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INGENIERIA S.A.

Structure Fire Gas Emissions

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WORCESTER POLYTECHNIC INSTITUTE · 1865 ·
WPI

Structure Fire Gas Emissions

An Interactive Qualifying Project Report
Submitted to the Faculty of Worcester Polytechnic Institute
In partial fulfillment of the requirements for the
Degree of Bachelor of Science

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Submitted On:
May 8, 2014

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IQP Sequence Number:
HXA CR03

Abstract

As part of Costa Rica's goal to reach carbon neutrality by 2021, all carbon emission sources must be inventoried. Each year there are about 1000 structure fires in Costa Rica. The Structure Fire Gas Emissions project calculates the carbon emissions from structure fires in Costa Rica. Four detailed models were created to calculate emissions from residential, hospital, warehouse and industrial buildings. A fifth model collects information in aggregate from the other models in order to provide a summary of total carbon emissions from structure fires across Costa Rica. Our sponsor SHP Ingenieria, in conjunction with the Benemérito Cuerpo de Bomberos de Costa Rica, and the Estado de Nación will use the models in order to monitor carbon emissions and make future policy recommendations.

Acknowledgements

Our team would like to thank the following departments and people for their support and contribution to our project and for their hospitality.

- Engineer Esteban Ramos, and the amazing staff of SHPI Ingenieria for constant support and incredible hospitality:
    - Ángela Solarte
    - Aaron Bolaños
    - Gabriel Barboza
    - Cesar Solarte
- Professor Susan Vernon-Gerstenfeld of the Interdisciplinary and Global Studies Division at Worcester Polytechnic Institute for directing the Costa Rica project site and making this experience possible.
- Professor Robert Traver for helping us prepare for our trip to Costa Rica.
- Our advisors, Professor Holly Ault and Professor Reinhold Ludwig for their continued support and guidance throughout our project.
- Mr. Tom Hohenstein, research librarian from the Worcester Polytechnic Institute library, for helping to guide our research.
- Dr. Jonathon Barnett, Olsson Fire & Risk, for answering any and all questions we had, and for guiding us in technical aspects of our project.
- Dr. Richard Hooker for setting us in the right direction at the beginning of the project
- Professor Nicholas Dembsey for providing further information on the fire protection research and industry
- Engineer Fernando Herrera for his help and hospitality at the Mormon Church construction site in San Ramon.
- El Benemérito Cuerpo de Bomberos de Costa Rica for providing us with data and for their hospitality when we visited various sites:
    - Sr. Jacinto Saborio
    - Sra. Ana Maria Ortega

Executive Summary

Background

In 2007 Costa Rica announced a plan to become carbon neutral by 2021. Carbon neutrality requires reducing emissions and then offsetting any emissions that cannot be reduced. Inventorying carbon emissions in Costa Rica is the first step towards carbon neutrality. Costa Rica has the opportunity to direct its growth in a sustainable direction in support of their goal to be carbon neutral. Annual reports from Estado de la Nación are valuable resources for educating the public on the state of the environment. Data from our project will be useful to their annual report.

The Benemérito Cuerpo de Bomberos de Costa Rica responds to about 1,000 structure fires every year. As a result of the varying structure and content of a building, a single fire can produce and release many chemical compounds which will negatively impact the environment. It is unclear currently how much carbon is emitted from structure fires in Costa Rica. Using a 2010 report from Robbins, Page, and Jaques and data from the World Bank, a general estimation was calculated that structure fires contribute to about 0.43 percent of the total emissions in Costa Rica.

Structure fires are categorized by the type of the building they affect. Building types are defined by International Building Code (IBC) standards. Residences fall under the R-3 classification, in which many material types are used. Codes and standards for industrial and warehouse buildings are stricter due to the risk they pose to public health. The building materials are more constant for the structure and combustible contents are strictly limited. Hospitals are built with even higher standards. Using IA standards, the highest fire protection standards, hospitals are careful to protect their patients.

Emissions are a factor of the emissions factor and the building's fuel loading. Current models first calculate how much fuel contributes to the fire from the structure and the contents of the building. After fuel loading is determined a material specific emissions factor converts the kilograms of material available to kilograms of carbon dioxide produced.

Goals, Objectives and Methods

The goal of this project is to develop five mathematical models to provide an estimate of carbon emissions from structure fires in Costa Rica. The first four models are building-specific for residences, hospitals, warehouses and industrial sites. The fifth model is an estimate of the total carbon emissions per year from structure fires using annual Costa Rican fire data and our building-specific models.

In order to accomplish this goal, our project includes the following five objectives:

1) Identify types and amounts of materials used to construct residences, hospitals, industrial buildings, and warehouses in Costa Rica.
2) Understand types and amounts of materials that make up the contents of residences, hospitals, industrial buildings, and warehouses in Costa Rica.
3) Develop a mathematical model for each of the four types of buildings that calculates carbon emissions from specific fire incidents by refining current models to be applicable to Costa Rica.
4) Evaluate the models and adjust them to best fit the needs of SHPI Ingenieria and the Bomberos.
5) Recommend a validation process to verify the accuracy of the models in the future.

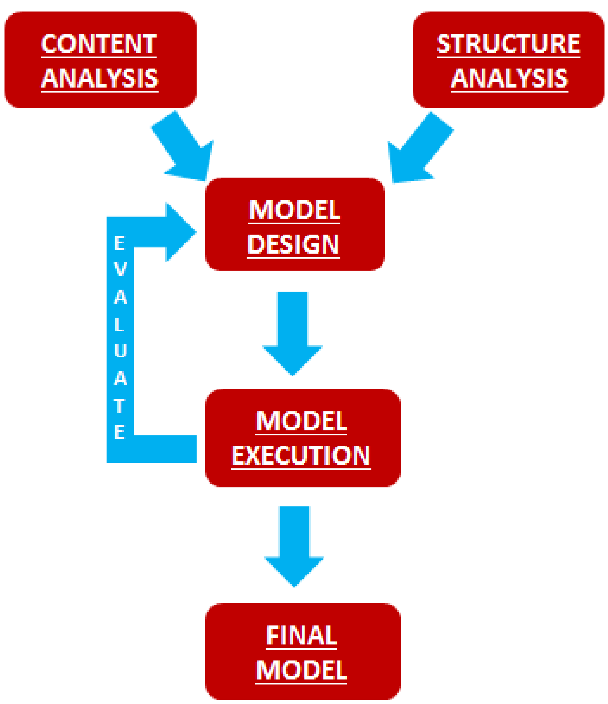

Figure 1: Methodology

The above flowchart the overarching process we followed while completing our project.

Objective 1: Identify types and amounts of materials used to construct residences, hospitals, industrial buildings, and warehouses in Costa Rica.

"Manual de valores base unitarios por tipologia constructiva" from the Ministerio de Hacienda outlines Costa Rica's building guidelines. In order to compare theoretical and actual everyday practices we conducted an interview with an engineer. The interview in conjunction with Bombero's detailed reports provided us with valuable information about the material make up of structures in Costa Rica.

Objective 2: Understand types and amounts of materials that make up the contents of residences, hospitals, industrial buildings, and warehouses in Costa Rica.

Investigations to determine the material make up of contents in Costa Rican buildings required a slightly different approach for each specific model. For residential buildings, real estate websites were utilized in order to determine contents in typical kitchens, bathrooms, dining rooms and so on. Visits to warehouses were utilized in order to determine what types of products and the density of contents in typical warehouses.

Information on residential and warehouse contents was further supported by Bomberos data. Content information for hospital and industrial sites relied on Bomberos data and user input. Due to the variability of warehouses and industrial sites, it was impossible to make generalizations about the content material make up.

Objective 3: Develop a mathematical model for each of the four types of buildings that calculate carbon emissions from specific fire incidents by refining current models to be applicable to Costa Rica.

The models use information gathered for Objective 2 in order to complete carbon emissions calculations. The residential model breaks down the calculations by individual rooms in order to streamline user input and provide a robust result. The hospital model similarly breaks down fires by the individual rooms it affects. Warehouses and industrial sites follow their own independent structure due to their unique fuel loading characteristics.

Objective 4: Evaluate the models and adjust them to best fit the needs of SHPI Ingenieria and the Bomberos.

The models will be evaluated by conducting a series of feedback sessions. The sessions were used to confirm the usefulness and convenience of the model. The participants were given the opportunity to use the model. The participants included the staff of SHPI Ingenieria. User feedback was used to develop a final design and data entry.

Objective 5: Recommend a validation process to verify the accuracy of the models in the future.

Since very little information exists on the emissions of structure fires, it is difficult to compare the outputs from the models and validate them.

Results

The content and structure analyses yielded a series of findings that were very instrumental in the development of the models.

First, it was determined that many of the buildings in Costa Rica are constructed with the same materials. Research was done to determine common building materials used in Costa Rica as well as building standards in Costa Rica. Analysis of the investigated reports of the Benemérito Cuerpo de Bomberos de Costa Rica provided valuable information on many of the different materials used.

Second, more than half of the four types of structural fires investigated are residential fires. During the seven year period of 2007 to 2013, 61% of the investigated fires were residential, where 55% of those fires affected more than half of the building. Industrial buildings experience the second highest number of fires, followed by warehouses and hospitals.

Third, the average building configuration for residential buildings yielded 803.43 metric tons of carbon dioxide emissions. The aggregate model estimates 1076 metric tons of carbon dioxide released by structural fires in Costa Rica from 2013.

Fourth, the models were easy to use and understand. Based on observations, evaluations and user feedback the models were very easy to learn. The users were given an overview of how the models were created as well as step by step instruction on how to use the model. It was determined that the models met the requirements of SHPI Ingenieria.

Fifth, a more detailed residential model is beneficial to the community. As a result of the feedback session, time was spent on providing a more detailed residential model and recommendations were created as guidelines to build a better industrial, warehouse and hospital model. Allowing the user to input more specific data into the residential model will provide a more accurate estimation of the carbon emissions.

Sixth, the residential models compare well against similar emissions from structure fires in Sweden, Denmark, Finland and Norway. The emissions output from the four studies are very close in value to what the created residential model produces for a similar residential building. This observation demonstrates the accuracy of the models.

Recommendations

Based on research, findings and analysis we have developed a list of recommendations to implement for improving the models and for using the models. The recommendations were developed for SHPI Ingenieria and other potential users of our models. We strongly recommend that:

1

- SHPI Ingenieria, or government agencies such as Estado de la Nación, use the models to keep a growing inventory of the carbon emissions from the structural fires examined and to improve building standards

2

- The carbon emissions for residential buildings be included in the investigative reports of the Benemérito Cuerpo de Bomberos de Costa Rica.

3

- The building specific models should only be used for the specific buildings that they were designed for. The aggregate model should only be used when trying to determine the yearly carbon emission for Costa Rica.

4

- SHPI Ingenieria and the users of the model follow the validation process for our models.

5

- Future research focus on improving the hospital, warehouse and industrial models

6

- Future research focus on other greenhouse gases that Costa Rica emits into the environment.

Conclusion

Five mathematical models were created to provide an estimate of carbon emissions from structural fires in Costa Rica. A final list of recommendations was also provided to inform the users and future researchers on how to use, improve and validate the models. We believe that our models and these calculations have the potential to contribute to many studies in the future: to improve the construction of buildings in Costa Rica, to maintain a carbon inventory and to study the effects of health for firefighters. With a growing inventory of carbon emissions from structural fires, Costa Rica will be able to determine the factors that are hindering the goal of carbon neutrality.

Authorship

This report is the collaborative effort of Alexandra Hardin, Eric Schattschneider, Tyler Stone and Kristina Walker. Each section has a primary author, but the entire report was edited by all members.

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1 Introduction

Global warming has become one of the hottest topics in the last decade. The global temperature has increased 0.8 degrees Celsius since 1901, and 2001-2010 was the warmest decade recorded to date (Environmental Protection Agency, 2013). If this trend continues, changes could occur around the globe that would drastically alter many delicate ecosystems. Global warming also directly correlates to an increasing sea level. Ice caps are melting from an increasing number of heat waves. This increased heat has a direct impact on habitats, water supply, crop production, and infrastructure (Environmental Protection Agency, 2013). The global warming trend has a widespread impact on the global community. The global temperature is expected to rise between 1.11 and 6.39 degrees Celsius by 2100, only worsening these environmental changes.

Greenhouse gas emissions are a main cause of global warming. Gases such as carbon dioxide cause environmental changes because they remain in the atmosphere and affect how much energy the atmosphere absorbs (Environmental Protection Agency, 2013). In a concerted effort to reduce greenhouse gas emissions, the United Nations is attempting to establish targets for emission reduction. Adopted in 1997, the Kyoto Protocol sets goals for countries to follow as a guideline towards reducing emissions. There are currently 191 countries participating in the discussion (United Nations Framework Convention on Climate Change, 2014). In addition, many countries are attempting to enact laws and standards to help fight global warming in sectors of industry that contribute to these emissions. One of the most outstanding initiatives is Costa Rica's plan to become the first carbon neutral country in the world with a deadline of 2021 (President Aims for Carbon Neutrality, 2007). With such a lofty goal, all carbon emissions must be identified and regulated.

While many international initiatives focus on industry, fires are noteworthy contributors to greenhouse gas emissions. Forest fires have long been observed and shown to emit a significant amount of carbon dioxide. Wiedinmyer and Neff state, "... a severe fire season lasting only one or two months can release as much carbon as the annual emissions from the entire transportation or energy sector of an individual [U.S.] state," (Wiedinmyer & Neff, 2007). Emissions from structure fires have been researched less, but can still have an environmental impact.

This project explored the carbon emissions of various types of structure fires, and developed a method for measuring emissions from these fires. Several factors contribute to the composition and amount of emissions from structure fires. Therefore, research topics included material composition and content of buildings, combustion properties of these materials, and duration of fire. Our research then allowed us to build mathematical models to provide an estimate of the carbon emissions from structure fires in Costa Rica. The final models and methodology will act as a guide for SHPI Ingenieria to inventory emissions from structure fires and better consult its clients on their potential for minimizing their carbon footprint.

2 Background

This section focuses on carbon neutrality in Costa Rica, and how this project fits into the country's carbon neutrality plan. First, this section defines carbon neutrality and explores the impact of structural fires on Costa Rica's carbon output. Next, it reviews emissions standards and building classifications on a global scale. Lastly, it discusses existing models for measuring structure fire gas emissions, giving a baseline for creating a Costa Rica-specific model.

2.1 Carbon Neutrality

This section provides an overview of Costa Rica's plan for carbon neutrality. By the end of the section, the reader should understand the definition of carbon neutrality and how it applies to Costa Rica. It will outline the problems Costa Rica faces in attaining this goal, and its progress to date.

2.1.1 Costa Rica Makes a Plan

Costa Rica, meaning "rich coast" in Spanish, is a small country in Central America. Located north of Panama, the country is part of the strip of land that divides the Caribbean Sea and the Pacific Ocean. Lying ten degrees above the equator, Costa Rica enjoys a tropical and subtropical climate. Its climate, along with unique geographical characteristics like mountain ranges and volcanoes, creates a biological wonderland like no other country in the world. With such a dependence on its environment, Costa Rica must give special attention to its environmental protection in policies. "[T]he nation has set aside 28 percent of its land to national parks and reserves, a larger percentage than any other country on Earth," (Baker, 2013).

Its dedication to the environment is not only demonstrated in reservation areas, but also in its governmental policies. In 2007, Costa Rica became a pioneer in environmental sustainability. Oscar Arias, President at the time, declared an initiative for carbon neutrality by 2021. If Costa Rica attains this goal by 2021, it will be the first country in the world to become carbon neutral (President Aims for Carbon Neutrality, 2007).

2.1.2 What is Carbon Neutrality?

Carbon neutrality is a two-part strategy that aims to reduce net carbon emissions to zero. Carbon neutrality requires reducing emissions and then offsetting any emissions that cannot be reduced. A baseline carbon emissions measurement provides a community with an important picture of how it can reduce its environmental impact. The remaining carbon output of a community can then be offset by capturing carbon emissions, through biological processes such as the growth of trees introduced through reforestation programs.

In preparation for Costa Rica's carbon neutrality deadline, many organizations have taken steps to reduce their carbon output. Bridgestone's manufacturing center in Costa Rica illustrates how a company can take a multifaceted approach to lowering its carbon footprint. Using light-emitting diode (LED) lighting and solar lamps are simple steps towards reducing carbon output by increasing energy efficiency. On a systemic level, Bridgestone has looked to modify their company culture to encourage more sustainable habits. Rewards, such as reserved parking spots for carpooling, helped modify employee behaviors (Bridgestone Costa Rica Aiming to be Carbon-Neutral, 2014).

After carefully reducing carbon emissions, organizations in Costa Rica can offset any emissions that cannot be further reduced through the Costa Rican Voluntary Domestic Carbon Market. Companies can purchase Costa Rican Compensation Units (UCCs) in order to secure the right to release carbon emissions into the atmosphere. Revenue from UCCs provide support for reforestation and conservation efforts throughout the nation that look to capture and reduce carbon emissions (Spross, 2013).

2.1.3 Progress and Problems to Date

There are some barriers to Costa Rica's effort to achieve full carbon neutrality. "[T]he country's existing policies have not been favorable to increased availability of renewable electricity like solar, wind and biomass due to legal barriers to private investment and no incentive to increase private generation," (President Aims for Carbon Neutrality, 2007). As a result, Costa Rica is becoming dependent on oil to generate electricity. Even though Costa Rica may want to decrease its oil dependence, its laws are not conducive to additional production of renewable electricity.

Increased population in Costa Rica is another barrier to energy self-sufficiency and carbon neutrality. With more people, there must be more infrastructure. This may result in reduced environmental preservation.

However, Costa Rica has an advantage over other countries that are also working towards carbon neutrality, like Iceland, New Zealand, and Norway (Wikipedia, n.d.). Costa Rica is a developing country according to The International Statistical Institute, which defines a developing country as one with a Gross National Income per capita less than USD$11,905 (International Statistical Institute, 2014). Many developed countries already have infrastructure that could limit the country's ability to reduce greenhouse gas emissions. Since Costa Rica is still developing, it has the opportunity to modernize and customize its infrastructure to attain its carbon neutrality goal.

2.1.4 Estado de la Nación

In 1994, an independent project in Costa Rica began as "el Proyecto Estado de la Nación" (PEN). This project began publishing annual reports on the state of the nation from economic conditions, to literacy and other statistics. The goal of the project was to educate Costa Ricans on the state of their country, and encourage them to take action in improving social and economic situations in Costa Rica.

In 2003, the project was restructured and became a national institute under “el Consejo Nacional de Rectores” (national advice from the government). Now, the project has subcategories that consult on national education and regional entities (Historia, n.d.). To date, the organization has produced 19 annual reports, and is the longest standing organization that has put out such reports in the world.

With Costa Rica’s carbon neutrality goal, the annual reports from Estado de la Nación will be important to educate the public on the state of the environment, and what individuals can do to help the environment. Data from our project may be useful to the annual report in educating the public on the impact of structure fires on the environment.

2.2 Role of Fire in Costa Rica’s Carbon Neutrality Plan

This section will discuss the role of fires in Costa Rica’s carbon neutrality plan. The reader should understand how fires contribute to Costa Rica’s carbon inventory and how emissions from fires affect the environment.

2.2.1 Environmental Impact of Fires

Although fires stem from different causes (accidental, intentional and undetermined)l, they still contribute to carbon emissions and hence compromise efforts to be carbon neutral. Fires can produce significant levels of greenhouse gases when amassed over time. In the United States, approximately 290 million metric tons of carbon dioxide are released into the atmosphere each year from forest fires, 4 to 6% of all yearly carbon emissions from the United States (Dybas & Hosansky, 2007).

The potential for fires to contribute to Costa Rica’s carbon output is high. In 2013 alone, the national fire department responded to over 1,000 building fires of varying size and duration (Benermerito Cuerpo de Bomberos de Costa Rica, 2014). Structure fires vary based on building size, fire protection equipment, composition, and purpose. These variables can make it difficult to generically quantify the carbon contribution of all fires.

2.2.2 Emissions Potential of Fires

As a result of the varying structure and content of a building, a single fire can produce and release many chemical compounds which will negatively impact the environment. One way to measure the potential for greenhouse gases to affect the environment is through the use of the global-warming potential scale. Global-warming potential determines how effective a certain gas is at impacting the climate by referencing the amount of energy it can capture over a specific duration of time. This system uses carbon dioxide’s energy absorption as a baseline, so carbon dioxide has a global warming potential of exactly 1 (Environmental Protection Agency, 2013).

2.2.3 The Significance of Structure Fire Emissions

It is unclear exactly how much carbon dioxide or other dangerous greenhouse gases are emitted from structure fires in Costa Rica on a yearly basis. Studies to determine the carbon output of a house fire have been carried out in New Zealand, which is planning for carbon neutrality by 2050. A study in 2010 found that the total carbon dioxide released from a timber-framed residential building fire in New Zealand averaged 38,000 kilograms of carbon dioxide if the building was completely lost (Robbins, Page, & Jaques, 2010).

Using this study, called "House Fire GHG Emissions Tool", and data from the Bomberos and the World Bank, one can estimate how structure fires contribute to Costa Rica's overall carbon output. The tool estimated emissions from house fires based on house structure, house contents, and installed fire safety equipment. The data collected during the New Zealand study on house contents and fire safety equipment may not be directly transferable to Costa Rica. Differences in building contents and fire safety equipment can arise due to cultural and technological differences. However, it is a strong estimation tool and can give good insight into emissions released by fires in structures.

To determine the extent to which structure fires contribute to carbon emissions in Costa Rica, we calculated an estimate percentage:

$$\frac{\textbf{mass of carbon emissions from structural fires}}{\textbf{total mass of carbon emissions}}\ \mathbf{x\ 100} \tag{1}$$

First, we estimated the mass of carbon emissions from structural fires using data from the "House Fire GHG Emissions Tool" study. According to this study, the structure of a house contributes to 31,800 kilograms of carbon dioxide emissions on average (46). The contents of the average home contribute to 6,000 kilograms of carbon dioxide emissions (51), for a total of 37,000 kilograms of carbon dioxide emitted per house fire (Robbins, Page, & Jaques, 2010). This study uses five scenarios to produce data. We are using data from scenario one, which assumes complete combustion of a home, or one-hundred percent area lost. So in using this number, the calculation will produce an overestimate of emissions from structure fires since not all fires result in complete damage.

According to data released by the Bomberos of Costa Rica from 2009 to 2012, there was an average of 926 structure fires per year in Costa Rica. About 53% of these fires were residential. For this calculation, we will assume the carbon outputs of all types of buildings are about the same.

Given the number of fires per year and the average mass of carbon emissions per fire, we can calculate the mass of carbon emissions from structural fires per year in Costa Rica:

$$37{,}000\ kg\ CO_2\ x\ 926\ \frac{fires}{year} = 34{,}262{,}000\ \frac{kg\ CO_2}{year}\ due\ to\ fire$$

Next, we will determine the total mass of carbon emissions in Costa Rica per year. According to the World Bank, Costa Rica emits 1.7 metric tons of carbon dioxide per capita each year (The World Bank, 2010). According to the CIA World Factbook, the population of Costa Rica was 4,695,942 in July 2013. Using these data, we can calculate the total carbon dioxide emissions from Costa Rica per year:

$$\frac{1.7\ metric\ tons\ CO_2}{capita} x \frac{1000\ kg}{1\ ton} x\ 4{,}695{,}942\ people = 7{,}983{,}101{,}000\ \frac{kg\ CO_2}{year}$$

Now we can calculate the percentage of carbon dioxide emissions that are contributed by structure fires:

$$\frac{34{,}262{,}000\ {}^{kg\ CO_2}/_{year}}{7{,}983{,}101{,}000\ {}^{kg\ CO_2}/_{year}} x\ 100 = \ 0.43\%$$

From our calculations, we can estimate that structure fires attribute to 0.43% of Costa Rica's total carbon dioxide output. Again, this is most likely an over estimate since the New Zealand calculation assumes full damage.

This number will not be used in calculations to determine the carbon output of structure fires. This will be a reference point to check the accuracy of our models.

2.2.4 Existing Measures to Limit Emissions

Currently, there are no specific methods for reducing carbon emissions from structural fires. Green building methods do exist and have been widely popularized in recent years. Costa Rica has started its own green building initiative, called Requisites for Sustainable Building in the Tropics (RESET). This guideline, however, focuses on minimizing the energy required during fabrication of materials, construction of the building, and overall energy efficiency of the building (Instituto de Normas Tecnicas de Costa Rica, 2012). These green materials are held to fire resistance standards, but there is no attempt made to limit the amount of carbon released into the atmosphere in the event of a fire. This is quite possibly an overlooked detail of many green building plans, including RESET.

2.3 Emissions Standards and Regulations Worldwide

This section reviews environmental emissions standards internationally. By the end of this section, the reader should have a general understanding of the need for carbon emission regulations and attention to the environment.

2.3.1 Kyoto Protocol

In 1992, the forward-thinking countries of the United Nations recognized a need for change. They created the United Nations Framework Convention on Climate Change (UNFCCC) in Rio de Janeiro as a beginning to the fight against global warming. At the Berlin conference in 1995, the UNFCCC started to outline emissions targets. And in 1997 in Kyoto, the protocol was edited and officially adopted. It became known as Kyoto Protocol, and to date one hundred ninety-one countries have ratified the agreement, including Costa Rica.

Kyoto Protocol not only outlines emissions standards, but provides incentives. Participating parties are required to submit a report that outlines national systems for estimating emissions, a current greenhouse gas (GHG) inventory, land usage, and future plans for reducing emissions. Compliant parties, those that achieve the requirements of Kyoto Protocol, are awarded "mechanisms." If a country is compliant, it can participate in an emissions trade and credit program that allows it to sell unused emissions permits (United Nations Framework Convention on Climate Change, 2014). Countries may also participate in a clean development program that allows them to implement emissions reduction programs in non-member countries. Lastly, compliant countries may participate in a joint implementation program. It gives countries carbon emission reduction units in the form of credits.

Countries are required to report their GHG inventory, along with plans and goals for the future. Furthermore, the compliance committee of Kyoto Protocol makes recommendations to non-compliant countries. The UNFCCC continues to make amendments and improvements on the Protocol. Countries are making an effort to decrease their carbon emissions and becoming more aware of their contribution to global warming.

Despite a global effort to reduce emissions, few countries indicate the same dedication to the environment as Costa Rica. As mentioned previously, Costa Rica is the world leader in percentage of land dedicated to national parks and reservations. Furthermore, Costa Rica ranks 36th in countries with the lowest particulate concentrations (Esty & Porter, 2001). There is, however, a growing international effort to reduce emissions and stop the effects of global warming. Conferences, standards, and groundbreaking initiatives will allow the conversation on global warming to continue. As more countries commit to these standards and initiatives, the world will become closer to curbing global warming. Our project contributes to this goal as more and more sources of greenhouse gases are being accounted for.

2.4 Building Classifications

This section outlines definitions of residential, industrial, warehouse, and hospital buildings in accordance to the International Building Code (IBC). Each of the sub-sections describes building materials and contents. Based on materials, we can determine the largest contributors to emissions. Our focus will be appropriately narrowed to a select few materials with the highest volume and carbon emitting potential.

2.4.1 Residential Buildings

A residential building has the residential (R) occupancy classification and covers a full range of different housing situations. Residential buildings span from single-family homes to high-rise apartment buildings. We will use the most common classification, R-3, as a preliminary description of residential buildings. The IBC describes the R-3 classification as “[r]esidential occupancies where the occupants are primarily permanent in nature,” (International Code Council, 2011). This classification would generally fall under the Type V building classification. This building type is one that “… allows the use of any materials, including combustible materials, throughout the structure,” (International Code Council, 2011).

2.4.2 Industrial and Warehouse Buildings

The risks posed by major industrial or warehouse fires are relatively large depending on the purpose of the industrial building. Consequently, there are more stringent building standards for these building types. The International Building Code states, “[t]he most common use of Type IIB construction is in big box retail stores, warehouses, and industrial buildings.” We will use Type IIB to define our industrial and warehouse building model (International Code Council, 2011). These types of buildings are required to be constructed of “wholly noncombustible materials.” This means that the structure will not be the primary concern when considering fire emissions. Instead, the contents will require special attention.

The content of these buildings can vary greatly depending on their use. Industrial buildings can potentially house hazardous or highly flammable material. These factors can affect their individual carbon output. The International Building Code sets limits on hazardous and flammable materials in buildings Table 2.

Table 2: Hazardous Material Limits for Type IIB Structures (International Code Council, 2011)

Material	Class	Cubic feet	Liquid gallons (pounds)	Gas (cubic feet @ NTP)
Combustible liquid	II IIIA IIIB	N/A	120 330 13,200	N/A
Combustible fiber	Loose Baled	100 1,000	N/A	N/A
Flammable gas	Gaseous Liquefied	N/A	N/A (150)	1,000 N/A

If any additional hazardous material is present in a warehouse or industrial building, the building would assume the hazardous (H) group occupancy. While these two types of buildings share a construction classification, warehouse buildings have the storage (S) occupancy group and industrial buildings have the factory (F) occupancy group. The storage occupancy group has a maximum area of 1625.8 m^2 (17,500 ft^2). Such information is useful when making calculations about content (International Code Council, 2011).

2.4.3 Hospital Buildings

Hospital buildings fall under the institutional (I) occupancy group, where occupants are physically unable to leave without assistance. Most hospitals are built with the construction Type IA or Type IB to provide maximum fire protection (Keyes Life Safety, 2011). Construction Type IA has the strictest fire safety requirements, requiring non-combustible materials to build the structure. Most of the structure is required to resist fire for up to three hours. This means that the structure of the building is not considered in our carbon emissions measurements.

In comparison to the structure, the hospital contents will produce greater carbon output. A fire incident in a hospital structure with strict construction standards such as Type IA will not cause significant damage to the building. While the structure is not flammable there are many highly flammable gases and materials that are present in a hospital that cause an additional concern.

2.5 Existing Models for Measuring Emitted Gases

This section outlines an existing method for modeling gaseous emissions from structure fires. The reader should understand the factors and variables used in the emissions calculation. Later in the report, in the methodology, the reader can find more details on how to calculate these components and use them in the model.

2.5.1 Emissions Measurement Model

While working for the EPA, the Eastern Research Group prepared a model for emissions from structure fires. This model demonstrates the core principles that will be critical in developing a model for our own project. The basic structure for the model is given in equation (2) below.

$$E = f * F_L \tag{2}$$

Where E represents the amount of emissions, f represents the emissions factor, and F_L represents fuel loading. The emission factor is a constant, reflective of the quantity of a gas released for a given mass of material burned, as described by the fuel loading. Fuel loading depends on the amount of combustible material and how much is burned during a fire. Using California Air Resource Board (CARB) data, Wiedinmyer et al. find that most structures have 70 kg of combustible material per square meter (Wiedinmyer C. , 2005) (Environmental Protection Agency, 2001). The percentage of material burned is calculated using damage costs relative to the total cost of the property.

Current research has focused on emission surveys of San Francisco, California. The use of existing models can be demonstrated by looking at example data. The Eastern Research Group used average household data to estimate emissions across their survey area. Average residence size was found to be 125 m^2. Existing CARB data allowed the Eastern Research Group to estimate each residence had 14.2 metric tons of combustible material available combining building contents and the structure itself. Fire reports were used to estimate percent loss during each fire. Across the San Francisco area it was found that on average each fire consumed 7.3 percent of the available fuel. When the average fuel consumption was multiplied by specific emissions factors, estimates for different gas emissions could be calculated.

2.5.2 General Model Details

Emissions factors describe how many kilograms of gas are released per kilogram of materials burnt. The CARB and EPA have developed emissions factors for different gasses and materials burned (California Environmental Protection Agency: Air Resources Board, n.d.).

Fuel loading describes the amount of material available during a fire. The amount of material that is available for the fire includes the contents and structure of the building in question:

$$\mathbf{F_L} = (\mathbf{b_s} + \mathbf{b_c}) * \mathbf{d_o} \tag{3}$$

Where F_L represents fuel loading, $\mathrm{b_s}$ represents amount of structure material, b_c represents building contents, and d_o represents percentage damage. Structure material is the combustible material from the structure. Current methods use California Air Resource Board (CARB) estimates for combustible material per square meter for different types of buildings (Environmental Protection Agency, 2001). In order to find the combustible material of a single building, the estimated mass for combustible material per square meter is multiplied by the area of the building as seen in equation (4).

$$\mathbf{b_s}\ (\mathbf{kg}) = \left(\begin{matrix}\textbf{Combustible Structure}\\ \textbf{Mass kg/m}^2\end{matrix}\right) * \left(\begin{matrix}\textbf{area of}\\ \textbf{building m}^2\end{matrix}\right) \tag{4}$$

The combustible building contents were similarly calculated. There are several key differences that need to be accounted for. The combustible building contents estimates how much fuel is available for a fire from furniture and other building contents. The combustible contents (kg/m^3) are multiplied by volume of the building. The floor space distinguishes areas such as staircases and other areas not used as living space from the rest of the building. The combustible building contents is calculated:

$$\mathbf{b_c}\ (\mathbf{kg}) = \left(\begin{matrix}\textbf{Combustible Building}\\ \textbf{Contents kg/m}^3\end{matrix}\right) * \left(\begin{matrix}\textbf{volume of}\\ \textbf{building m}^3\end{matrix}\right) \tag{5}$$

Finally, Percent loss is used to estimate the amount of potential fuel actually consumed during a fire. Percent loss is calculated as a fraction of area affected by the fire over the total area of the building. Records on property damage are readily available through the Bomberos organization, see next section.

2.6 The Bomberos of Costa Rica

El Benemérito Cuerpo de Bomberos de Costa Rica, typically called the Bomberos, is a semi-privatized organization that provides fire protection, prevention and safety services for Costa

Rica. Since the organization is recently privatized, there are now smaller companies that also provide fire prevention and safety services. The Bomberos file a report for every emergency they respond to. These reports, along with any other statistical data kept by the Bomberos, are important to our research on the frequency and impact of structural fires.

2.7 SHPI Ingenieria

SHPI Ingenieria is a small, private consulting firm in Costa Rica. The company is named after a fire protection engineering document published by the Bomberos of Costa Rica, "Manual de Disposiciones Técnicas Generales sobre Seguridad Humana y Proteccion contra Incendios" (Manual of General Technical Regulations on Human Safety and Protection Against Fires). This document is also the main point of reference for consulting companies, contractors, and engineers on best construction practices to protect buildings against fires.

The owner of the company, Esteban Ramos, worked for the Bomberos of Costa Rica in the engineering department, where fires are investigated, for 23 years. In 2012, he left the Bomberos to start SHPI Ingenieria.

This project was created simply by the interest of SHPI Ingenieria. Currently, there are no methods for calculating structure fire gas emissions in Costa Rica. This project will help SHPI in its consultation services.

3 Methodology

The goal of this project is to develop five mathematical models to provide an estimate of carbon emissions from structure fires in Costa Rica. The first four models are building-specific for residences, hospitals, warehouses and industrial sites. The fifth model is an estimate of the total carbon emissions per year from structure fires using annual Costa Rican fire data and our building-specific models to provide our sponsor with data on the impact of structure fires on Costa Rica's carbon output on an annual basis.

Data from our models will be useful to the Estado de la Nación as a part of Costa Rica's carbon inventory. Lastly, we provide SHPI Ingenieria with a suggested validation process for our model to ensure accuracy for future use. The following objectives were achieved in order to complete the project.

Objective 1: Identify types and amounts of materials used to construct residences, hospitals, industrial buildings, and warehouses in Costa Rica.

Objective 2: Understand types and amounts of materials that make up the contents of residences, hospitals, industrial buildings, and warehouses in Costa Rica.

Objective 3: Develop a mathematical model for each of the four types of buildings that calculates carbon emissions from specific fire incidents by refining current models to be applicable to Costa Rica.

Objective 4: Evaluate the models and adjust them to best fit the needs of SHPI Ingenieria and the Bomberos.

Objective 5: Recommend a validation process to verify the accuracy of the models in the future.

3.1 Identifying Materials in Costa Rican Buildings

This section outlines the steps that were taken in order to determine building definitions for residential, industrial, warehouse, and hospital buildings. Initial building classifications were discussed in the background chapter of this report and acted as generalizations for each type of building. This chapter outlines the process that was taken to refine those building classifications. These classifications are determined by the building codes used in Costa Rica, the contents of a building, and the structure of a building.

3.1.1 Building Codes Used in Costa Rica

Costa Rica's building guidelines are outlined in a document known as "Manual de valores base unitarios por tipologia constructiva" from the Ministerio de Hacienda. This document outlines several building types based on their structural materials, such as walls, roofing, and flooring. Using this information, a classification of major building materials can be made.

As a start to creating building definitions from the IBC definitions, we read through this document and specified the materials found in each type of building.

3.1.2 Structure

The "Manual de valores base unitarios por tipolgia constructiva" provides a strong understanding of the construction materials in typical Costa Rican buildings. However, it is important to note that in practice, contractors and engineers may deviate from the guide. In addition, the guide provides no indication of the amounts of each material used to construct the building.

We visited the city of San Ramón, where a Mormon church was under construction. Here, we not only got to see first-hand the materials used in Costa Rica, but we also gained an understanding of the amount of materials used in buildings. We also interviewed the engineer and contractor on site to confirm information from the Ministerio de Hacienda on building classifications and building type. The amount of materials used in the buildings was also determined through our interviews. Please refer to Appendix A which provides the interview questions and surveys used.

In addition to a construction site visit and engineer and contractor interviews, fire incident reports from the Bomberos was another important source of information. These reports also gave an indication of the types of materials used in building construction.

3.1.3 Contents

The contents of buildings are also significant contributors to carbon emissions during a structure fire. In many cases, the materials used in the structures of buildings in Costa Rica are not combustible. Therefore, combustion of the contents may contribute more to the emissions of a structure fire than from combustion of the structural materials.

To understand the contents of residential buildings, we used several sources. First, real estate websites in Costa Rica provided a basic understanding of the major contents in a typical residence. Our methodology was selected based on a review of different fuel load surveying techniques in 2013 in the *Fire Safety Journal* (Zalok & Eduful, 2013). We were able to determine the number of beds, tables, chairs, etc. per square meter in a residence. To refine these data, we visited a warehouse of typical household items. There we were able to understand the types and sizes of furniture in a Costa Rican home.

In addition to visiting a warehouse with typical household items, we visited several general warehouses to obtain information on the contents of warehouses. The visits provided us with two important pieces of information: the size of Costa Rican warehouses and the type and density of materials in a warehouse.

To understand contents of hospitals and industrial sites, our research was completely reliant on the Bomberos fire incident reports. All hospital and industrial fires are investigated by the Bomberos in an extensive written report. The details from these reports provided data on the contents of industrial and hospital buildings.

3.2 Model Methodology

This section discusses our approach to developing models. Each building type was approached differently to attain the most accurate models. In addition, this section outlines our aggregate model approach, which will provide data on the contribution of structure fires to carbon emissions in Costa Rica on an annual basis.

3.2.1 Building Specific Models

Our models require two key sources of information in order to estimate carbon emissions from structure fires. The types of materials and amount of each material consumed during a fire must be established in order complete the emissions calculations. The models use a combination of user input and previously known data in their estimates. The residential model breaks down the calculation by the type and number of rooms affected by a fire. The hospital model follows a similar structure as it breaks down fires by room.

The weight and material composition of the contents of typical rooms are used to calculate the fuel available in a residence. Data from the Furniture Reuse Network is used to convert average contents to an average weight for each room. The Furniture Reuse Network (FRN) is a UK non-profit organization that distributes donated household items to those in need. The FRN publishes average weights of individual household items it regularly receives (FRN Average Weights).

There will be two versions of the residential model. The first will be a user friendly, streamlined version that requires minimal user input. The simple model will use existing weights and emissions factors for the emissions calculations. The second version will be a more technical version of the residential model. It will allow users to input custom fuel loading and emissions factors in order to produce a more accurate result. The technical version of the model ensures that the models will be usable in the future even if there is a change in common materials used in residences. From this point on the report will detail the technical discussion. When appropriate the assumptions made by the simple model will be detailed.

The industrial and warehouse models are structurally different due to variability seen in the contents at warehouses and industrial sites. Fuel loading in warehouses is a function of the density of warehouse shelving and the contents stored in the building. The model utilizes user input to determine the configuration of the shelves and the types of materials stored in the building.

Industrial sites see even greater variability. The variability of industrial sites prevents the model from utilizing any assumptions in its equations. The user describes the materials present from a list of known materials built into the industrial model. By describing the contents of the industrial site and the area of the site affected by the fire, the industrial model is able to calculate the carbon emissions from each industrial fire.

3.2.2 Aggregate Model

To estimate the annual emissions due to structure fires in Costa Rica, we used data from the Bomberos investigative reports from 2007 to 2013. Using these data, we defined the average fire in a residence by structure material, area, area burned, and number of rooms where necessary. We then inputted the data to find the amount of carbon emitted from an average house fire.

Annual data from the Bomberos provides the number of structure fires based on building type for 2013. By only using 2013 data, we made our calculation more specific, and therefore more useful for the yearly report for Estado de la Nación. We multiplied the number of residential fires by the amount of carbon dioxide released by the average residential fire to determine a total amount of carbon dioxide released by residential fires in 2013. However, the Bomberos respond to other fire incidents as well as residential fires. To compensate for this, we multiplied the total by a factor to account for the remaining percentage of buildings unaccounted for by our residential model. This allowed us to obtain and estimate of the carbon emissions due to structure fires from 2013.

3.3 Model Usability and Aesthetic Evaluation

This section outlines our approach to evaluating the usability of the four building-specific models. With several potential end users, it is important to ensure the model is easy to understand and use in practice. By the end of this section, the reader should understand our process for evaluating our models.

3.3.1 Model Users

The models were created with two principal users in mind. These users include employees of SHPI Ingenieria and members of the engineering staff of Benemérito Cuerpo de Bomberos de Costa Rica. The employees of SHPI Ingenieria will use the model in order to develop trends for buildings and building materials that would emit the most carbon in a fire, while also maintaining a carbon inventory from structure fires. With this knowledge they will be able to inform their clients on factors of structural fires that may impact Costa Rica’s plans for carbon neutrality. Members of the engineering staff of Benemérito Cuerpo de Bomberos de Costa Rica may also use our models and will be able to include the results from our models in their investigative reports for these four building types.

Although these two groups will most likely be the primary users of our models, our models were created with simplicity so other groups with less technical knowledge would be able to use them. Another organization that has showed interest in using the model is El Estado de la Nación. El Estado de la Nación would use the model to publish Costa Rica's current carbon emissions inventory in the annual report. A step by step process is provided in Appendix E, similar to a user's manual, to allow new users to feel comfortable using the model.

3.3.2 Model Feedback Sessions

After creating our first model, a feedback session allowed us to receive input from actual users of our model. A feedback session is similar to a focus group. It keeps participants on topic, but still allows them to speak freely and completely about behaviors, attitudes, and opinions (Gubrium & Holstein, 2001) regarding our model.

The feedback session was used to confirm the usefulness, convenience, and aesthetic quality of the model. The participants were given the opportunity to use the model, and provide feedback. Although the session followed an unstructured format, the group covered the following topics and questions to obtain the most information on how to improve the models:

1. How easy is it to enter data?
2. Was the amount of data you had to enter overwhelming?
3. How easy is it to understand the data you have to input?
4. Is the model visually appealing?
5. What improvements do you suggest?

The participants' identifying information during these studies remained anonymous.

3.4 Model Accuracy Evaluation

There are several different approaches to validate the accuracy of our models. We will recommend validation processes to our sponsor. In addition, we used two methods of validation to evaluate the accuracy of our model. The first validation test confirmed the linearity and the usable range of our model. Test cases of varying sizes were run through the models. The results were graphed in order to check for linearity. If a nonlinear region was found for either very small fires or very large fires we would have to limit the usable range for our model.

There was a second validation method available for the residential model. Unlike the hospital, industrial and warehouse models, existing research has been conducted to find emissions from residential structure fires. Our results were compared with reports from New Zealand, Norway, Finland, Denmark and Sweden.

3.5 Survey Instruments

This section provides an overview of survey and interview techniques that were used to obtain information not readily available. By the end of this section the reader will have a clear understanding what methods were chosen and why.

3.5.1 Worksheets

Worksheets were designed to provide the group with the desired information in the most direct way possible. These worksheets allow the group to stay on target as they speak with the representative. After the worksheets are completed the group is able to continue to speak with the representative in order to explore specific topics of interest beyond what the worksheet permits. The information obtained from these interviews was used to identify how the model could be customized for Costa Rica.

The group went to construction sites and warehouses to obtain information about buildings in Costa Rica. The personnel at these locations provided firsthand insight about construction techniques and building contents in Costa Rica. The worksheets are designed to answer two underlying questions:

1. How buildings are constructed in Costa Rica?
2. With what materials are buildings constructed in Costa Rica?

The participants' identifying information during these studies remained anonymous.

A detailed outline of the worksheets can be found in Appendix A.

4 Data Collection

This section reviews the results of our investigations and research, and our analysis of the results. By the end of this section, the reader should understand the data obtained from various investigations, and how the data contributed to assumptions made in making our models.

4.1 Creating Basic Building Definitions

This section discusses the results of our construction site and warehouse visits, as well as data collection from the Bomberos fire incident reports.

4.1.1 Information from Bomberos Reports

In order to determine information about structural fires in Costa Rica, we investigated two types of Bomberos reports: the general reports and investigative reports. This section describes each report, and the type of information we were able to obtain from each type.

General Report

In addition to fires, the Bomberos respond to several different types of emergency situations throughout the country. Hazardous material spills, car accidents, and rescues are all examples of emergencies the Bomberos respond to each year. For each incident, the Bomberos fill out a general report that details the following:

1. Date and time of response
2. Type of emergency (identified by a code)
3. Location (includes exact GPS location and a point of reference)
4. Number of firefighters that responded

The information in the Bomberos general reports is extremely limited. No numerical data is included. Since a report is filed for every type of emergency, specific numbers such as area burned or number of deaths are not relevant to each report. The only useful data from these reports is the emergency code, which not only describes an emergency as a structure fire, but also distinguishes the structure fire by type of building. These data were important in creating our aggregate model. Furthermore, since the reports currently do not include any numerical data, it may be is unrealistic to recommend that the Bomberos include data from our models in their general reports.

Investigative Report

Each year, of the approximately 1000 recorded fires in Costa Rica, about ten percent are investigated by the Bomberos engineering department. These 100 fires are investigated for a number of reasons:

1. All insured buildings that experience fire damage are investigated.

2. All fires that cause death are investigated.
3. Any fire with suspicion of arson or intent to harm is investigated.

Since all hospitals and industrial sites are insured, all fires in these buildings are investigated. Our research on these buildings, their structure, contents and origin of fire was heavily dependent on these reports.

The investigative Bomberos reports do not follow a highly structured format, however similar information can be found in all reports. Information on the building type and structure can be found, usually in tabular form, in these reports. Information on the structure is very detailed, and includes the material composition of external walls, internal walls, ceiling, roof, and floors. The reports also include information on response time, total area of the building, area burned, and area saved. After numerical data, the report begins to detail the investigation. If necessary, pictures and interviews are added. There is a description of internal and external damage. Lastly, the report describes the origin of the fire, the ignition source, and the classification: accidental, intentional or undetermined.

Figure 2, below, shows the breakdown of total fires in Costa Rica from 2007 to 2013. A total of 95 fires were examined from the Bomberos investigative fire incident reports: 58 residential fires, 24 industrial fires, 7 warehouse fires and 6 hospital fires. More than half of the fires (61%) that occurred during this seven year window were residential fires. Of the four building types, residential buildings experience the most fire incidents. Therefore our residential model will be used the most in practice. Industrial sites experience the second largest number fires, then warehouses followed by hospitals. Refer to Appendix D for breakdowns of the fires investigated for each year. These data are important to our aggregate model, and we will compare these percentages to the data from all fires per year in Costa Rica.

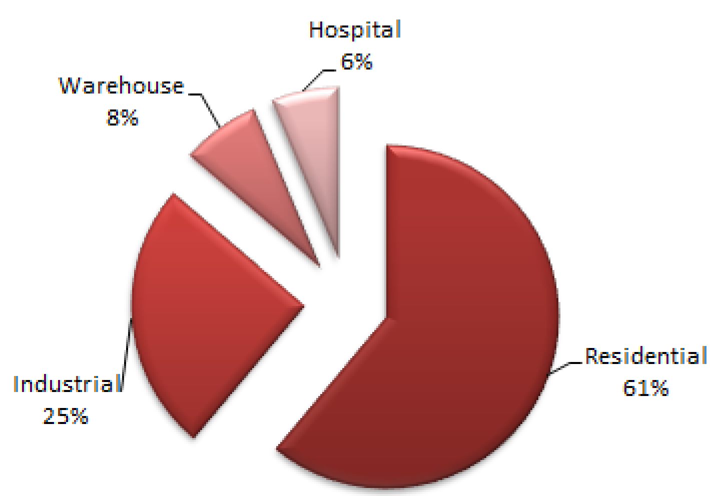

Figure 2: Breakdown of Total Fires Investigated in 2007 – 2013 by Building Type

After examining the data obtained from the investigative reports from the Bomberos the most common materials that the buildings are made of were noted. The data that were used when generating these assumptions can be found in Appendix D. Table 3 below displays the most commonly used material for specific structure types. For situations where there were two equally commonly used materials, the most combustible material was chosen as the most common material.

Ninety-five fires were examined when creating the table: 58 residential fires, 6 hospital fires, 24 industrial fires and 7 warehouse fires. The percentage shown to the right of the material displays the frequency that each material was used in the specific building type for the specified structural element.

Table 3: Most Used Construction Material by Building Type and Area

Structural Element	RESIDENTIAL		HOSPITAL		INDUSTRIAL		WAREHOUSE	
	Material	Frequency of Use	Material	Frequency of Use	Material	Frequency of Use	Material	Frequency of Use
External Walls	Concrete	86%	Concrete	100%	Concrete	88%	Concrete	57%
Internal Walls	Concrete	69%	Concrete	83%	Concrete	42%	Wood	14%
Ceiling	Gypsum	64%	Gypsum	50%	Gypsum	21%	-	-
Roofing	Galvanized Iron	95%	Galvanized Iron	67%	Galvanized Iron	100%	Galvanized Iron	100%
Floor	Ceramic	71%	Ceramic	50%	Concrete	96%	Concrete	57%

4.1.2 Results of Construction Site and Warehouse Visits

Construction sites were visited in order to determine the percentage of specific material for the specified structural element. Results showing building type compositions are shown in Appendix B. Three of the four building types were investigated: warehouses, industrial sites, and hospitals. The most common materials are concrete and iron, used for the walls and roofing respectively.

Warehouses were visited in order to determine common characteristics between warehouses in Costa Rica. The isle width between shelves and basic dimensions of a shelf used in warehouses were obtained. This information will be used as defaults for the warehouse model. Results from the warehouse visit can be found in Appendix C.

4.1.3 Real Estate Data Collection

For the residential model, twenty-two homes were surveyed by using images posted to real estate websites. Houses were surveyed over a range of prices in order to determine the typical number of rooms and average room contents. The price distribution can be seen in Figure 3.

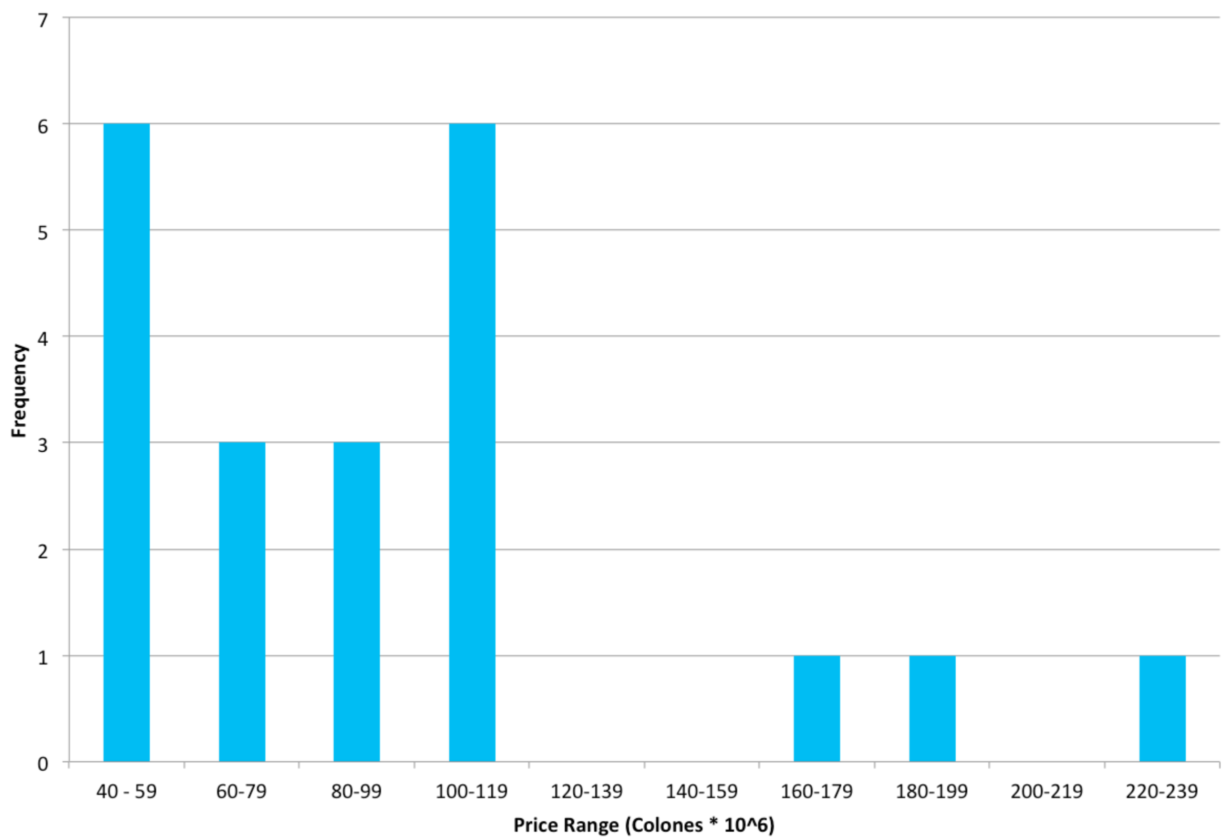

Figure 3: Price distribution of Houses Surveyed

Table 4 below lists the average values and standard deviations for different statistics gathered for the 22 homes.

Table 4: Survey Home Statistics

Statistic	Average	Standard Deviation
Area (m^2)	166	60
Cost (Colones)	95822619	46309074
Number of Bedrooms	3	.6
Number of Floors	1.5	.6
Number of Cars in Garage	2	1.2
Number of Bathrooms	2	.9
Number of Other Rooms	3	1.1

We used data from the residential contents survey and the Furniture Reuse Network to identify the contents of a typical Costa Rican kitchen, bedroom, bathroom, dining room, living space, and laundry room. Each room was assigned a fuel loading by mass (kg). The room contents and their weights can be found in Table 5.

Table 5: Fuel Loading for Residential Buildings by Room

	Item/Content	Average Weight (kg)	Fraction of weight of item per room
Kitchen	Refrigerator	45.5	0.33829
	Oven	50	0.371747
	Microwave	19	0.141264
	Cabinets	20	0.148699
	Total	**134.5**	
Bedroom	Bed	78.5	0.429102
	Air Conditioner	18.5	0.101126
	Television	15.94	0.087132
	Lamp/Light	5	0.027331
	Side table	14	0.076528
	Curtains	5	0.027331
	Wardrobe	46	0.251449
	Total	**182.94**	
Bathroom	Shower Wall	7	0.106061
	Toilet	30	0.454545
	Vanity Unit (w. sink)	29	0.439394
	Total	**66**	
Dining Room	Table	29	0.408451
	Chairs (6)	42	0.591549
	Total	**71**	
Living Space	Couch	42	0.306704
	Carpet	5	0.036512
	Lamp/Light	5	0.036512
	Television	15.94	0.116401
	Love seat	37	0.270191
	Chair	27	0.197167
	Curtains	5	0.036512
	Total	**136.94**	
Laundry Room	Washer	65	0.625
	Drier	39	0.375
	Total	**104**	

5 Model Development

This section discusses our building-specific approach to developing models. In the background, we introduced the two variables of emissions modeling: emissions factors and fuel loading. This section discusses how these variables are used in the final models, and how we determined values for each model.

5.1 Residential Model

The observations recorded during the contents survey are used to create default values for the models. In the simple residential model the average room weights are used in order to determine fuel loading. For the detailed model the user inputs individual pieces of furniture. The weights of the individual pieces are summed together in order to get a more customized and accurate weight of contents per room. The emissions factor for each item in the room is averaged to create a custom emissions factor for each room.

The model takes into account the number of rooms affected by the fire. The following data are input into the model by the user:

a_t = area total

a_b = area burned

n = number of rooms burned

d_o = percent damage

The typical room models are used to find the weight of the contents in each room. The area of each room is assumed to be the same. The percent damage per room is used to describe how much of the fuel is consumed by the fire. The total content weight of each room is multiplied by the damage factor in order to determine how much of the fuel was consumed by the fire. This process can be seen described in the equation (6) below.

$$b_c\ (kg) = (w_c * d_o) \quad (6)$$

b_c = building contents

w_c = weight of room contents

The variable w_c is known from residential survey as detailed in the methodology.

The emissions from each room are calculated by applying the appropriate emissions factor to the building contents from each room as seen in equation (7). The emissions from each room (e_r) are summed together to find the emissions from room contents (e_c).

$$e_r = (b_c)(f) \quad (7)$$

f = emissions factor for each room

e_r = emissions from room contents by room

e_c = total emissions from room contents = sum of e_r

In order to determine emissions from the structure, the user then inputs the materials used for the roof, ceiling, flooring, exterior and interior walls of the structure. The structural contributions to the fire are determined by adding together the weight per square meter of different types of combustible materials found within the roof, ceilings, floors, external walls and internal walls. The weight of various materials per square meter is gathered from a report from Penn State College of Agriculture written by Jon Carson (Carson, 1989). Table 16 detailing residential structural materials can be found in Appendix E.

The weights per square meter of different combustible materials are added together in order to determine the weight of combustible structure materials available per square meter. Due to lack of readily available and detailed information, the length of internal walls are based on the perimeter of the exterior walls. The lengths of the internal walls are assumed to be equal to the length of the external wall. The total mass of combustible structure materials is calculated by multiplying the combustible structure materials per square meter by the area burned.

$$b_s\ (kg) = (w_s)(a_b) \quad (8)$$

b_s = amount of structural material

a_b = area burned

w_s = sum of the weights of combustible structure components (i.e. wood from ceiling, wood from roofing, etc.)

The burned structure weight (b_s) is used to find the carbon emissions from the structure as seen in equation (9).

$$e_s = (b_s)(f) \quad (9)$$

e_s = emissions from structure

f = emissions factor

The emissions from residential structure fires are determined by summing e_s and e_c in order to determine E_{tot}. E_{tot} the final value reported by the residential model.

The building contents and structure together describe the fuel loading in the residential model. For the simple residential model the fuel loading was treated as wood, the emissions factor for wood is used to convert the fuel consumed by the fire to kilograms of carbon dioxide emitted. The contents for the simple model were assumed to be wood in order to minimize user input and streamline use. The above details for the residential model describe the technical version of the residential model.

A detailed example calculation can be found in Appendix H.

5.2 Hospital Model

The hospital model uses a structure similar to that of the residential model. The hospital model differs in that the structure does not contribute to carbon emissions during structure fires. During the review of Bomberos investigative reports six hospital structures were assessed. The most common building materials for different components of the hospital were found to be non-combustible. The details of our structural assessment can be seen in Table 6.

Table 6: Most Common Hospital Structural Materials

Type of Structure	HOSPITAL	
	Material	Frequency of Use
External Walls	Concrete	100%
Internal Walls	Concrete	83%
Ceiling	Gypsum	50%
Roofing	Galvanized Iron	67%
Floor	Ceramic	50%

The hospital model breaks down fires by individual rooms, each with a corresponding fuel loading. The user identifies how many patient rooms, general storage, records storage, or administrative offices were involved in a fire, and percentage damaged that describes the damage to each room. The weight of the contents of each room in a hospital fire is calculated by multiplying the fuel loading by the area of the room affected. The b_c per room are calculated using equation (6).

Data on fuel loading of hospital rooms was obtained from a survey done in Hackney Hospital (Green, 1977), and can be found in Table 7 below. Outside of patient care rooms, most of the contents found by the Hackney fuel survey were found to be wood or wood by-products. Within patient rooms, due to medical instrumentation and devices, the fuel loading is primarily plastic. The emissions factor for wood is used for all of the rooms except patient care rooms, in which the emission factor for polystyrene is used.

Table 7: Fuel Loading for Hospital Buildings by Room

Type of Room	Fuel loading (kg/m^2)
Patient room	8.4
General storage	46.5
Records storage	292.55
Office & administrative	27.3

The emissions from each room are calculated using equation (10). To obtain the total emissions from the building, the emissions from each individual room are summed together, using the equation (10):

$$E = \sum(b_c)(f) \tag{10}$$

A detailed example calculation can be found in Appendix H.

5.3 Industrial Model

The industrial model encompasses buildings with greatly varying characteristics. Due to a lack of consistent and detailed information in the Bomberos reports our report is not able to note any trends or patterns with industrial contents. The contractor and Bomberos reports were able to confirm that industrial structures are built similarly to warehouses. In order to determine fuel loading due to structure, the user enters the primary structural material. The fuel loading from the structure is calculated as seen in equation (11).

The user then selects the material that most closely corresponds to the combustible material contents in the building. Based on user input about the area affected by the fire and the density of the given material, the model is able to calculate the fuel loading due to contents. The final emissions calculation sums the emissions from each of the sources as seen in equation 11 below:

$$E = w_m * p_m * a_i * d_o * f \tag{11}$$

w_m = weight of material

p_m = percentage material by weight

a_i = area of industrial site

A detailed example calculation can be found in Appendix H.

5.4 Warehouse Model

The warehouse model follows a unique structure due to its differing fuel loading characteristics. In contrast to residences, the warehouse's structure does not contribute to carbon emissions. Through the Bomberos investigative reports the structure of 24 warehouses were analyzed. The most common materials for warehouses, by each structure component, are seen in Table 8. Note that many warehouses do not include ceilings or internal walls, thus the low percentage of material use in these structural elements.

Table 8: Most Common Warehouse Structure Materials

Type of Structure	WAREHOUSE	
	Material	**Frequency of Use**
External Walls	Concrete	88%
Internal Walls	Concrete	42%
Ceiling	Gypsum	21%
Roofing	Galvanized Iron	100%
Floor	Concrete	96%

The user inputs the dimensions of the warehouse, the distance between shelves and the height of the shelves. The model assumes a width of 1.8 meters for shelves, the width of two standard pallets. The standard size for a pallet in Costa Rica was confirmed after interviewing Federico Bolaños, who imports electrical and Internet cables, and personal observation during warehouse visits. Fuel loading is calculated using the number of shelves in a given area and their density. If a user does not know the distance between shelves, the model will default to a value of 1.8 meters, an average value gathered from warehouse visits. The model assumes that the shelves run the long dimension of the warehouse unless otherwise specified by the user. First, the number of shelves is calculated:

$$\mathbf{N_s} = \frac{\mathbf{w}}{(\mathbf{1.8m+D})} \tag{12}$$

Where N_S represents number of shelves, w represents the width of the warehouse, and D represents the distance between shelves. The total volume of material in the warehouse is calculated using the number of shelves in a warehouse and the number of levels to each shelf as seen in the following equation:

$$\mathbf{V} = (\mathbf{L} * \mathbf{1.8m} * \mathbf{1.2m} * \mathbf{N_L} * \mathbf{N_s}) \tag{13}$$

Where V represents total material volume, L represents shelf length, and N_L represents number of shelf levels. The shelf height of 1.2m was gathered during warehouse visits. If the number of shelf levels is not known due to fire damage the model treats assumes that the contents are stacked to the ceiling in order to estimate the fuel loading in the warehouse.

The user inputs information about the materials stored in the warehouse. The user can select household appliances, electronics, clothing, food supplies, wood, and storage materials. The emissions factor is generated for each subcategory by averaging the emissions factors and density of example items with in each category. An example, using the electronics subcategory is seen in Table 9. The density for each category is used to convert the material volume (V) to a weight, the fuel loading due to contents in the warehouse.

The appropriate emissions factor is applied to each portion of material that makes up the warehouse contents. The emissions factor for each type of storage was calculated using average emissions factors of items found in the type of warehouse specified. Table 9 below demonstrates the type of items found in the appliance subcategory and the calculations made for average emissions factor and density. The results for the other subcategories can be seen in Appendix E. Due to a limited time frame we were not able to fully populate the data tables for the warehouse model.

Table 9: Emissions Factor data for Electronics Subcategory

Primary Use	Items	Emissions Factors (kg CO_2/kg Fuel)	Density (kg/m^3)
Electronics/Appliances	TV	1.8	N/A
	Computer	2.5	N/A
	Fridge	2.22	N/A
	Dishwasher	1.62	N/A
	Microwave	2.5	N/A
	Gas Stove	2.5	N/A
	Electric Stove	2.5	N/A
	Washer	2.43	N/A
	Dryer	2.5	N/A
	Polycarbonate	N/A	1360
	Average	2.29	1360

6 Model Evaluation

This section describes the evaluation process for our models. We received feedback that helped to make our model look and perform as our sponsor expected. The model accuracy evaluation shows some results from our models in comparison to other studies.

6.1 Results of Model Usability and Aesthetic Evaluation

During our time in Costa Rica, our team was able to complete one feedback session with the staff of SHPI Ingenieria. During this session, our sponsor and other members of the company gave us suggestions for improving our model.

In terms of aesthetics, our sponsor asked for a image on the model that would display his company's logo, his name, and WPI's logo.

In terms of usability, our sponsor found the model easy to use and understand. In the feedback session, we determined that our industrial, warehouse, and hospital models functioned well enough for a final product. Instead of adjusting these models, we decided to recommend a process of refining these models in the future and focus on refining the residential model. The residential model was most important to our sponsor because over half of the structure fires in Costa Rica are residential.

It was also in the feedback session that we decided to create a second residential model that allowed for more specific data input. In our second residential model, the user can input percentages of material used in the structure. Our simple model assumes a 100% composition of the inputted material. In addition to material percentages, the user can input new materials into the detailed residential model. However, the user must also know the emissions factors of these new materials, so this model requires additional technical knowledge.

6.2 Results of Model Accuracy Evaluation

The residential model was compared against similar emissions estimates from structure fires in Sweden, Denmark, Finland and Norway (McNamee, 2009). The residential model was run three times. The first run aimed to produce low emissions. To do so, the model house was composed primarily of non-combustible materials. This low-emissions house is typical of many Costa Rican homes. The second run simulated the houses described in the European reports. Finally, the last run simulated the maximum potential output of a residential structure fire if the house was made entirely of wood. A comparison of the carbon dioxide emitted per square meter of each model can be seen in Table 10. Details of the structure characteristics of the three simulations can be seen in Table 11.

Table 10: Comparison of Emissions Model Results

Study Location	Sweden	Denmark	Finland	Norway	WPI (Low)	WPI (Med.)	WPI (High)
Kg CO_2 emitted per Square Meter	58.87	58.88	58.84	58.89	7.87	53.63	114.64

Table 11: Structure Characteristics for Validation Tests

	Low Test	Medium Test	High Test
Size (m^2)	160	160	160
External Walls	Concrete	Wood	Wood
Internal Walls	Concrete	Gypsum	Wood
Ceiling	Gypsum	Gypsum	Wood
Flooring	Ceramic	Wood	Wood
Roofing	Iron	Wood	Wood

In addition to the direct comparison, all the models were evaluated for linearity. Test cases were run for each model with fires, ten in total, ranging from 10 m^2 to 1000 m^2. All the models were found to be linear for the range tested. The results can be seen in Table 12 and Figures 4 and 5 below.

Table 12: Linearity Test Results

Size (m^2)	Residential Emissions (kg)	Hospital Emissions (kg)	Warehouse Emissions (kg)	Industrial Emissions (kg)
10	0.494	0.193	63.3	106
25	1.24	0.483	158	264
50	2.47	0.966	316	528
100	4.94	1.93	632	1056
200	9.89	3.86	1264	2112
300	14.8	5.8	1896	3168
400	19.8	7.73	2528	4224
500	24.7	9.66	3160	5280
750	37.1	14.5	4740	7920
1000	49.4	19.3	6320	10560

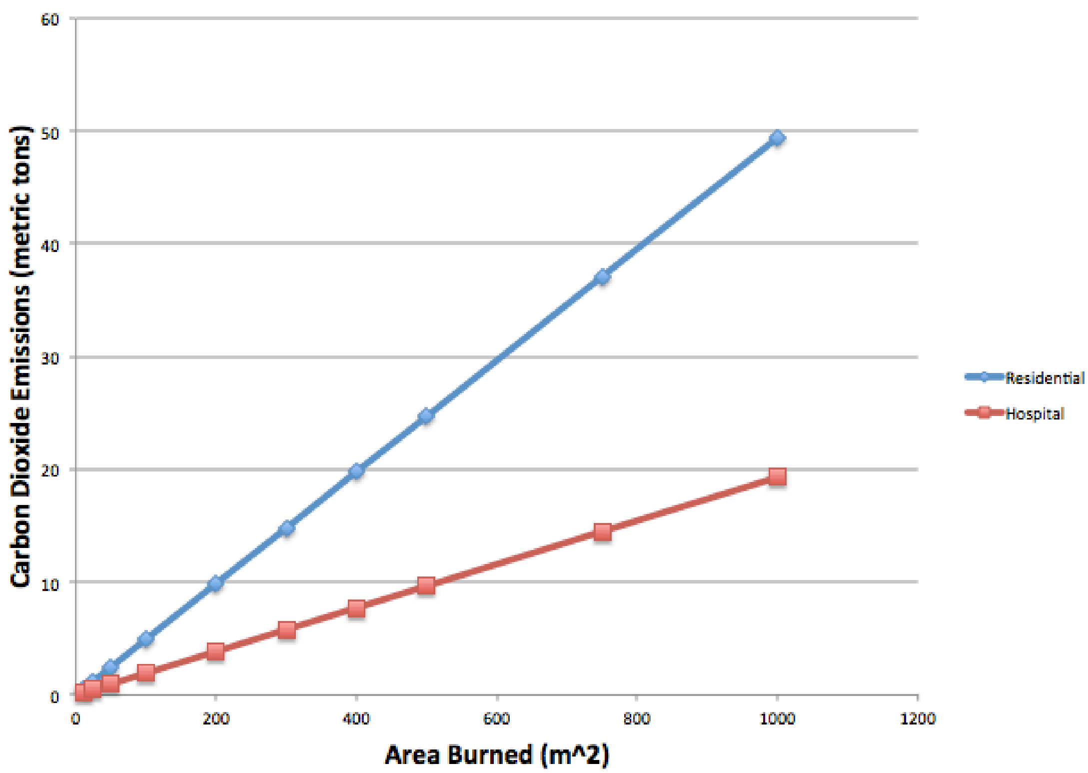

Figure 4: Linearity Test for Residential and Hospital Models

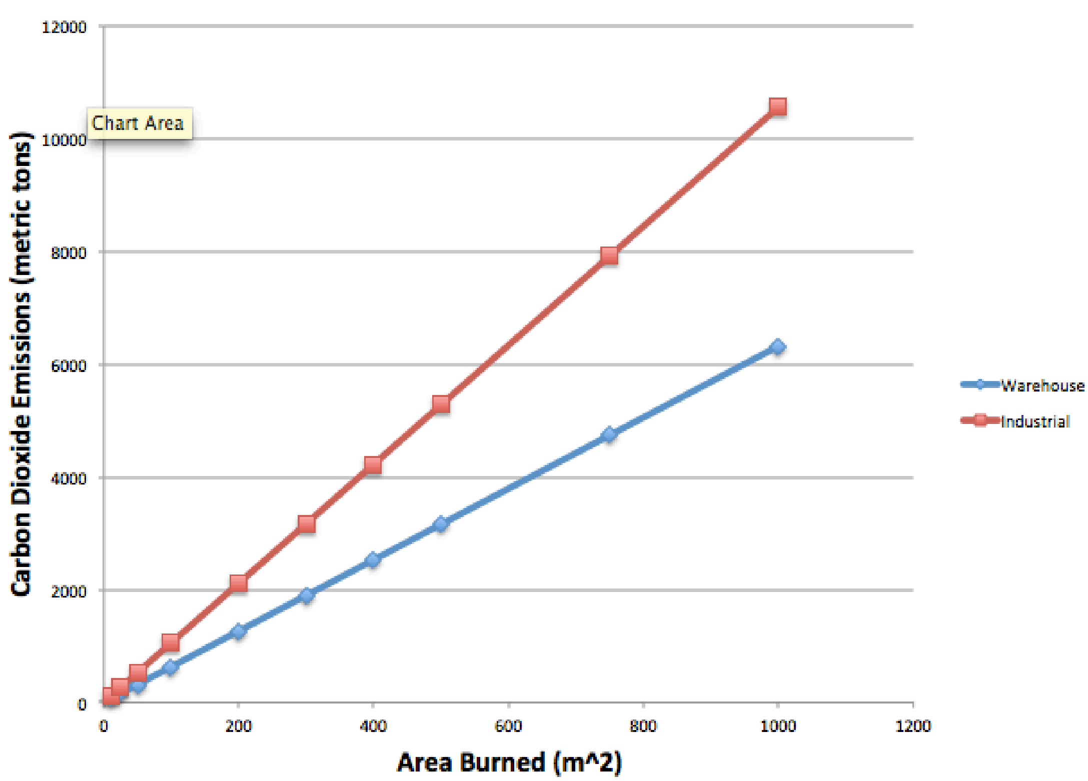

Figure 5: Linearity Test for Warehouse and Industrial Models

6.3 Aggregate Model

When we analyzed the Bomberos data of investigated fires from 2007 to 2013, we determined an average residential building fire in terms of area, area burned, and materials used in construction. The tables below outline the average building definition that was inputted into the model.

Table 13: Average Residential Input- Content Information

Input	Average
Area (m^2)	462
Number of Bedrooms	3
Number of Bathrooms	2
Number of Other Rooms	3

Table 14: Average Residential Input- Structure Information

	Material	Percentage
External Walls	Concrete	86%
Internal Walls	Concrete	69%
Ceiling	Gypsum	64%
Roofing	Galvanized Iron	95%
Floor	Ceramic	71%

Average total area: 462 m^2, Average area burned: 191 m^2

Average damage percentage: 20%

We inputted these average settings into our simple residential model to find the average amount of carbon emitted from each of these types of fires. Our model outputted the following results:

Table 15: Average Residential Fire Emissions

	Emissions (metric tons) per incident	# incidents in 2013	Total emissions (metric tons)
Residential	1.13	711	803.43

Residential fires only account for 65.7% of structure fires in Costa Rica in 2013. To account for the other 34.3% of fires, we multiplied this total by a factor of 1.343:

$$(803.43\ CO_2) * 1.343 = 1{,}076\ total\ metric\ tons\ CO_2$$

Thus, our aggregate model estimates 1,076 metric tons of carbon dioxide released by structure fires in Costa Rica from 2013. The same process can be followed in future years, using percentages and data specific to the year. Once the other specific models have more detail and are more reliable they can be used to make the aggregate model more accurate.

7 Conclusion

In 2007 the current president of Costa Rica announced a plan for carbon neutrality by 2021. The issue of carbon neutrality is important in the world today because carbon dioxide and other greenhouse gases are affecting the environment. Many of these emissions are produced by processes created by humans. The future of Costa Rica depends on our actions today.

Five mathematical models were created to provide an estimate of carbon emissions from structural fires in Costa Rica. Four of these models focus on specific buildings and the fifth model is an aggregate of the first four. The four buildings investigated are residential, industrial, warehouses, and hospitals. The models will provide SHPI Ingenieria with the ability to keep an inventory of the carbon emission from the four structural fires.

With an inventory of the carbon emissions from structure fires, Costa Rica comes one step closer to achieving their goal for carbon neutrality. A final list of recommendations was also provided to inform the users and future researchers on how to use, improve and validate the models. With a growing inventory of carbon emissions from structural fires, Costa Rica will be able to determine the factors that are hindering the goal of carbon neutrality.

The findings in this project are completely new and different for Costa Rica. We believe that our models and these calculations have the potential to contribute towards many studies in the future. They can be used to improve the construction of buildings in Costa Rica, to maintain a carbon inventory, and to study the health effects of carbon dioxide on firefighters.

8 Recommendations

In order to use the mathematical models effectively, recommendations are provided for using the models, as well as potential ways of improving the models. We believe that these models have the potential to play a significant role in Costa Rica's goal for carbon neutrality.

Our team has provided six recommendations. The first two recommendations involve the output of our models and how the information is useful to our sponsor and other organizations. The next recommendation focuses on how to use the models and obtain the best results. The last three recommendations address the improvement of our models. Our recommendations are as follows.

We recommend that SHPI Ingenieria, or government agencies such as Estado de la Nación, use the detailed residential models to keep a growing inventory of the carbon emissions from the residential structural fires examined and to improve building standards.

By keeping an inventory of the carbon emissions from structural fires, Costa Rica will be able to determine what building materials have the potential to emit the most carbon dioxide. We believe that this information is very useful as Costa Rica strives for carbon neutrality.

The model can be used to reduce the overall carbon emissions from residential structural fires. The model was designed to determine the carbon emissions of a building after a fire has occurred, but the model is not limited to usage in that order. The model can be used to determine the potential carbon output of a building if a fire were to occur. With the potential emissions known in addition to the current inventory of emissions, specific standards could be implemented in order to prohibit the construction of buildings that will emit more than a specified threshold of carbon emissions. By preventing the construction of buildings that emit a large amount of carbon, Costa Rica will have a stronger control on its carbon dioxide output.

We recommend that the carbon emissions for residential buildings be included in the Bomberos investigative reports.

The investigative reports that are completed by the Bomberos keep a record of numerical data for various fire incidents. By adding the amount of carbon dioxide released from residential structure fires to the reports, the Bomberos will have additional data to conduct studies and maintain statistics. In addition, the input data that the models require is already included in the investigative reports.

We recommend that the detailed residential model is only used for residential buildings. When calculating emissions from other building types, the models should be used with caution. We also recommend that the aggregate model is used only when calculating the yearly carbon emissions for Costa Rica.

We have not looked at all the possible structures in Costa Rica. This project only focused on four specified structure types: residential, industrial, warehouse, and hospital buildings. Extensive research has been conducted in order to properly define residential building types.

The detailed residential model was created with this definition as the base. If a building-specific model were used for a building other than it was created for, the output may be a misrepresentation. Therefore we recommend that users take caution when using the other three building specific models. A grocery store fire may be well represented by the warehouse model, but a school fire may not be well represented by any of our models.

The aggregate model uses the residential model to determine the carbon emissions from all types of structure fires and includes building types that are not defined by our models. However, this is only to obtain a number for the overall carbon emissions in Costa Rica.

We recommend SHPI Ingenieria and the users of our models follow a validation process for our models.

Future validation would involve detailed surveying of buildings contents. This would be necessary in both undamaged buildings and buildings that have experienced fire damage. By weighing the contents of different buildings, the building model's fuel-loading estimate could be compared to actual fuel loading. All building types would need to be surveyed in order to further validate each model. Future investigations could determine if any information would be needed to provide more accurate fuel loading estimates.

A detailed fuel loading survey of undamaged buildings would also provide information about the material makeup of the contents and structure of building. Such information is valuable as it will allow investigators to confirm the proper emissions factor is being used for the materials in the fire. A detailed survey after a fire could be used to confirm the accuracy of the investigators estimates of percentage of a room burned and the area affected by a fire. Validation for our models will involve confirming the accuracy of each input as much as possible.

We recommend that future research focus on improving the hospital, warehouse and industrial models.

There is limited existing research on emissions modeling for hospital, warehouse and industrial buildings. Improving those models will involve gathering detailed information. Current weaknesses in our model revolve around two key areas: the measurement of the contents and structure available as fuel during the fire and an accurate emissions factor for the materials involved in the fire. Continued improvements on these inputs will provide more accurate results from the models.

The fuel loading can be improved by doing a detailed survey of building contents and structure materials. A variety of hospitals, warehouses and industrial sites should be visited in order to weigh and survey contents in order to provide an accurate fuel loading data for each type of building in Costa Rica. A patient room in Costa Rica may look very different from a patient room in the studies that we used to make our model.

The emissions factors can be further improved to increase the accuracy of our models. Emissions factors should be found for the specific materials found in the fuel loading surveys. For example, our residential model uses emissions factors specific to the appliances and furniture in homes. Emissions factors for all the materials found in future surveys are likely not currently available. Additional lab-based tests are recommended for materials that do not have existing known emissions factors for carbon dioxide.

Improved information about fuel loading and emissions factors will allow the models to produce a value with higher accuracy. There will be different rooms and areas of buildings with widely varying fuel loading and emissions factors. As the quality of data going into the models improves, the results will become more accurate.

We recommend that future research focus on other greenhouse gases that Costa Rica emits into the environment from structure fires.

While this project focused on the carbon emissions from four different structure fires, we believe that more research should be conducted in order to determine the effects of other gases produced in structure fires. As Costa Rica becomes closer to achieving their goal for carbon neutrality, it also needs to also consider the environmental impact of the other gases. Once all the factors are determined for the other gases, we recommend that the models be better refined to account for all other gases emitted from structure fires.

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Appendix A: Survey Instruments

Construction Site Visit

Construction Site Visit Script

I am part of a group that is studying emissions from structure fires. We need information about construction materials, and we would like to speak with you on the following topics:

1. What materials do you use to build a building?
2. Where in the buildings do you use these materials?

I will be speaking with you today, but my partners will let me know if they think of any other possible questions. They do not speak Spanish very well, and will therefore speak to me in English. We have prepared worksheets for you to fill out to assist us with obtaining the desired information.

1. What are the main materials used in constructing:
    a. Residential Buildings?
    b. Industrial Buildings?
    c. Warehouses?
    d. Hospitals?
2. What are the proportions of the materials that you use?
3. Can you tell us any other information about the construction of these buildings that might affect a structural fire?

Construction Site Visit Worksheet

Type of building: **Residential**
Date: ______________________________________

Type		Material		Location		Percentage of Location Specified
Concrete		Cement		Structure		
		Cement		Walls		
		Brick		Walls		
		Ceramic Tile		Floor		
		Ceramic Tile		Walls		
		Wood (Cedar)		Door		
		Aluminum		Window Frame (Lining)		
		Plyrock		Walls		
		Gypsum		Walls		
		Paint		Walls		
		Iron		Roofing		
		PVC		Roofing		
		Polycarbonate		Structure		
		Glass		Windows		
		Tar		Roofing		
		Porcelain		Floor		

Type		Material		Location		Percentage of Location Specified
Wood		Concrete		Structure		
		Concrete		Walls		
		Wood (Cedar)		Structure		
		Wood (Cedar)		Walls		
		Wood (Cedar)		Door		
		Wood (Cedar)		Windows		
		Iron		Roofing		
		Tiles		Floor		
		PVC		Ceiling		
		Clay Tile		Floor		
		Ceramic Tile		Floor		

Type of building: **Hospital**

Date: ___________________________________

Type		Material		Location		Percentage of Location Specified
Hospitals		Concrete		Structure		
		Concrete		Walls		
		Gypsum		Walls		
		Plyrock		Walls		
		Iron		Roofing		
		PVC		Roofing		
		Glass		Ceiling		
		Aluminum		Ceiling		
		Ceramic Tile		Floor		
		Polycarbonates		Roofing		
		Porcelain		Floor		
		Epoxy		Floor		

Type of building: **Industrial**

Date: ___________________________________

Type		Material		Location		Percentage of Location Specified
Industrial		Concrete		Structure		
		Concrete		Walls		
		Iron		Walls		
		Iron		Roofing		
		Polycarbonate		Roofing		
		Ceramic Tile		Floor		
		PVC		Roofing		

Type of building: **Warehouse**

Date: ___________________________________

Type		Material		Location		Percentage of Location Specified
Warehouse		Concrete		Structure		
		Concrete		Walls		
		Iron		Roofing		

Type of building: ___________________________
Date: _____________________________________

Type		Material		Location		Percentage of Location Specified

Warehouse Visits

Warehouse Visit Script

I am part of a group that is studying emissions from structure fires. We need information about typical building contents, and we would like to speak with you on the following topics:

1. Is there an available inventory?
2. Is there a maximum weight on shelves?

We have prepared worksheets for you to fill out to assist us with obtaining the desired information. I will be speaking with you today, but my partners will let me know if they think of any other possible questions. They do not speak Spanish very well, and will therefore speak to me in English.

Warehouse Visit Worksheet

Size		Material	
Dimension		**Structure**	
Shelf Height		Name	Prevalence
Aisle Width			
# Aisles			
# Shelves			
		Content	
		Name	Prevalence (#, size, # of aisles, etc.)

Appendix B: Construction Site Visit Results

The group visited a construction site in San Ramon, Costa Rica as part of the research on types and amount of materials used in the construction of buildings. The on-site engineer, who has worked on hospital, industrial and warehouse construction sites, filled out the worksheets and answered any remaining questions that the group had. The results from the visit are displayed below.

Date: April 2, 2014

Type of building: **Hospital**

Type	Material	Location	Percentage of Location Specified
Hospitals	Concrete	Structure	**100%**
	Concrete	Ex. Walls	**50%**
	Gypsum	In. Walls	**50%**
	Iron	Roofing	**100%**
	Glass	Walls	**20%**
	Mineral Fiber	Ceiling	**100%**
	Ceramic Tile	Floor	**100%**
	Porcelain	Floor	**100%**
	Epoxy	Floor	**2%**

Type of building: **Industrial**

Type	Material	Location	Percentage of Location Specified
Industrial	Concrete	Structure	**100%**
	Concrete	Walls	**70%**
	Iron	Walls	**30%**
	Iron	Roofing	**100%**
	Concrete	Floor	**100%**

Type of building: **Warehouses**

Type	Material	Location	Percentage of Location Specified
Warehouses	Concrete	Structure	**90% - 100%**
	Concrete	Walls	**90%**
	Iron	Roofing	**100%**

Appendix C: Warehouse Visit Results

Below are the results of our warehouse visits. When at the warehouse, we decided not to analyze the structure because we received sufficient information from the construction site visit. We also decided to only consider standard shelf width, as all other data would be variables in the model that the user can input (dimension, shelf height, etc.).

Size		**Material**	
Dimension	X	**Structure**	
Shelf Height	X	Name	Prevalence
Aisle Width	90 cm x 2	X	X
# Aisles	X	X	X
# Shelves	X	X	X
		Content	
		Name	Prevalence (#, size, # of aisles, etc.)
		Furniture/Household items	Most warehouses we visited had a large portion dedicated to these materials (80%)
		Construction materials	These types of warehouses exist, but are not as prevalent
		Clothing	Also a prevalent material in warehouses

Appendix D: Bomberos Case Study Data

The figures below displays graphs depicting data obtained from the Bomberos investigative reports as mentioned in chapter 0.

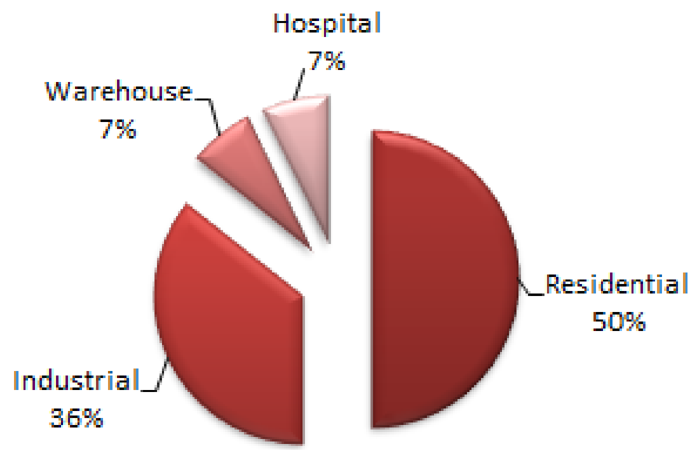


Figure 6: Breakdown of Fires Investigated in 2007 by building type (14 total fires)

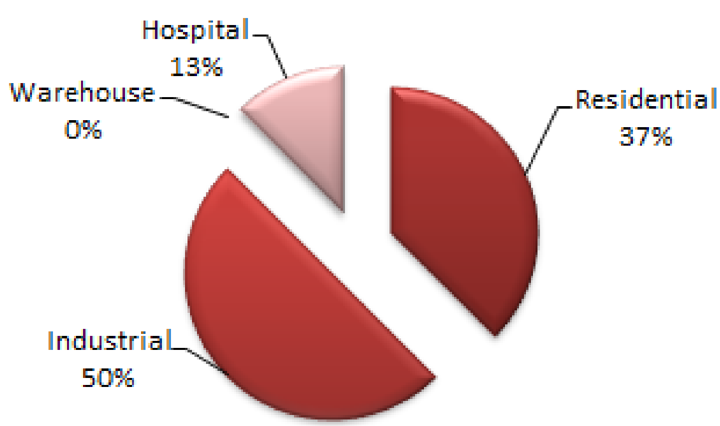


Figure 7: Breakdown of Fires Investigated in 2008 by building type (16 total fires)

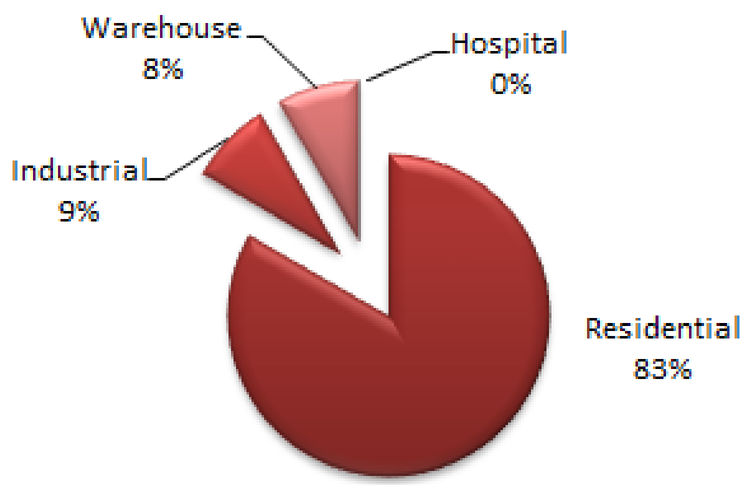


Figure 8: Breakdown of Fires Investigated in 2009 by building type (12 total fires)

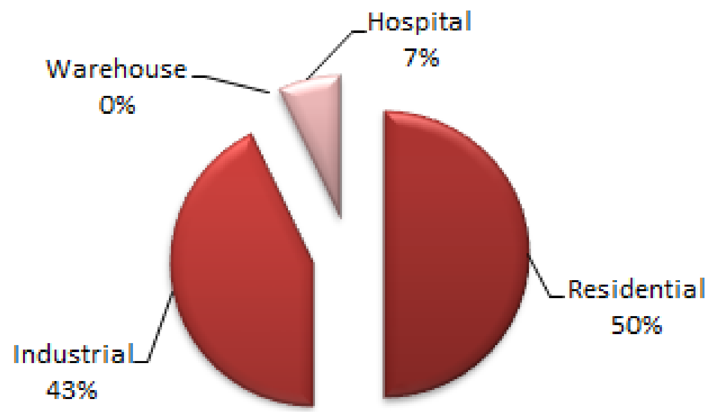


Figure 9: Breakdown of Fires Investigated in 2010 by building type (14 total fires)

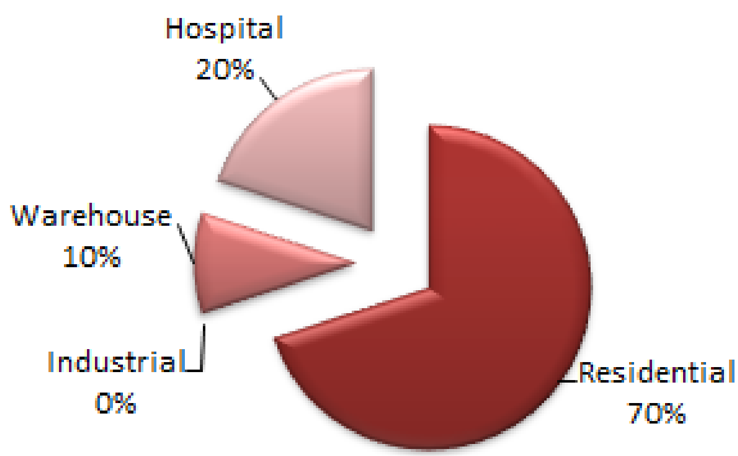


Figure 10: Breakdown of Fires Investigated in 2011 by building type (10 total fires)

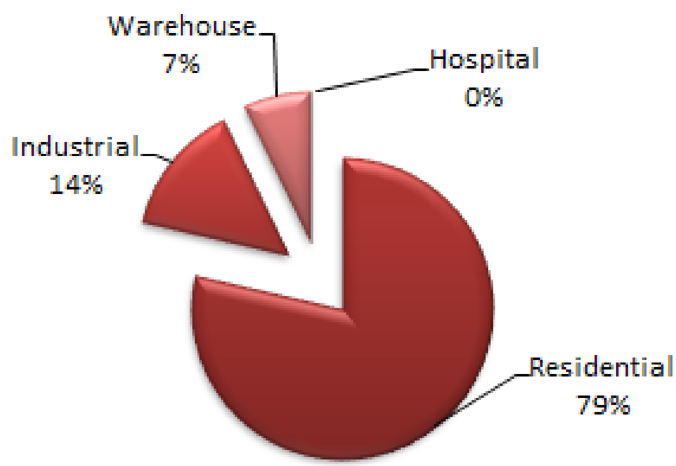


Figure 11: Breakdown of Fires Investigated in 2012 by building type (14 total fires)

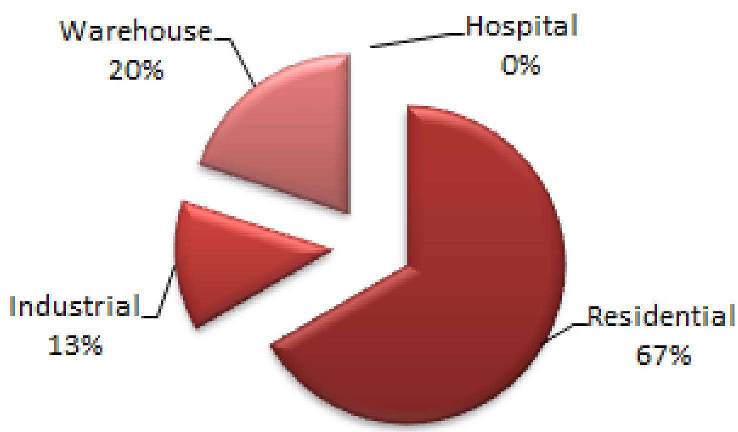


Figure 12: Breakdown of Fires Investigated in 2013 by building type (15 total fires)

The following figures were used to determine the most common materials used in the four types of structures, as mention in chapter 0.

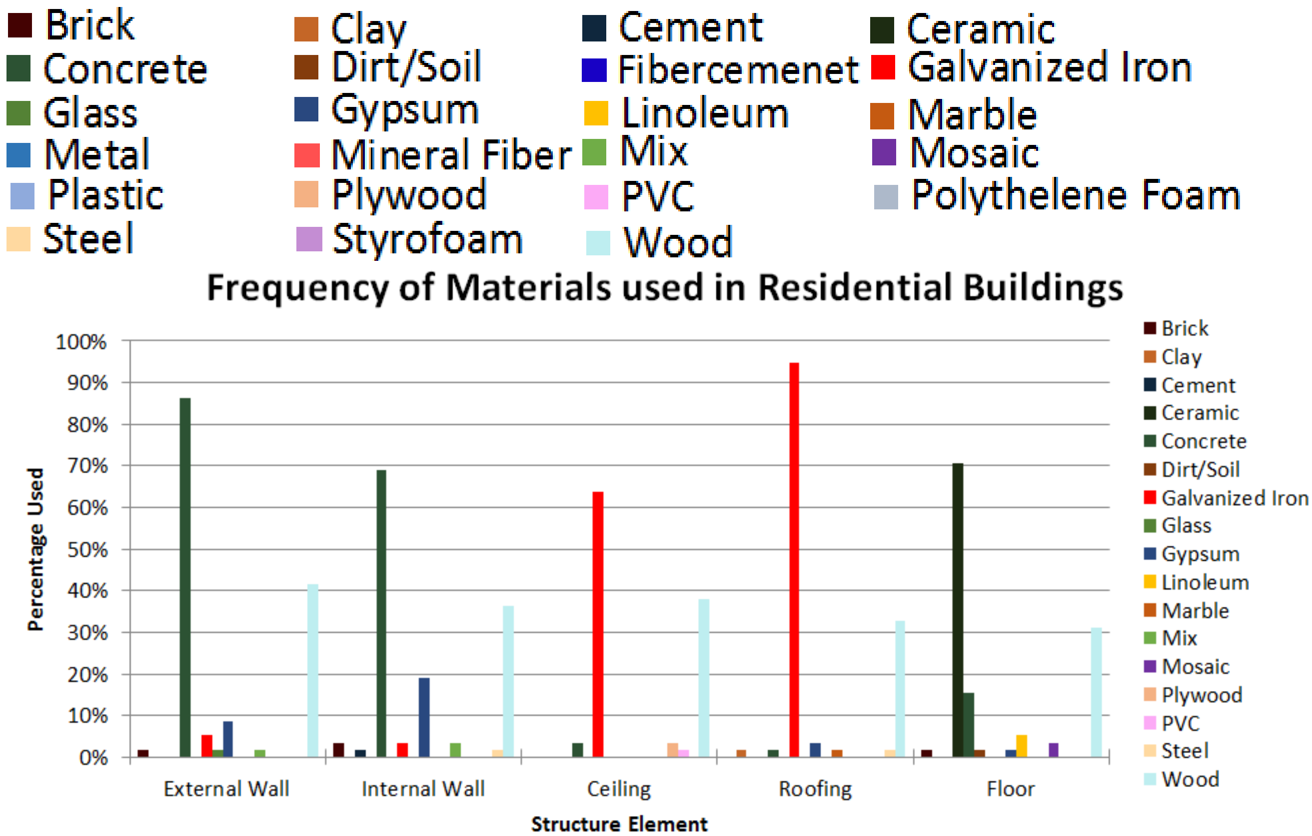


Figure 13: Frequency of Materials used in Residential Buildings

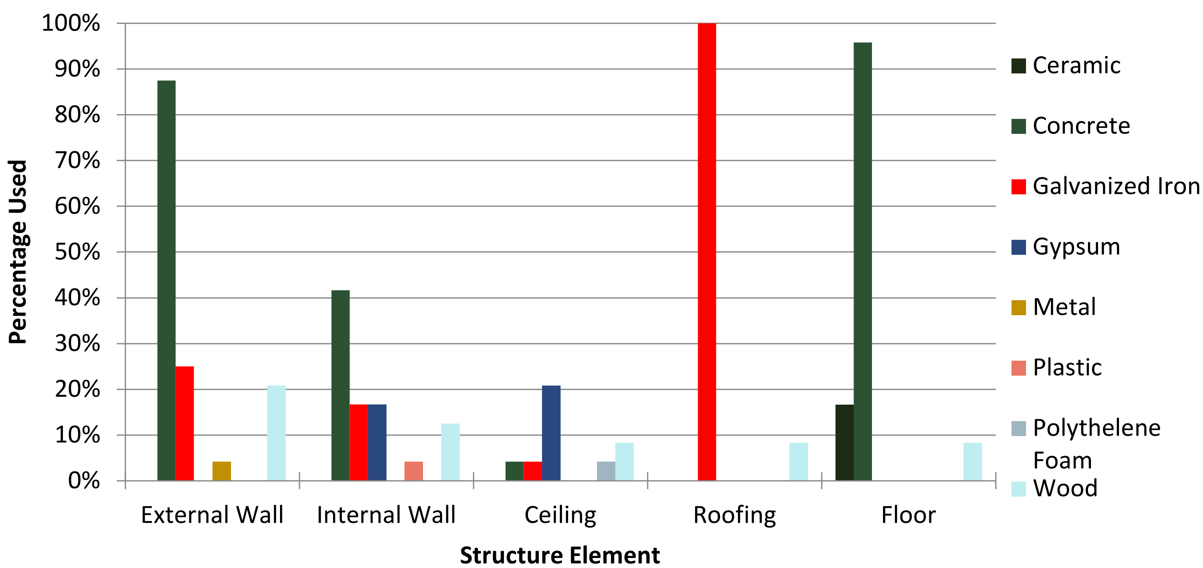


Figure 14: Frequency of Materials used in Industrial Buildings

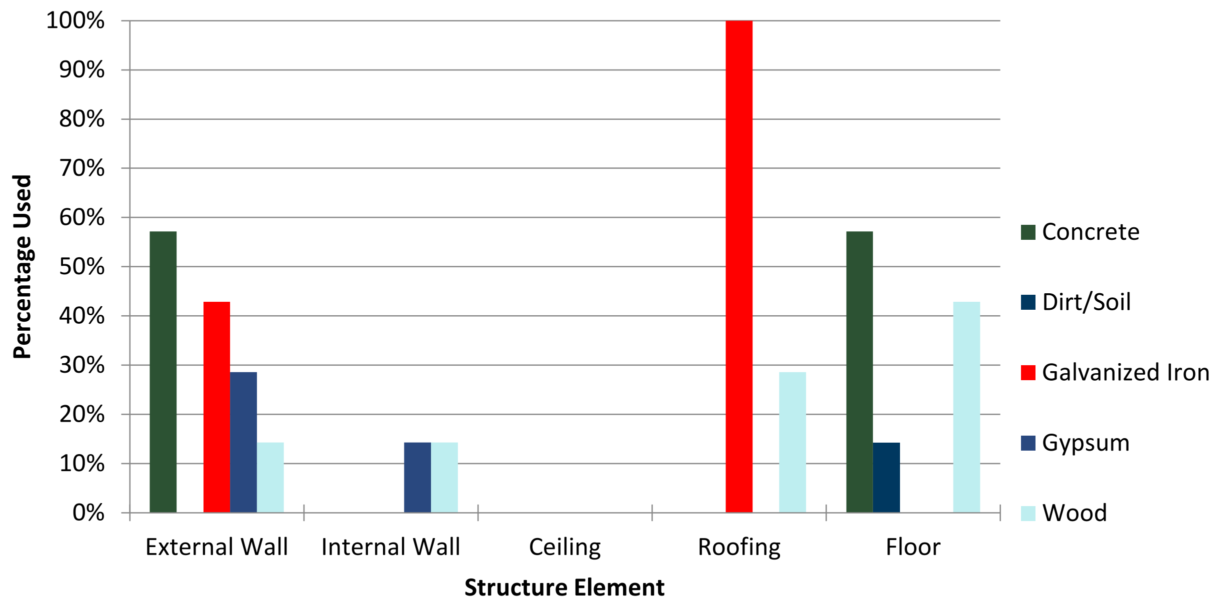


Figure 15: Frequency of Materials used in Warehouses

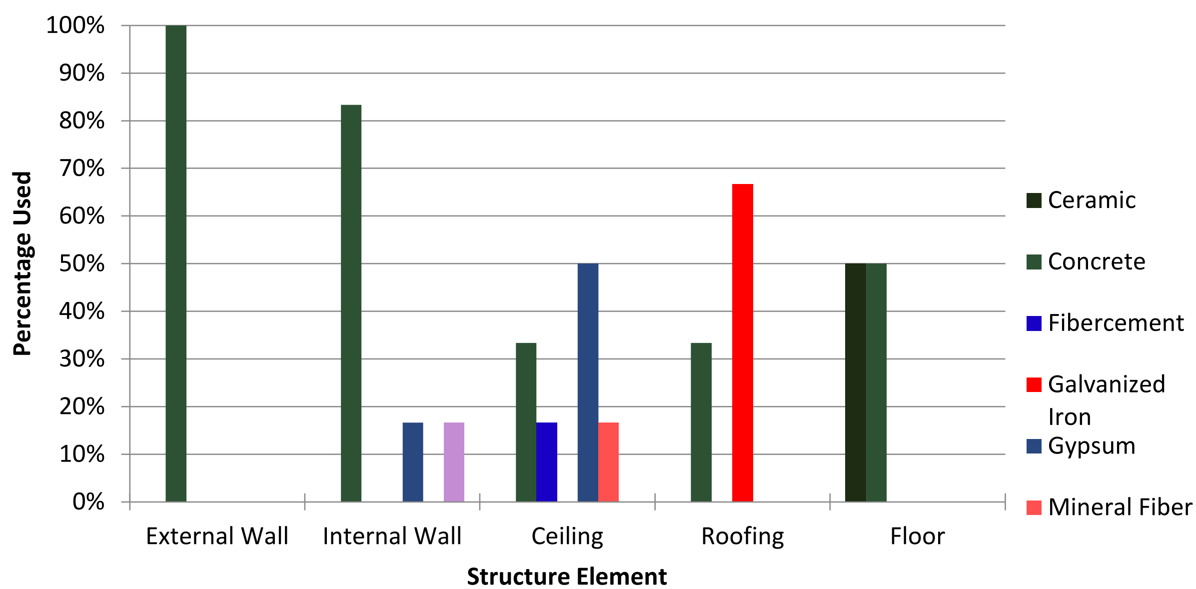


Figure 16: Frequency of Materials used in Hospitals

Appendix E: Content and Structure Material Characteristics

Table 16 below specifies the weights used in order to determine fuel loading from residential structures. This table is referenced in section 5.1.

Table 16: Structural Material Weights

Building Material	Unit Weight (kg/m)
Aluminum	835
Cast Iron	2200
Cement	459
Concrete	732
Gypsum (5/8)	12.7
Mineral Fiber (Fiberglass)	9.76
Wood 2X4	18.7
Wood 2X6	29.3
Wood 2X8	12.9
Plywood (1/4)	3.47
Plywood (5/8)	8.64
Steel Roofing	3.91
Aluminum Roofing	1.46

Table 17 below specifies information about each subcategory for the warehouse model. Due to a limited time frame we were not able to fully populate the data tables for the warehouse model. This table is cited in section 5.4.

Table 17: Full Emissions Factor data for Warehouses

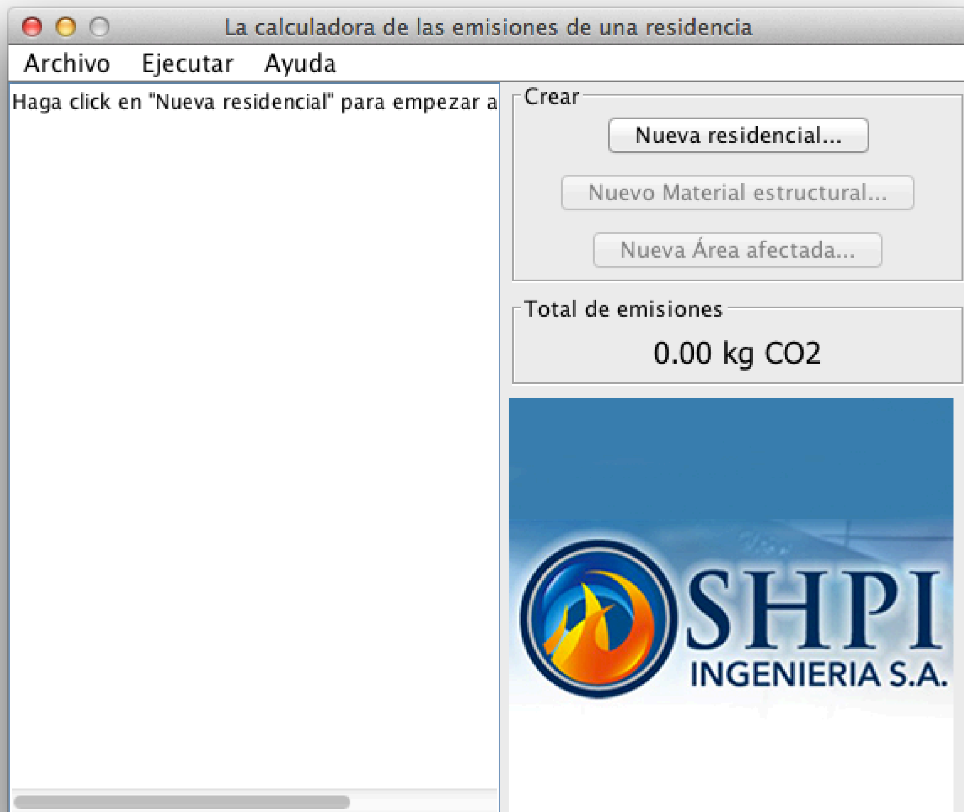
Primary Use	Items	Emissions Factors (kg CO_2/kg Fuel)	Density (kg/m^3)
Electronics/Appliances	TV	1.8	N/A
	Computer	2.5	N/A
	Fridge	2.22	N/A
	Dishwasher	1.62	N/A
	Microwave	2.5	N/A
	Gas Stove	2.5	N/A
	Electric Stove	2.5	N/A
	Washer	2.43	N/A

	Dryer	2.5	N/A
	Polycarbonate	N/A	1360
	Average	2.29	1360
Furniture	Upholstered Chair	1.6	N/A
	Sofa	1.6	N/A
	Entertainment Unit	2.5	N/A
	Coffee Table	1.33	N/A
	Bookcase	0.29	N/A
	Loveseat	1.6	N/A
	Ottoman	1.6	N/A
	Desk	1.33	N/A
	Futon	1.6	N/A
	Bed	1.6	N/A
	Wardrobe	1.33	N/A
	Chairs	1.9	N/A
	Table	1.33	N/A
	Cabinet	1.33	N/A
	Wood	1.33	630
	Average	1.50	630
Clothing	Clothes	2.2	N/A
	Cotton Fiber	2.2	1540
	Average	2.2	1540
			N/A
Construction Materials	Wood	1.27	630
	Average	1.27	630
Food	Beef	1.33	N/A
	Rice	N/A	870
	Result	1.33	870
Mixed Purpose	Average	1.72	1100
	Result	1.72	1100

Appendix F: Using Models

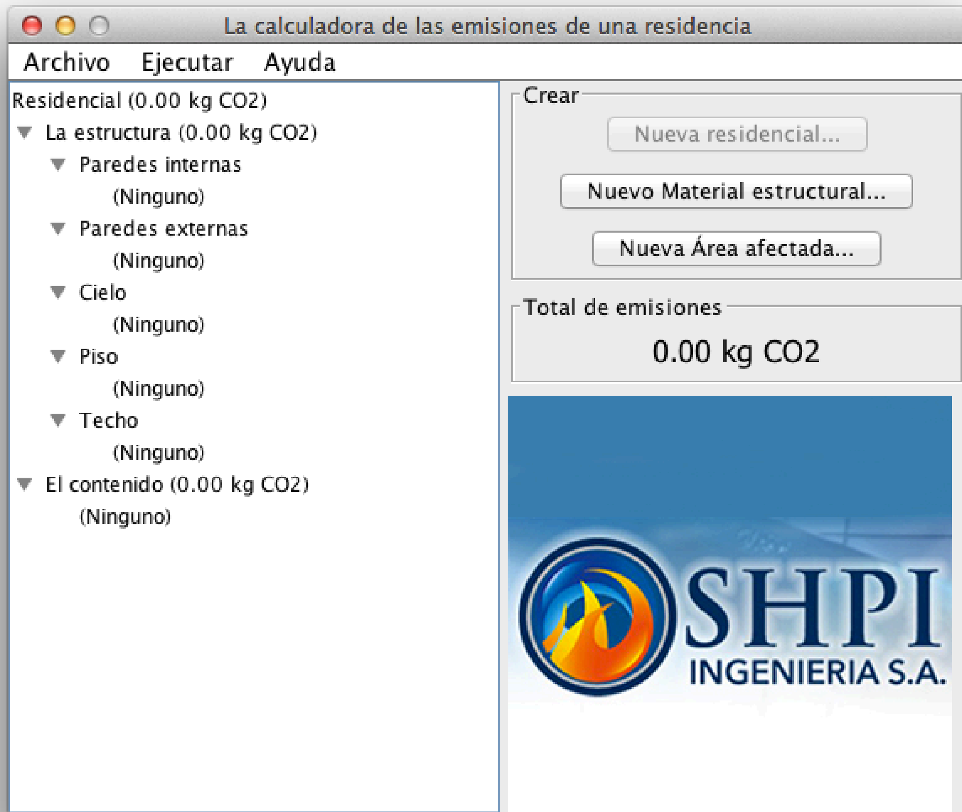
Detailed Residential Model

Step 1: When the user opens the detailed residential model they are presented with the following screen.

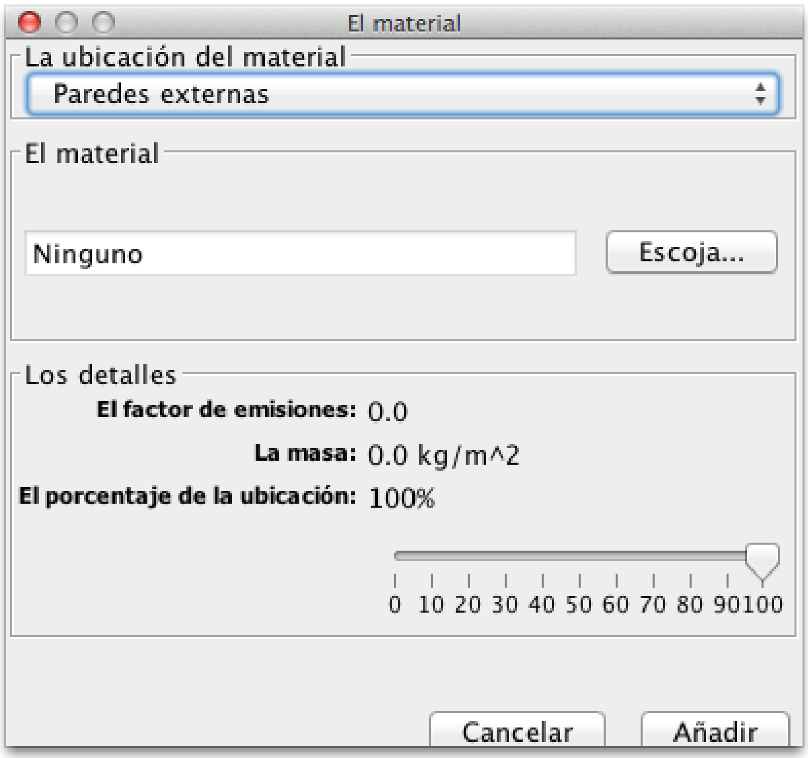


Step 2: The user begins the process by clicking *New Residential Building*. Once they click the *New Residential Building* button a window opens asking the user to specify the total size of the residence and the area burned by the fire.

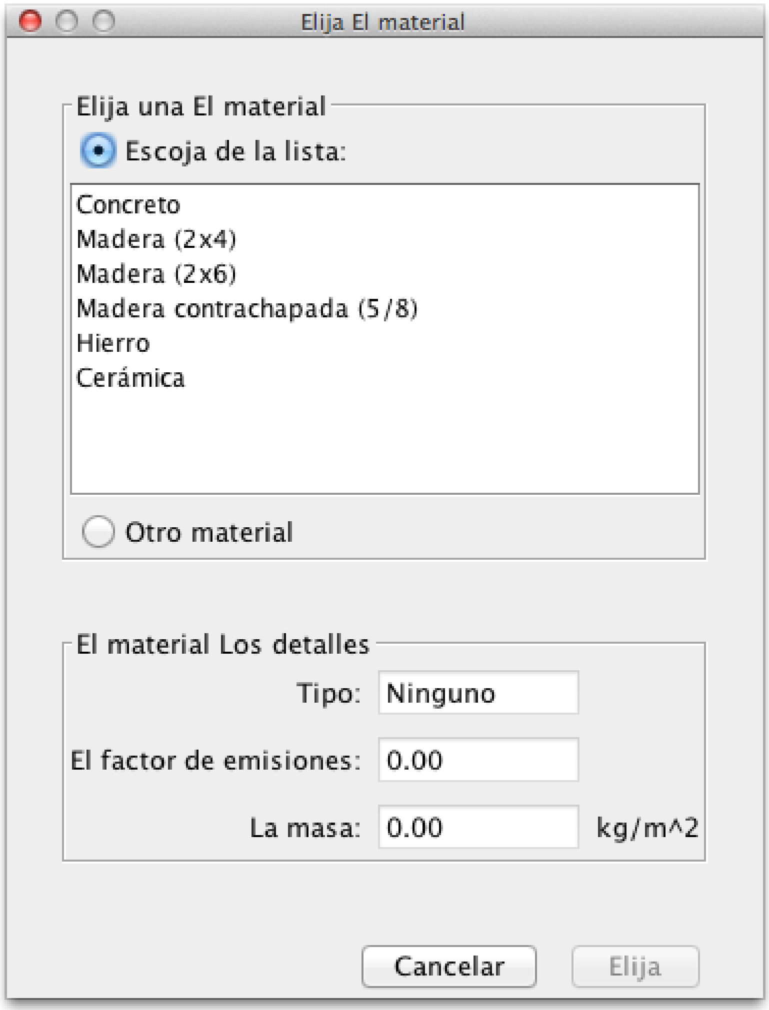
Step 3: Once the size of the building is entered a skeleton structure of the building is produced by the model as seen in the left hand pane of the program. The user now proceeds by entering information about the structure of the residence by clicking the *New Structural Material* button.



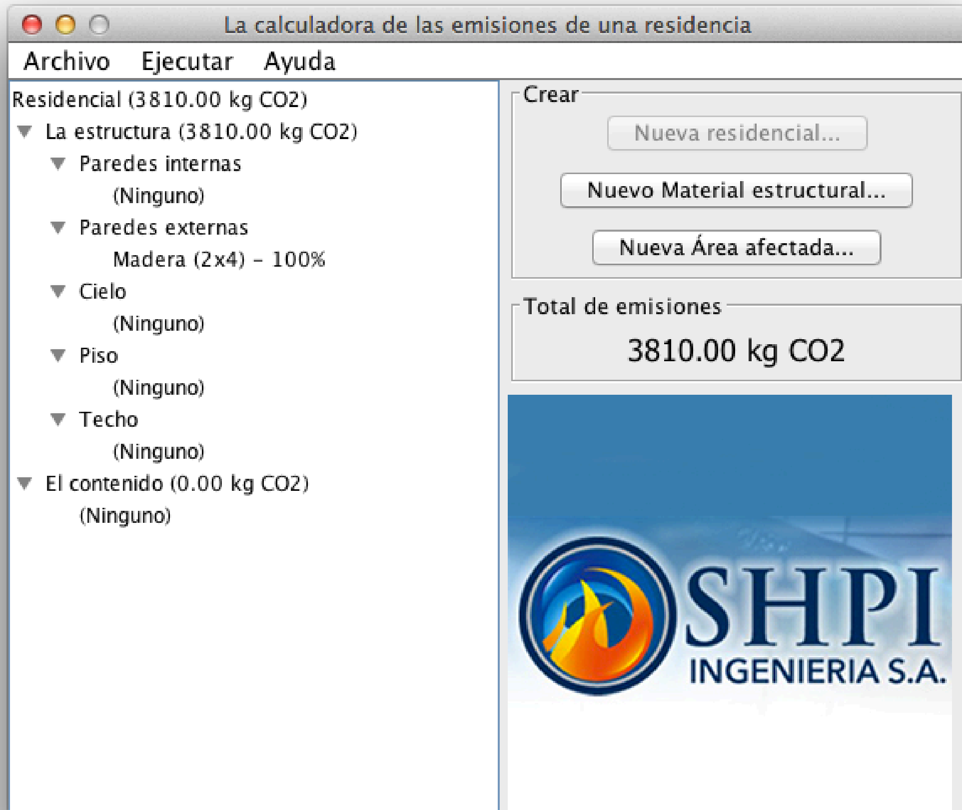
Step 4: Once the user clicks the *New Structural Material* button a window will open asking the user to enter specifics about the building materials. The user can choose where the material is located (External and internal walls, ceilings, etc.) and what percentage of the building component that material is used. For instance an external wall can be 50% wood and 50% concrete. The model will prevent the user from entering more than 100%. Each type of material is entered individually for each building component. The user chooses what material to use by clicking the *Choose* button in the material section.



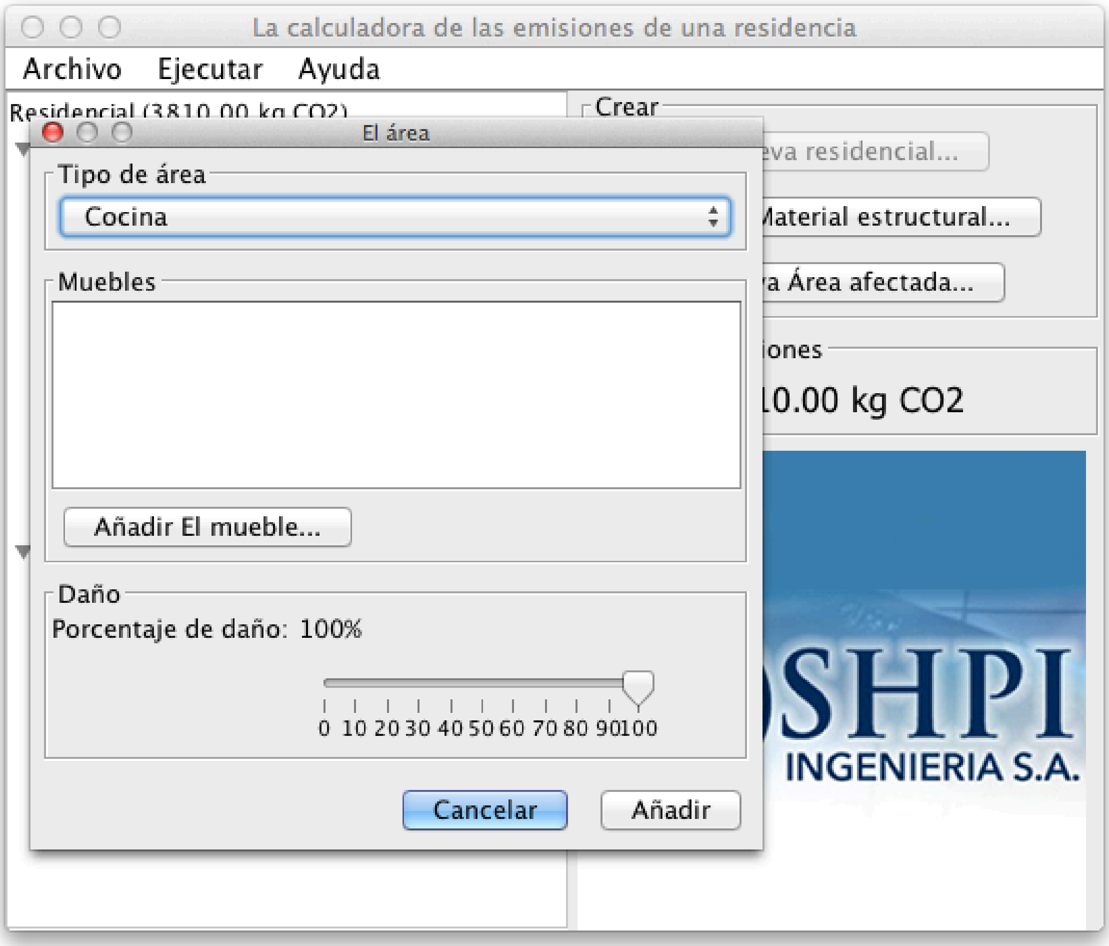
Step 5: After clicking the *Choose* button the user will be given options of known materials that can be used for the residential structure. If the material needed is not listed under the existing materials the user can input a custom material by selecting *other material*. Once a user inputs a custom material it will be saved for future use in other parts of the model.



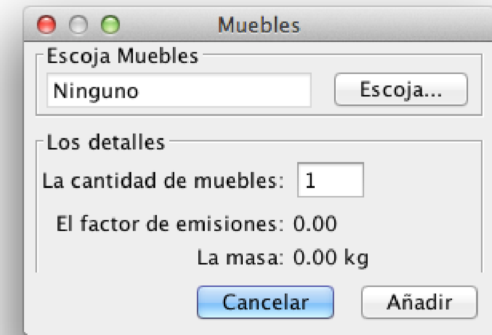
Step 6: Once that is completed the updated material information can be seen in the left hand pane of the main model window. A live update of the total CO_2 emissions can be seen on the right hand side of the screen.



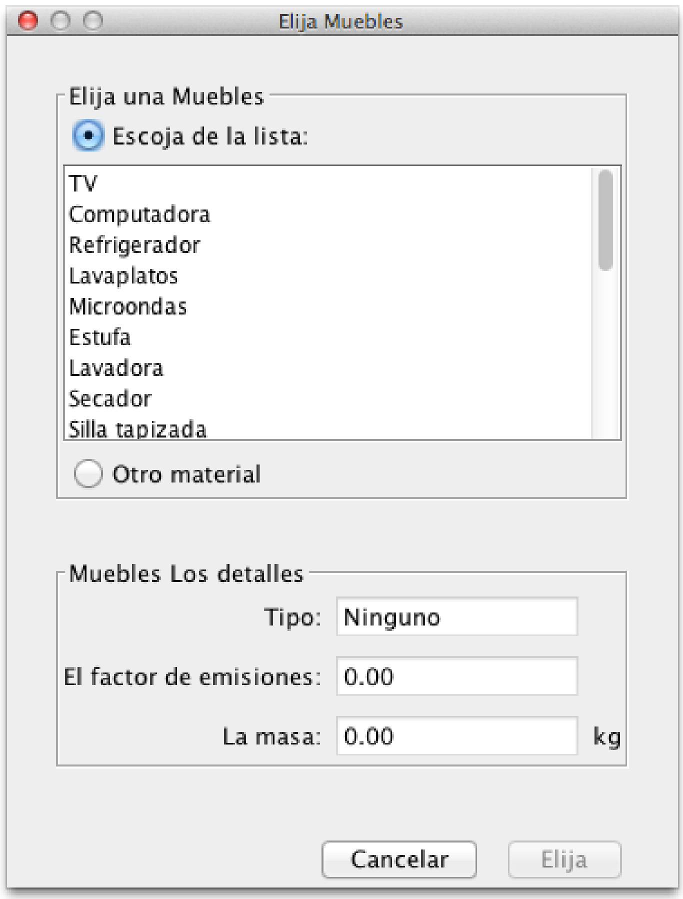
Step 7: The user repeats the structure input for all of the building components as seen in Steps 4-6. The user can now define the building contents by clicking *New Area Affected.*



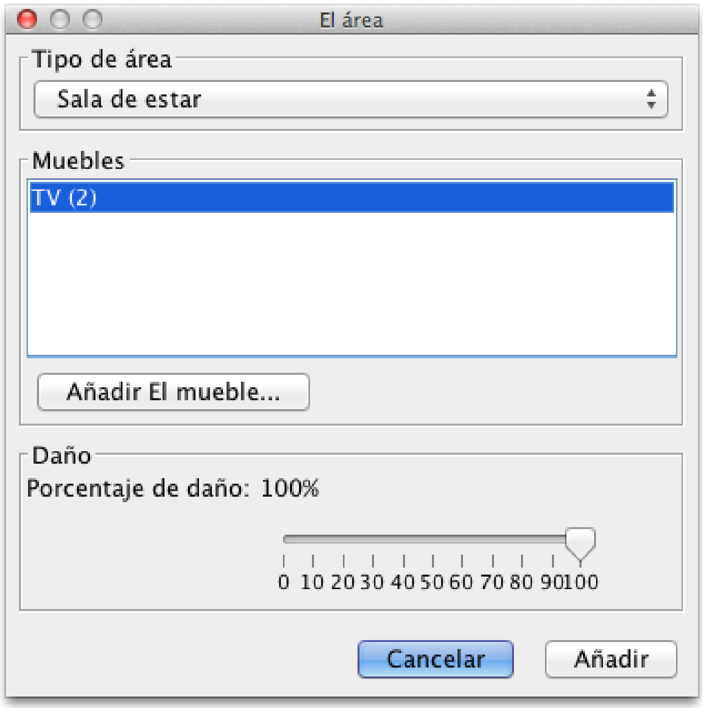
Step 8: After clicking *New Area Affected* the user will be asked to define what type of room was affected and what was in each room. The damage to each room can by specified by adjusting the *Percent Damage* slider at the bottom of the window. The user defines what is in each room by selecting the button, *Add a Furniture Item.*



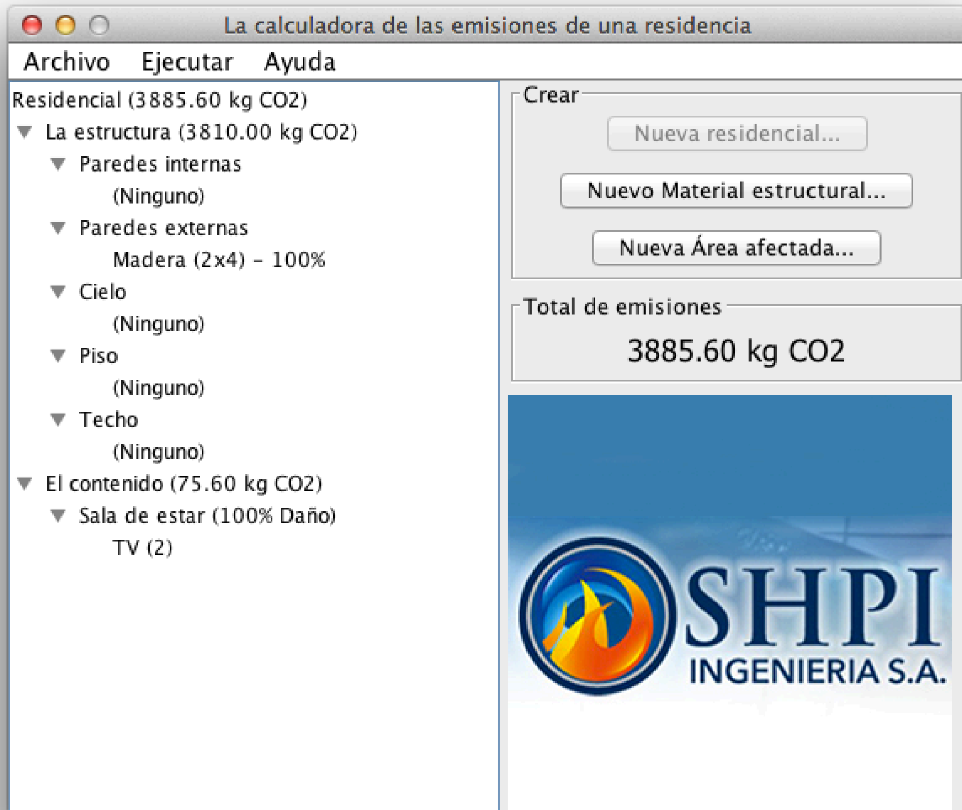
Step 9: After clicking the *New Furniture Item* button the user is prompted to choose the type of furniture and the quantity within the given room. The user chooses which furniture item to add to the room by clicking the *choose* button. The user can choose a predefined furniture item or enter a custom item by selecting *Other Material* and entering their own weight and emissions factor for the item.



Step 10: Once the new item is added to the room it will be seen in the room details window. Steps 8 and 9 are repeated for each item in the room.



Step 11: Once the user completely defines the contents of the room and clicks *next*, the room is added to the outline of the building as seen in the left hand pane of the main window. The emissions from the structure are automatically updated based on user input.

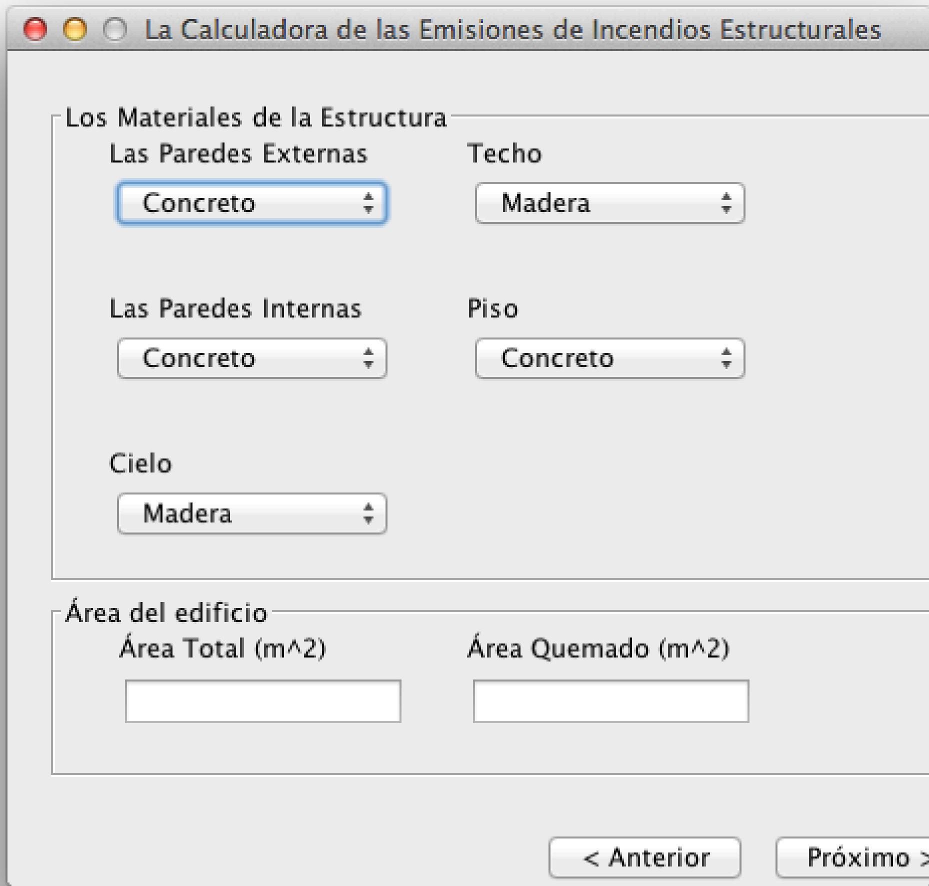


Step 12: Once the user defines all the structural components and all of the rooms affected, the *total emissions* will reflect the total emissions of the fire. The results and details of the building specified can be saved to a PDF by clicking the Export option at the top of the main screen.

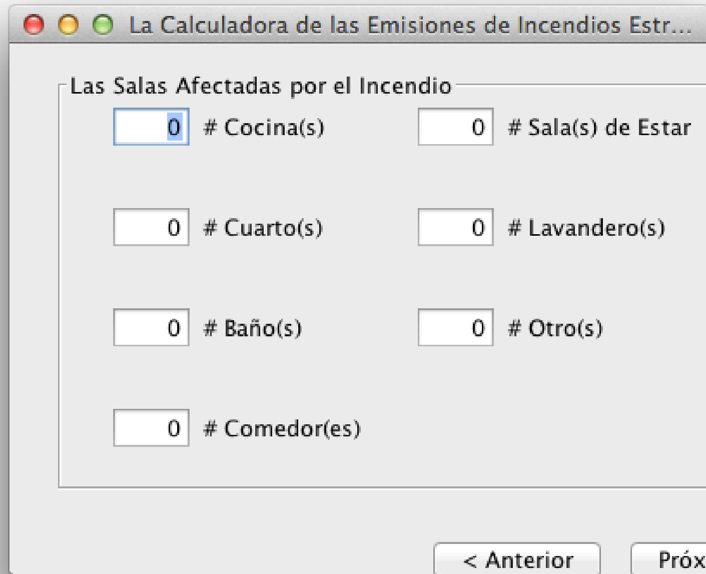
Simple Residential Model

Step 1: When the user opens the simple residential model they will be presented with the following screen. The user then selects *Residential Building* and clicks *next.*

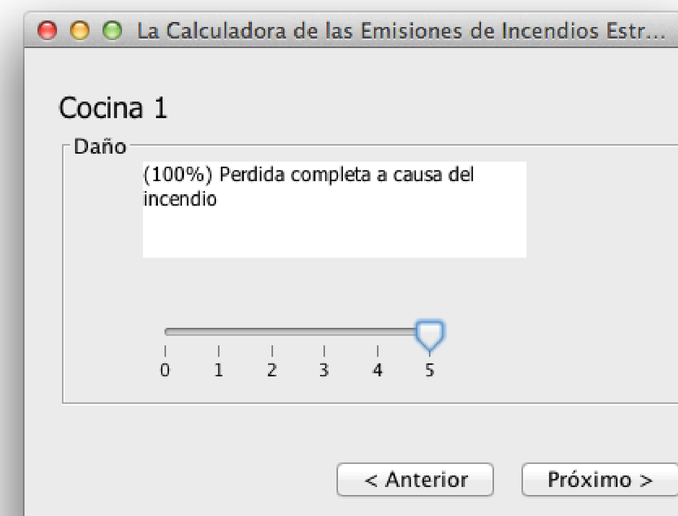
Step 2: After clicking *next* the user will be presented with the following screen. The user is asked to specify the materials used for different structural components of the building and the size and area affected of residence. After specifying the building materials the user clicks *next.*



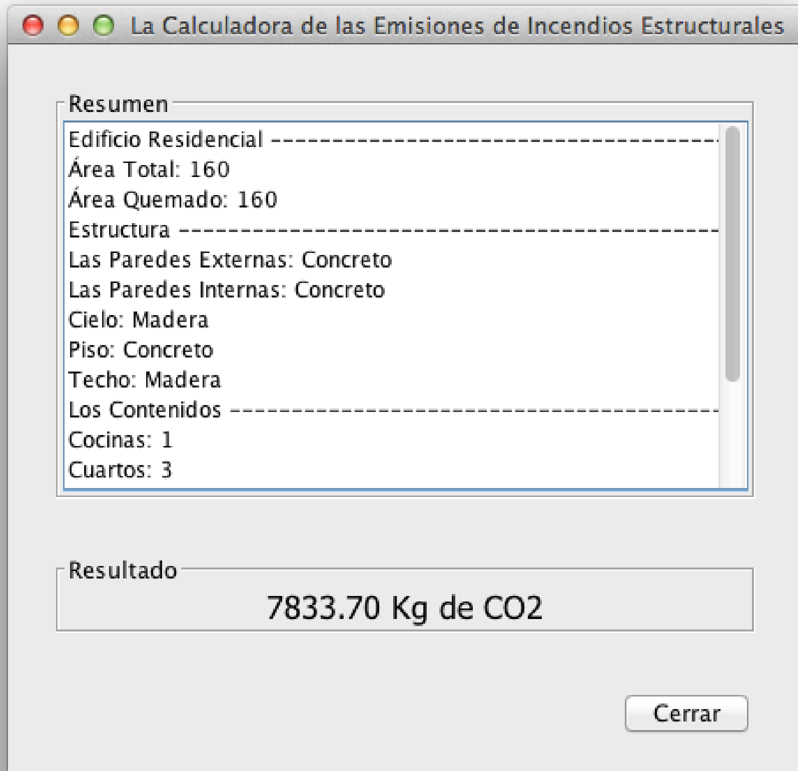
Step 3: The user is asked to specify the types and numbers of rooms affected by the fire. After specifying the number and type of rooms affected the user clicks next.



Step 4: For each room listed in Step 3 the user is asked to input the percent damage for each room.



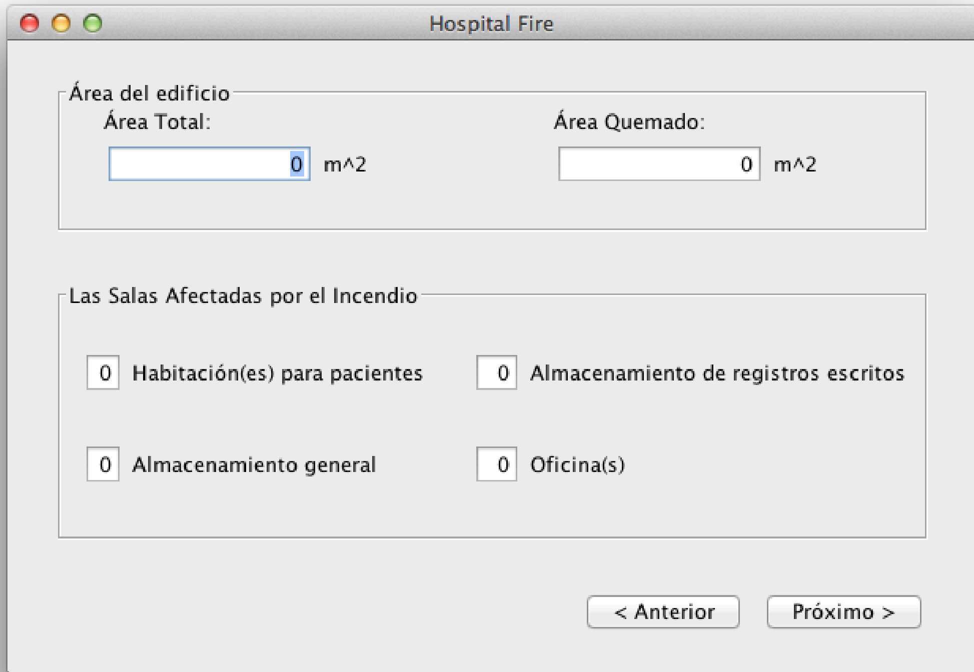
Step 5: After specifying the damage to each room the model outputs the CO_2 emissions from the residential fire.



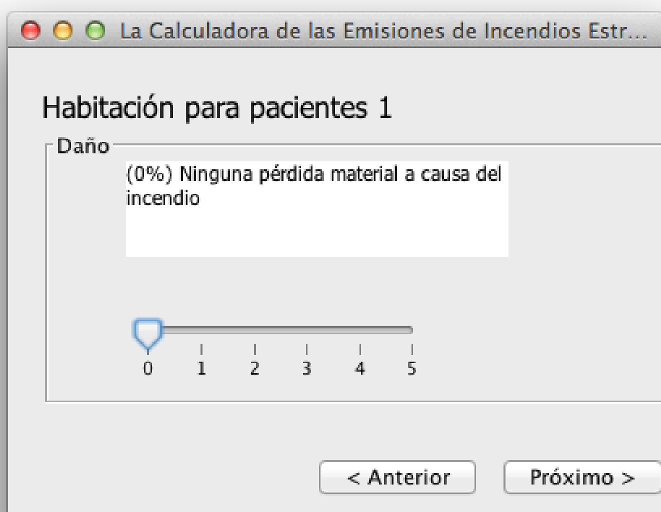
Hospital Model

Step 1: When the user opens the simple residential model they will be presented with the following screen. The user then selects *Hospital* and clicks *next.*

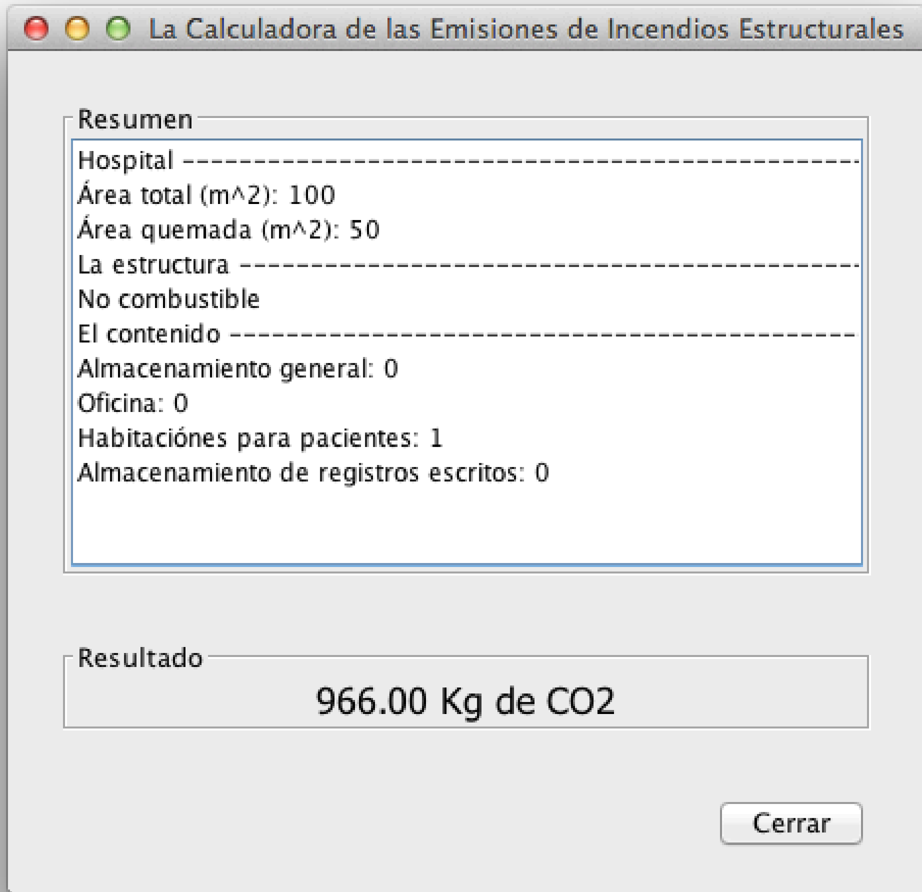
Step 2: The user is asked to specify the total area of the hospital, the area burned by the fire and the types of rooms affected by the fire.



Step 3: The user is asked to input the percent damage for each room affected by the fire.



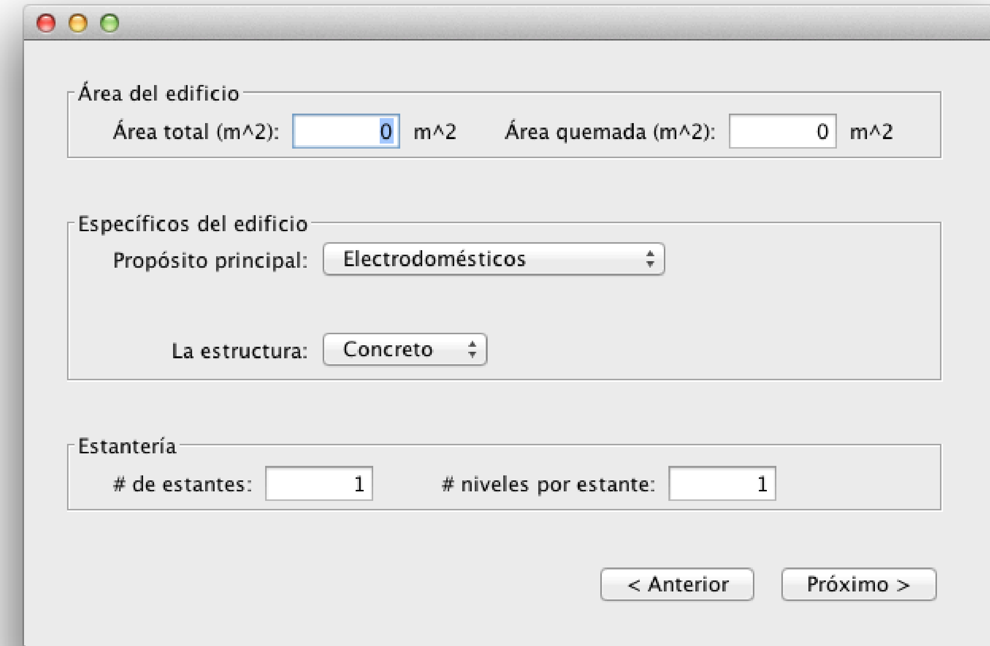
Step 4: After specifying the damage to each room the model will output the CO_2 emissions produced by the fire.



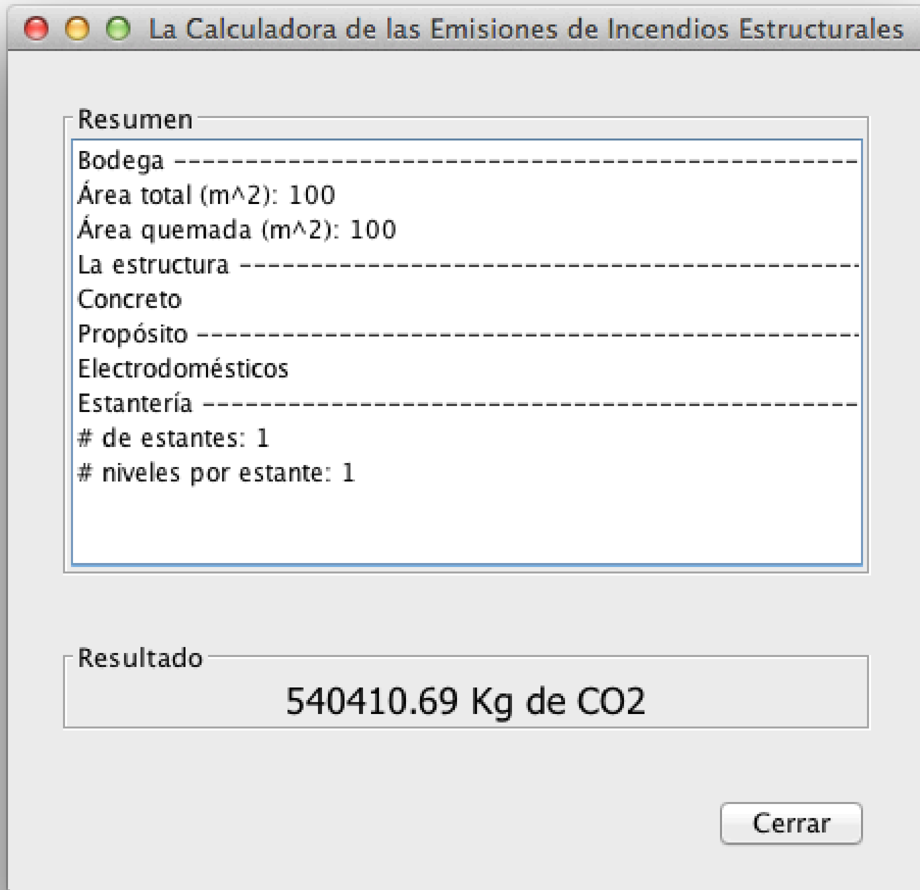
Warehouse Model

Step 1: When the user opens the simple residential model they will be presented with the following screen. The user then selects *Warehouse* and clicks *next.*

Step 2: The user is asked specify the total area and the area burned in the warehouse. The user also inputs the primary item stored in the warehouse and material of the warehouse structure. Details of the number of shelves and levels per shelf are also input by the user.



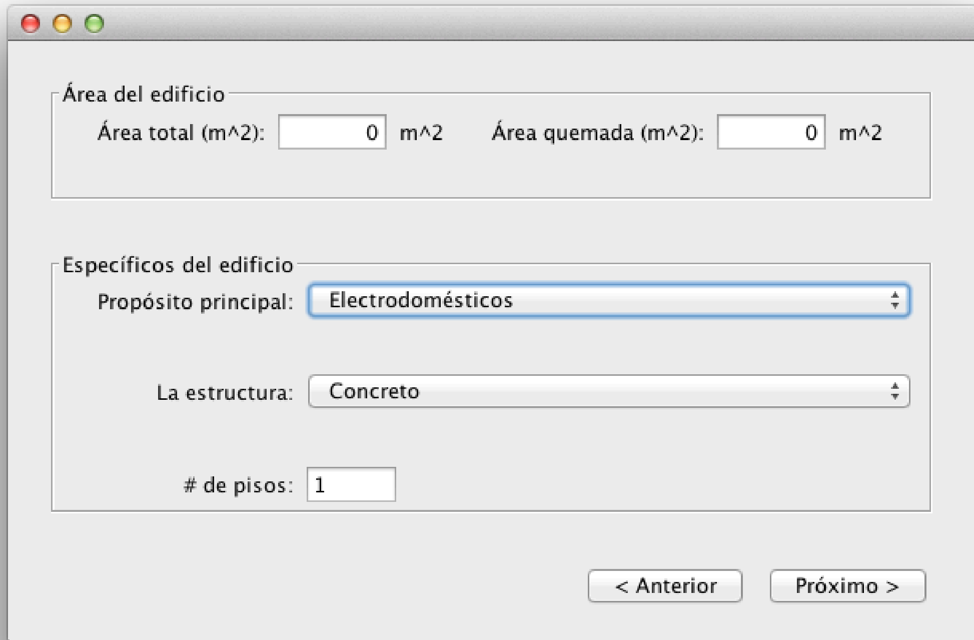
Step 3: After specifying the information in Step 2 the model outputs the $C0_2$ emissions from the specific warehouse fire.



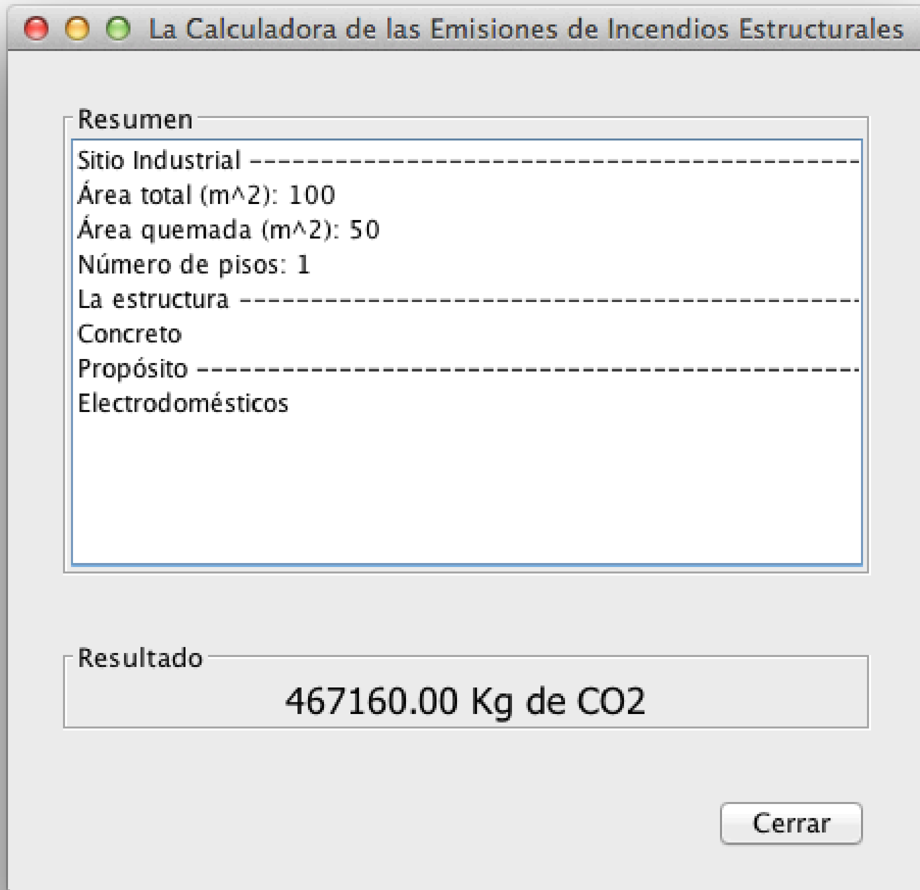
Industrial Model

Step 1: When the user opens the simple residential model they will be presented with the following screen. The user then selects *Industrial Site* and clicks *next.*

Step 2: The user begins by inputting the total area of the industrial site and the area burned by the fire. The user then details the primary material of the contents, structure and number of floors of the industrial site.



Step 3: After specifying the information in Step 2 the model outputs the $C0_2$ emissions from the industrial fire.



Appendix G: Flow Charts Showing the Logic of the Models

Simple Models

The figures below depict the flow of the program for the simple models.

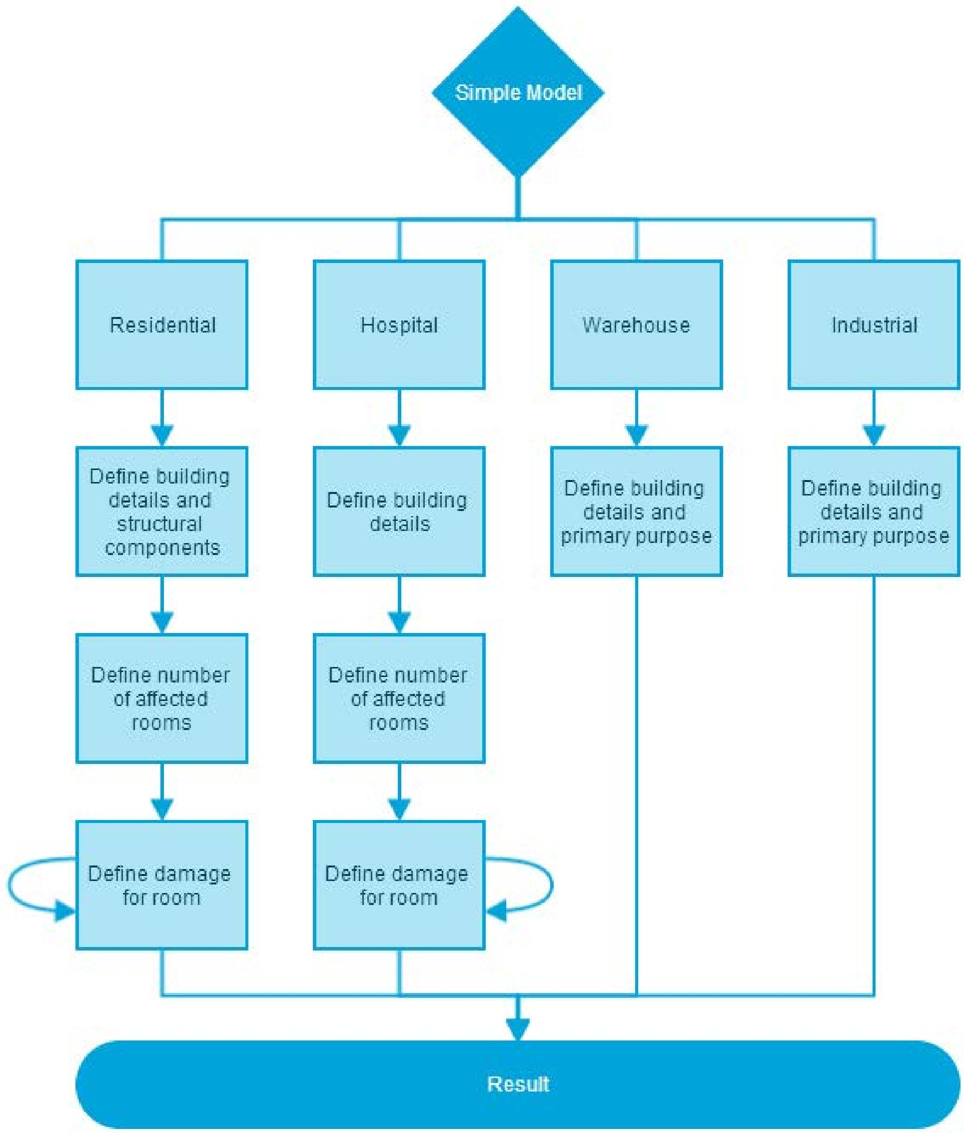


Figure 17: Flow Chart of the Program Logic for the Simple Model

Detailed Residential Model

The figures below depict the flow of the program for the detailed residential Model.

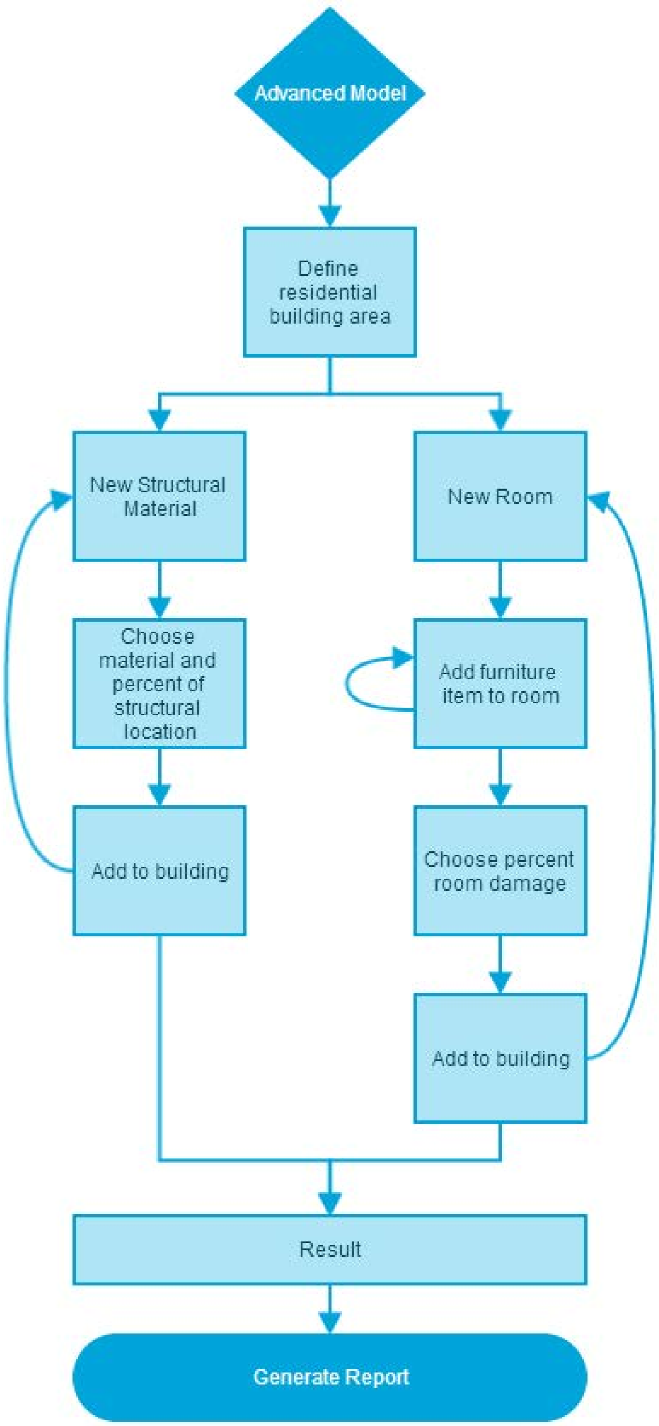


Figure 18: Flow Chart of the Program Logic for the Advanced (Detailed) Model

Appendix H: Detailed Model Equation Examples

Residential

User Input:
a_t = area total
a_b = area burned
n = number of rooms burned
d_o = percent damage per room

All rooms are assumed to be the same size

b_c = building contents
w_c = weight of room contents
w_c is known from residential survey as detailed in the methodology and model development chapters.

$$b_c\ (kg) = (w_c * d_o)$$
$$b_c\ Kitchen\ (kg) = (134\ kg * 100\%)$$

f = appropriate emissions factor for each room
e_r = emissions from room contents by room

$$e_r = (b_c)(f)$$
$$e_r = (134\ kg)(2.21\ kg/kg)$$

e_c = total emissions from room contents = sum of all calculated e_r

b_s = burned structure
a_b = area burned
w_s = sum of weights of combustible structure components (i.e. wood from ceiling, wood from roofing, etc.)

$$b_s\,(kg) = (w_s)(a_b)$$
$$b_s\,(kg) = (18.75 + 29.29)(160\,m^2)$$

e_s = emissions from structure
f = emissions factor

$$e_s = (b_s)(f)$$
$$e_s = (7686.4\,kg)(1.27\,kg/kg)$$

E_{tot} = emissions total

$$E_{tot} = (e_s) + (e_c)$$
$$E_{tot} = \ 10{,}0859.12\,kg\ CO_2$$

Industrial

User inputs type of industry:
Manufacturing
Agricultural
Chemical
Other

Have user make estimates about the contents using previously used densities:

- Polycarbonate (Dow Chem. Emerge 4202-15 MFR):
  - 1360 kg/m^3
- Wood:
  - 630 kg/m^3
- Cotton Fiber:
  - 1540 kg/m^3
- Rice:
  - 870 kg/m^3
- Mixed (Average of above):
  - 1100 kg/m^3

The user will select the material that most closely resembles the combustible material in the industrial incident.

The area affect will be treated as a single block of (a) given material(s) at this time for fuel loading and emissions factor.

$$Emissions = \Sigma(density\ of\ material)(area\ burned)(percent\ of\ make\ up\ of\ material)$$
$$(emisssions\ factor\ for\ each\ material)$$

$$Emissions\ from\ Plastic\ Contribution\ to\ Industrial\ Fire = (1360\ kg)(50\ m^2)(80\%\ by\ weight)(2.2\ kg/kg)$$

$$Emissions\ from\ Wood\ Contribution\ to\ Industrial\ Fire = (630\ kg)(50\ m^2)(20\%\ by\ weight)(1.33\ kg/kg)$$

$$Emissions\ Total = 128{,}059\ kg\ CO_2$$

Hospital

$$scaler = \frac{1}{\sum room\ damage\ percentage}$$

$$scaler = \frac{1}{100(1)}$$

For one room burned completely

$$Burned\ Contents\ (kg) = \sum (fuel\ loading * (scaler)(damage\ factor) * (area\ burned))$$

For each type of room use the following fuel loading

Table 18: Fuel Loading for Different Types of Rooms in a Hospital

Type of Room	Fuel Loading (kg/m^2)
PT Rooms	8.4
General Stores	46.5
Records Storage	292.55
Office/Administrative	27.3

$$Burned\ Contents\ (kg) = \sum (fuel\ loading * (scaler)(damage\ factor) * (area\ burned))$$

$$Burned\ Contents\ of\ a\ Storage\ Room\ (kg) = \left(46.5\ kg * \left(\frac{1}{100}\right)(100\%) * (20\ m^2)\right)$$

$$Emissions = \sum (Room\ Burned\ Contents)(Room\ Specific\ Emissions\ Factor)$$

$$Emissions = (930\ kg)(1.33\ kg/kg)$$

$$Emissions = 1{,}236.9\ kg\ CO_2$$

Polystyrene is used for the emissions factor for patient rooms. Wood is used for the emissions factor for all other types of rooms in hospitals.

Warehouse

The user will input the dimensions of the warehouse, the total area burned, the height of the building, and the primary use of the building.

Fuel loading will be determined by the following equations:

$$Length\ of\ Shelf = (Length\ of\ Warehouse - 2 * distance\ between\ shelves)$$

$$Length\ of\ Shelf = (100\ m - 2 * 2\ m)$$

$$Number\ of\ Shelves = \frac{Width\ of\ Warehouse}{(90cm^{1} * 2\ +\ distance\ between\ shelves)}$$

$$Number\ of\ Shelves = \frac{75\ m}{(90cm^{2} * 2\ +\ 2\ m)}$$

$$Number\ of\ Shelf\ Levels = \frac{Height\ of\ building}{1.2\ meters\ per\ shelf\ level}$$

$$Number\ of\ Shelf\ Levels = \frac{6\ m}{1.2\ meters\ per\ shelf\ level}$$

$$Total\ Volume = (Length\ of\ Shelf * 1.8m * 120cm * Number\ of\ Shelf\ Levels * Number\ of\ Shelves)$$

[1] The standard pallet size in Costa Rica is 90x90cm

$$Total\ Volume = (96\ m * 1.8m *$$
$$1.2m * 5\ levels * 19\ shelves)$$

$$Weight\ (kg) = Density\ \left(\frac{kg}{m^3}\right) * Volume\ (m^3)$$
$$Weight\ (kg) = 1540\ \left(\frac{kg}{m^3}\right) * 19699.2\ m^3$$

The emissions factor and density for clothing were used to simulate a clothing warehouse.

$$Emissions = Weight * Emissions\ Factor$$
$$Emissions = 30{,}336{,}768\ kg * 2.2\ kg/kg$$
$$Emissions = 66{,}740{,}000\ kg\ CO_2$$