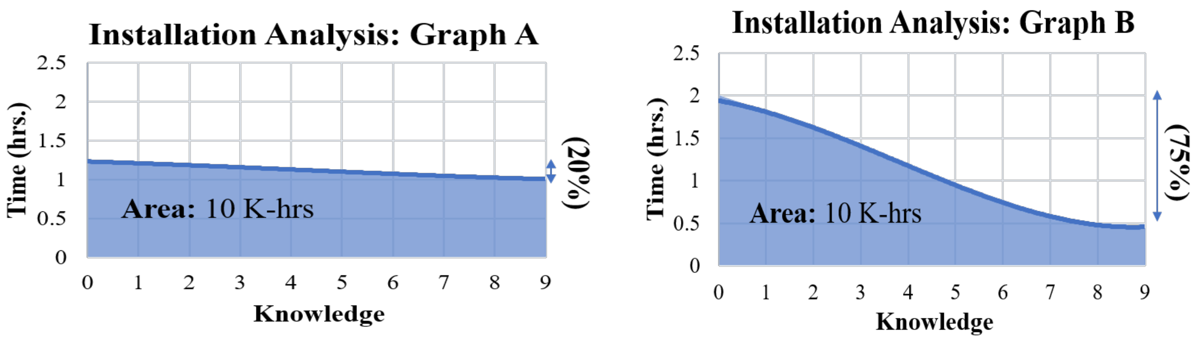

Figure 3. Installation Analysis of Two Performance Curves.

The two graphs shown in Figure 3 above represent possible curves for a product installation. Notably, both curves have a similar area meaning that on average, their installations require similar effort. However, the second graph has a 75% change in time while the first graph has a 20% change in time. This portion of the metric represents the variability of the installation effort across the performance curve. The graph with a 20% change in time is less variable across the curve. An installer with minimal knowledge would not spend a significant amount of time more on the installation than an installer with maximum knowledge. On the other hand, the graph with a 75% change in time has a greater variability in effort across the performance curve. An installer with maximum knowledge will take a significantly less amount of time to perform the installation than an installer with minimum knowledge.

4 Installation Cost

This framework also seeks to understand the costs associated with installation and performance; the installation analysis curve can be adapted to reflect installation costs. Because the knowledge and skills of a laborer are often reflected in their hourly pay, the knowledge scale on the x-axis is adapted to represent hourly wages of installers. From this change, the cost of installation can be determined.

In Figure 3, the current performance curve is a representation of either the data collected through sampling installations or from the manufacturer questionnaire. The individual data points are a combination of the laborer's wage, W_n, and the installation time T_i. Together these can provide the total installation cost for each installation, C_i. Each individual installation will have its own cost depending on the labor hired to perform the installation. This cost adaptation can then be used to find the current average installation cost for the product being analyzed.

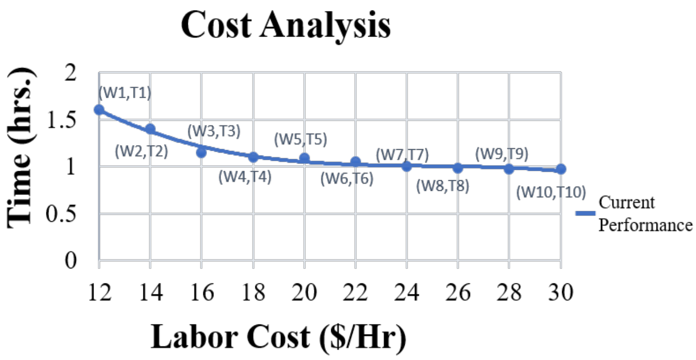

Figure 4. Cost Analysis of Installation.

$$\text{Installation Cost (\$)} = \text{Installation Time (hr) x Labor Wage } (\frac{\$}{hr})$$

$$C_i = T_i \text{ x } W_n \tag{2}$$

5 Probabilistic Investment Return

Together, the cost of installation, the cost of the product, and the energy savings for a performance level can provide a general return on investment in terms of years required for the product to pay for itself. We describe this in terms of Probabilistic Investment Return or PIR. The cost of each installation along with the product material cost is then divided by the yearly energy savings of each performance to determine the number of years required to break even on the investment. This is represented as

$$\text{PIR} = \frac{P(C_i) + C_P}{C_E \cdot P(\Delta\, \xi)} \tag{3}$$

where

$P(C_i) = P(T_i * C_w); Probability\ of\ Installation\ Cost$ (\$)

$T_i = Installation\ Time\ (hrs)$

$C_w = Installer\ Wage\ (\frac{\$}{hr})$

$C_P: Product\ Cost$ (\$)

$C_E: Energy\ Cost\ (\frac{\$}{BTU \times yr})$

$P(\Delta\, \xi): Probability\ of\ Change\ in\ Energy\ Consumption$ (BTU)

6 Conclusion

Throughout this research, we have provided evidence that specialized building products such as HVAC systems and heat pumps are impacted by installation. More specifically, the installers' knowledge is related to how well the product performs. Poor installation of products can result in energy waste in regard to the entire building and its envelope. We have provided a framework for analyzing the impact of installation building performance and its corresponding energy and cost factors. These methods have quantified the contributions of installers to performance levels, the extent of product performance gaps, and the probabilistic return on investment for installing a product. These efforts can then be considered a framework for a holistic understanding of the product installation process and its far-reaching effects on building performance. From this framework, products can be evaluated on an installation basis to determine their effects on building performance and to move toward overall reduced energy consumption in current buildings, retrofit projects, and future constructions.

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