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SYSTEMS MODELLING FOR SUSTAINABLE BUILDING DESIGN

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SYSTEMS MODELLING FOR SUSTAINABLE BUILDING DESIGN

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To my family

Whatever you are, be a good one.

Abraham Lincoln

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ABSTRACT

This dissertation involves the study of a retrofit building design in order to make it more sustainable.

To achieve sustainability in any system, we need to look at the whole processes where the system is involved and not only for the system that we are trying to make more sustainable. Such approach brings early conclusions and bad sustainable strategies.

As any system, a building is an open system, i.e., itself is a subsystem of other system and, besides, it has other systems inside. Such fact makes this system becoming a complex problem, mainly because of the existent interconnectivity which for many reasons, as lack of information or overview, couldn’t be expose. Thus it’s essential the use of tools capable to work with questions of complexity and networks in an effective way.

In this work will be used the Sensitivity Model of prof. Frederic Vester, described in his book “The Art of Interconnected Thinking” which was an essential tool in the development of the present work.

This work follows the nine steps of the Sensitivity Model which its main aim is reveal the role of some variables in the system through changes in the model input data and verifying which changes occurred in the model output data. Thus, throughout the use of alternative scenarios it’s possible to understand the system behaviour and which variables play the biggest role in that behaviour.

In general, due to the complexity of the problem, there are some restrictions and limitations in the study as well as uncertainties in the input data. However, the use of this model allows reducing the impact of those uncertainties and, thus, establishing the reliability of the results.

Regardless of the problems to solve, this model presents good results when sustainability is main goal.

The present work is divided in five chapters. In the first chapter an introduction to the present work is done: context, main goals and work structure are presented. In the next chapter an approach to building sustainability importance is done, the role of structural engineer while designer and the application of methods which allow the achievement of more sustainable building designs. In the third chapter the Sensitivity Model is approached, issues like method operation, main features and applicability of it are explained. In the fourth chapter the sensitivity model is applied in the building design of a case of study and the nine steps of model essential to achieve conclusions are covered. At last, the fifth chapter is dedicated to conclusions observed after application of the method as well as design recommendations in order to improve the study building design and for the use of this kind of method in construction field.

KEYWORDS: system, sensitivity, analysis, sustainability, building, interconnectivity

RESUMO

Esta dissertação envolve o estudo do melhoramento/aperfeiçoamento do projeto de um edifício de forma a torna-lo mais sustentável.

Para alcançar sustentabilidade num determinado sistema é necessário observar todos os processos em que este sistema está envolvido, e não apenas para o sistema que estamos a tentar tornar mais sustentável. Este tipo de abordagem traz conclusões precoces e más estratégias de sustentabilidade.

Como qualquer sistema, um edifício é um sistema aberto, isto é, contêm outros sistemas e ele próprio é um subsistema de outro sistema. Tal facto faz com que o estudo deste sistema se torne num problema complexo devido, essencialmente, à interconectividade existente a qual, por diversas razões, tais como falta de informação ou visão geral, pode não ser totalmente exposta. Desta forma, é essencial o uso de ferramentas capazes de trabalhar com questões de complexidade e redes de forma eficaz. Assim, neste trabalho será utilizado o Modelo de Sensibilidade do prof. Frederic Vester descrito detalhadamente no seu livro "The Art of Interconnected Thinking", o qual foi ferramenta essencial para o desenvolvimento deste trabalho.

O presente trabalho segue, assim, os nove passos do modelo de sensibilidade e tem como principal objetivo revelar o papel de algumas variáveis no sistema através de alterações nos dados introduzidos no modelo e verificando que alterações ocorreram nos dados que saem do modelo. Desta forma, através do uso de cenários alternativos, é possível entender o comportamento do sistema, e quais as variáveis que maior papel interpretam nesse comportamento.

Em geral, devido à complexidade do problema, existem algumas restrições ou limitações no estudo assim como incertezas nos dados introduzidos, a utilização deste modelo permite reduzir o impacto dessas incertezas e, assim, estabelecer a reliabilidade dos resultados.

Independentemente do problema a resolver, este modelo apresenta bons resultados quando o sistema pretende alcançar sustentabilidade.

Este trabalho encontra-se dividido em cinco capítulos. No primeiro capítulo é feita uma introdução ao trabalho incluindo uma descrição detalhada do sistema de estudo. No capítulo seguinte será feita uma abordagem à importância da sustentabilidade dos edifícios, o papel do engenheiro estrutural enquanto projectista e a aplicação de métodos que permitem a obtenção de projectos mais sustentáveis. No terceiro capítulo é exposto o Modelo de Sensibilidade, questões sobre funcionamento do método, principais características e áreas de aplicação são explicadas. No quarto capítulo será aplicado o Modelo de Sensibilidade no projecto do edifício de estudo, percorrendo os nove passos necessários para obter conclusões. Por fim, o quinto capítulo dedica-se a conclusões observadas após aplicação do método, assim como recomendações para melhoramento do projecto em estudo e para o uso deste tipo de métodos na área da construção.

PALAVRAS-CHAVE: sistema, sensibilidade, análise, sustentabilidade, edifício, interconectividade

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SYMBOLS, ACRONYMS AND ABBREVIATIONS

CLT – Cross Laminated Timber

CO_2- Carbon Dioxide

et al. – el alia (and others)

EE – Embodied Energy

Fig. - Figure

GHG – Green House Gas

LCE – Life Cycle Energy

ICE – Inventory of Carbon and Energy

SM – Sensitivity Model

Ref. - Reference

1

INTRODUCTION

1.1. CONTEXT

Currently, among the uncontrolled growth of the population, arises the consequent environmental and economic preoccupations and it’s essential an adequate resources management. Being the construction industry one of those that more resources consume, it’s important a prior planning of all the different phases involved in this activity in way to obtain more sustainable solutions.

According to ASCE (2016), sustainability is the capacity of the society to maintain and improve its quality of life indefinitely without degrading the quantity, quality or the availability of economic, environmental and social sources. As engineers, we have the responsibility to find effective and innovative building design solutions in order to reduce materials consumption, improve quality of life for people, better economic performance and preserve natural resources for future generations (Ochsendorf, 2005).

The concept of sustainable development is not new and has evolved greatly in the last years. Rio 92 was the first international conference attended by world leaders, among 108 countries, to discuss the environmental issues and introduce the concept of sustainable development. Before this conference another two were important in this field: the Stockholm Conference in 1972 and Brundtland Commission in 1987, both were an essential basis for Rio 92. Agenda 21 was one of the documents resulting from Rio 92 conference, which reflects the importance of each country to study solutions for their socio-environmental problems.

However, being the construction sector a larger industrial sector, after the Rio 92 conference there was the necessity to develop an international agreement on sustainable construction. In 1999, the International Council for Research and Innovation in Building and Construction (CIB) published its *Agenda 21 on Sustainable Construction* (Du Plessis, 2002).

Over the years the understanding of sustainability in buildings has changed. In the beginning the focus was on limited resources, especially energy, and how to reduce impacts in the natural environment (Bourdeau, 1998). In the last years, the main concern is on building materials and components, construction technologies and on energy related design concepts.

The building design is the first phase of building process and one of the most important when sustainability is the goal. It is up to architects and engineers, not forgetting the other actors in construction sector, the decision of more sustainable options, among materials and technics, in the earlier stages of the design process.

However, sustainability causes complex interdependencies in design and planning of buildings. Such happens because a building is, as said before, an open system, which contains other systems and, itself is part of others systems. The city that the building belongs, the construction materials manufacturing and the local environment, are some of the systems that affect and are affected by the building system. It's important to understand that the system is not isolate and because of that, to make it more sustainable, it's necessary take into account the relations and interactions with other systems, i.e., the interconnectivity.

To lead with such complex system as a building design, it's critical the use of a modelling tool where we can simplify the real world and to understand the complex interrelations involved.

Among the systemic management methods, Frederic Vester (2007), a German biochemist, has defined an easy way to use discussion based approach called sensitivity modelling which is, also, a successful tool dealing with complex systems. Sensitivity models have been used since the 1980s in many important studies, e.g. by Ford (Motor Company) and the UNESCO (Funk *et al.*, 2014).

A system is a group of interconnected elements which in their set they form a whole. The sensitivity model reflects the dynamics that determine how a system develops (Vester, 2007). Sensitivity analysis is the basis for sensitivity modelling.

The sensitivity analysis allows understanding the disturbances effect in the system in is normal behavior and thus identify the important parameters to control it. This can be understood when the output model values are very affected by new input values in the model. Therefore, it's possible to know which parameters are the most important in the system and which ones affect it more. This is the main aim of the sensitivity analysis. Since we know the importance of each variable in the system we are able to understand the important connections within that system.

In buildings, to achieve the goals of sustainability it is required to adopt a multi-disciplinary approach covering a number of features such as energy saving, improved use of materials including water, reuse and recycling of materials and emissions control (Ramesh *et al.*, 2010).

1.2. OBJECTIVES

The present work main aim is the sensitivity modelling of a case of study building design. Applying the nine steps of the Sensitivity Model it will be possible to understand how the system works and how different variables concerned to the system affect it, especially, its behavior. In short, the main steps of this thesis are following described:

- ✓ Get to know the study system in detail: find problems and define goals and boundaries;
- ✓ Gather a list of actuating variables concerned to the study system;
- ✓ Through application of Sensitivity Model discover which of those variables are relevant for system behavior and how these variables affect it;
- ✓ Build a partial scenario with the relevant variables based on the question that it's expected to answer "How can we reduce the embodied energy demand by the building?";
- ✓ Simulate that partial scenario through mathematical relations between variables using a suitable software and thus identify relevant control parameters for the previous question;
- ✓ Identified the relevant control parameters, find the best design options and give recommendations for case study building design and for future research as well.

1.3. THESIS STRUCTURE

This thesis is structured as follows: In chapter one, a contextualization of the thesis topic is made. The sustainability in construction sector is emphasized and the important role of Sensitivity Model in the achievement of sustainable solutions.

The chapter two approaches the importance of sustainability in the construction sector. The reasons to introduce the concept of sustainability in this sector as well as the role of structural engineers as building designers. The importance of building modelling to achieve designs with better environmental performances.

The Chapter three is totally dedicated to the description of the Sensitivity Model developed by Frederic Vester. Main issues as well as how the Sensitivity Model works, areas of use and applicability of it are approached.

In the fourth chapter, the case of study is presented. The nine recursive steps of Sensitivity Model are applied to the study system, a building design, in order to understand how the system works, its problems and define its goals. A set of variables concerned to the system is gathered and according to their roles it’s possible to understand the cybernetic character of each variable and their importance in the system. In way to focus on particular issues, partial scenarios are built and simulated in order to understand the system cybernetics and reveal the control parameters which are an essential information to define design strategies. Last step is dedicated to the viability of the study system where the eight biocybernetic rules of any viable system are applied.

The fifth and last chapter presents the conclusions of the Sensitivity Model application in the case of study. Furthermore, design recommendations for future researchers and hints about future research in this area will be recommended. Even the possibility of continuing this research will be left open.

2
BUILDINGS SUSTAINABILITY

2.1. IMPORTANCE OF SUSTAINABILITY CONCEPT IN CONSTRUCTION SECTOR

From all the activities performed by humanity, building construction is the most critical in terms of environmental impact and resources consumption. Construction, operation and maintenance of buildings have had serious impacts on the environment. To clarify this idea, let's have a look in some numbers taken from (Langston, 2008, Torgal and Jalali, 2010):

- ✓ 50% of material resources taken from nature are building-related;
- ✓ Over 50% of national waste production comes from building sector;
- ✓ 40% of energy consumption in Europe is building-related;
- ✓ 30% of carbon emissions result from building sector.

These facts above clearly show the unsustainability of this sector and why it was necessary to implement the concept of sustainable development into construction industry in order to reverse those facts. Sustainable construction focuses on the issues of procurement, assembly and commissioning, materials selection, recycling and, in particular, waste minimization (Langston, 2008). These three first concepts won't be approached in this work since they are related with clients, contractors and users of the facility. On the other hand, the others concepts are important for this study since their approach starts in the design phases.

In order to better implement the sustainable construction concept and define the main goals of it, the CIB (*Conseil International du Bâtiment*, in English *International Council for Building*) as defined seven principles for sustainable construction – see table 2.1.

Table 2.1 - Kibbert (1994) Principles of Sustainable Construction (Torgal and Jalali, 2010).

1	Reduce resources consumption
2	Reutilization of resources
3	Use of recyclable resources
4	Nature protection
5	Elimination of toxics
6	Application of life-cycle analysis in terms of economics
7	Improve quality

2.1.1. Portuguese situation

In Portugal, in contrast with other countries in Europe, the construction sector intensified during the 90s. Currently, this sector is at same level as other European countries. Between the 70s and finals of 90s, were built more than two millions of habitational units which justify the intensive growth of this sector in Portugal (Castro *et al.*, 2012).

In the last years, the population has been growing (about 1.9% between 2001-2011), which result in the necessity of construction of new habitations buildings. In this way, in Portugal, the main building function is habitation. However, the problem here is that the majority of these buildings present nowadays problems like lack of thermal and visual comfort and bad quality of indoor environment. These problems are associated to the increase of resources consumption (energy and water) during operational phase of the building and thus the increase of environmental impacts (Castro *et al.*, 2012).

Besides, the conventional construction is associated with large resources consumption, large use of materials and energy consumption. Materials as concrete, aluminum and brick masonry are materials used in large scale in Portugal, which their production implies great consume of energy with release of GHG.

The sustainable building solutions, in Portugal, are mostly related with the reduction of operational energy. The solutions are the use of passive systems based in solar energy, ecologic insulation materials and LED illumination. However, comparing with other countries in north of Europe, Portugal has a long journey to cover in this thematic.

With the growing environmental awareness and the necessity of facing the negative impacts of traditional construction materials and methods, the construction professionals started to search for new materials and technics, more efficient and ecologic for new buildings construction. However, it still missing an improvement at education level where this topic should be more debated in universities in order to raise awareness of the future professionals in construction sector to this problem. The lack of education and professionals specialized in this thematic also contributes the unsustainability of this sector.

2.2. Sustainable buildings

2.2.1. Building designers: the role of the structural engineers

Due to the non-ecological structure of the building industry and the historical lack of environmental awareness of many building professionals, the process of building has become the worst environment enemy (Graham, 2009). That is the reason why sustainable practices should be seriously taken into account by construction professionals, including building designers. According to Miller and Doh (2015) many of the factors leading to unnecessary resource consumption result directly from the inefficient design of buildings and their associated infrastructure.

It’s crucial that designers are aware of sustainable developments concepts and practice them as a matter of routine in order to reduce these numbers. A proper design is an important component in the achievement of financial return, social contribution, energy efficiency and minimal environmental impact objectives (Langston, 2008). An effective planning of these fields results in effective sustainable design solutions.

In short, according to Torgal and Jalali (2010) the prior considerations when designing a building are shown in fig.2.1.

Figure 2.1 – Considerations on a sustainable building design (Torgal and Jalali, 2010).

During design process the role of structural engineers is very limited since the main preoccupations lately have been the reduction of operational energy. This energy is the energy used for maintaining the indoor comfort of the building (electricity, heating, etc.) and it's the main responsible for GHG emissions during building life-cycle. However, in the last years, some studies were performed and consequently the importance of embodied energy has risen. Although this fact, the variability and the uncertainty of the publications make this issue difficult to approach by the structural engineers.

Furthermore, it is also the building designer's role to be informed about new technologies and technics that enhance the environmental performance of buildings. Besides, they have a professional obligation to broaden the understanding of construction owners and clients who may in turn demand sustainable design (Miller and Doh, 2015).

2.2.2. Structural Engineering: typical problems to tackle

Currently and over the years, structural engineering has as trends reinforced concrete and steel structures, which have contributed in a large scale for the environmental impacts in construction industry. Each ton of Portland cement, the larger component of concrete, is responsible for approximately one ton of CO_2 emissions (Ochsendorf, 2005). On the other hand, steel production is energy intensive with the release of greater quantities of GHG, however the infinitely recyclable property of steel make it almost an irreplaceable building material.

However, are not only these two materials that contribute for environmental problems, in general building materials play an important role in sustainable construction context. Such happens because every building material derives from a raw product which can exhaust after extreme extraction. In this way, it's important to know the materials sources for better choices among them. Their choice should focus on the following properties described in Torgal and Jalali (2010):

- ✓ With low embodied energy;
- ✓ Recyclables;
- ✓ Materials that can reuse wastes from other industries;
- ✓ Materials from renewable sources;
- ✓ With low GHG emissions;
- ✓ Durables;
- ✓ Not toxic.

Another problem resulting from “bad” design is the structural inflexibility. The impossibility of changes in the use/function of certain building results in an earlier demolition since these buildings become obsolete. It results in expensive retrofitting and several consequences as energy outlay and demolition wastes (most of them not reusable or recyclable). Sustainable practices must include ease upgrade, flexibility, adaptability and recycling potential (Langston, 2008).

Besides the problems above, other considerations should take place during a sustainable building design. A proper siting and orientation, natural lighting and ventilation, insulation, low energy and long life are today’s essential concepts for successful building designs.

Design must be understood to comprise the trilogy of form, function and cost. Form is the solution to accommodate the desire function. Function is the translation of the needs of the client, and in a wider range the needs of the society. Cost includes the initial and recurrent expenditure over the life cycle of the building (Langston, 2008).

The energy used during building operational phase (heating, ventilation and air conditioning) is also an issue that should be taken into account. That can be solved with designs which reveal a poor dependence in energy for maintaining building comfort.

The main goal here is to find strategies from material selection to radical designs that embody both passive and active solutions to create more comfortable spaces at reduced cost and energy (Langston, 2008).

Regarding all these considerations above, it’s a first step to improve building design solutions in order to make them more sustainable and thus preserve the future generation’s quality of life.

2.3. BUILDING DESIGN MODELLING

A successful project always begins with a good planning. The construction industry is very fragmented. Over all stages, including design phase, teams composed by many different professionals from different areas are built and, in the case of design team, they need to cooperate to achieve a successful building project for a specific client. Each professional has its own responsibility and ideas which together generate great amounts of information. However, due to the lack of a good information structure, this information may not be correctly worked and part of it can even be lost or neglected. To solve this problem a mediation session would be essential. Besides the lack of mediation, also the poor decision-making found in building design phase contributes for the great difficulty in find sustainable solutions.

To counter this situation, it is necessary the use of effective planning and management tools to replace this fragmented responsibility and decision-making and to help in the achievement of successful design solutions.

Modelling, applied to design phase, is the process of creating a model of a building design to estimate a certain issue that the modeller wants to study. However, to modelling a certain building design it is needed to use specialized tools where it is gather all the possible data (input data) about the building like function, materials, size, etc. and about the surrounding area like location, surrounding activities and places etc. The aim here is to achieve the generated information (output data) about how the building performs itself about the study issue.

With all the problems that the construction sector brings in many areas, this process becomes essential in the building design phase since it’s possible a detailed analysis and try solutions and see how it works, preventing bad decisions. Furthermore, this new methods are a major contribute to enhance building designs and to help building professionals to become more creatives, raising their productivity.

In this work will be used a modelling tool combined with sustainable principles, the Sensitivity Model, two desirable features to analyze a building design.

3
THE SENSITIVITY MODEL

3.1. INTRODUCTION

Dealing with complex systems can be a problem for us. Our whole education leads us to draw simple logical conclusions and defining obvious cause-and-effect relations. However, this way of thinking leads to the most common errors made in dealing with complex systems (Vester, 2007).

A complex system is like an organism which consists of a number of distinct parts (organs) that co-exist in a specific dynamic arrangement. In this way, it is impossible an intervention without changing the relationship of each part to every other and hence the overall character of the system. Furthermore, real systems are open which means that they are in constant interchange with their environment (Vester, 2007). Hence, complexity is not an easy question due to the interlinked networks involved and thus it's essential to approach it with efficient tools. In Vester (2007), six errors committed when dealing with complex systems are described as follow:

i. **False description of goals:** Instead of setting about enhancing system's viability, people try to solve individual problems;
ii. **One-dimensional analysis of situations:** The dynamics of the system remain a mystery because people refuse to grasp the cybernetic nature of it. They gathered large amounts of information without producing a structure;
iii. **Irreversible foregrounding:** people insisted on a single point of emphasis, initially acknowledged as correct;
iv. **Neglected side effects:** people pursued their search for measures to improve the situation in a very single-minded manner, without analyzing side effects.
v. **Tendency to oversteer:** in the beginning people act with small interventions then, if nothing occurs in the system, they do something major. When finally repercussions occur they immediately stop. However, the first interventions go unnoticed.
vi. **Tendency towards authoritarian behavior:** the most effective approach for complex systems is not to swim against the current but to swim with it.

Frederic Vester tried to correct these errors with the Sensitivity Model where tools and concepts are approached to tackling complexity.

3.2. About the method

3.2.1. Sensitivity model description

The Sensitivity Model helps us to tackling complexity in an easy and successful way. This model not only reflects the dynamics that determine how a system develops, it's capable to develop the cybernetic that prevail inside those dynamics. By rendering cause-and-effect flows visible, the method allows the person who is using it to influence those flows, establishing new courses, to improve all system by self-regulation, and with the aid of simulations to examine how the system behaves as consequence/result (Vester, 2007).

In the present work context, using this model allow us to visualize the cause-effect flows and thus influence those flows to enhance the design project in the way to obtain more sustainability.

The success of this method is due to one of the main features of the model, the mediation capacity. This mediation characteristic can be understood by the different convictions and opinions, from each project participant, that can be placed in the same model and in the end they recognize that they are interconnected when sustainability is the goal.

The model is composed by nine recursive steps represented in fig. 3.1. This recursive feature is explained by the fact that each stage remains open until the end and thus the entirely model can be constantly updated, being the initial faults successively corrected by the following steps (Vester, 2007).

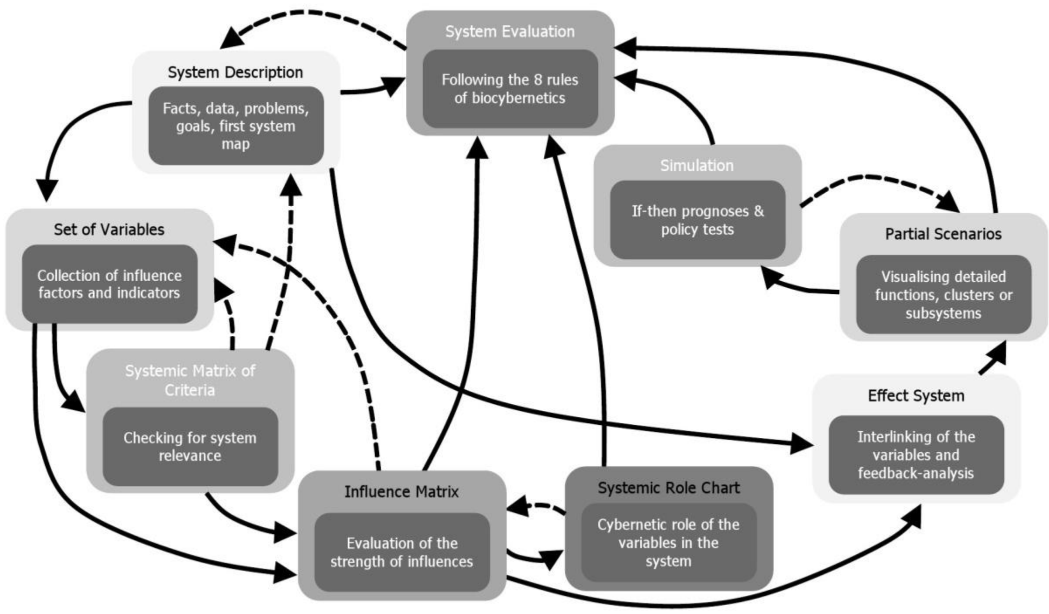


Figure 3.1 – Sensitivity Model structure (Wolf *et al.*, 2012).

The process begins with the system description and it ends in the system evaluation. After the first step (system description), in the next four steps (set of variables, systemic matrix of criteria, influence matrix and systemic role chart) the interactions present in the system are examined and the system interconnectedness is visualized. The cybernetic role of each variable concerned to the system is known and also how it's affect the system behavior in order to characterize it.

Then, in the following two steps (effect system and partial scenarios) the specific interplay between variables is defined and thus the interplay between variables renders the system chain of effects and feedback loops visible. The interesting parts of effect system are built like partial scenarios. Next step, simulation, the partial scenarios are simulated according to “what if” forecasts. Last step, system evaluation, eight basic rules are used to evaluate system’s viability and long-term sustainability. At this step, particular strategies and measures are achieved for dealing appropriately with the system (Wolf *et al.*, 2012).

This model is applicable to any system striving for sustainability because of its neutral design - independent of the problem to solve. It has been applied in many projects among different study areas and it is recognized as a very successful tool when sustainability is the goal.

The Sensitivity Model can be found in a computerized version called *Malik Sensitivity Model®*$^{Prof.Vester}$ which performs all the steps and allows an easy visualization of results, however, in this work was not possible to use it due, mainly to its cost. Instead of using that, was used Microsoft Excel to perform the initial steps and for simulation step was used the MATLAB tool, Simulink.

3.2.2. MAIN FEATURES OF THE MODEL

The Sensitivity Model due its success to the main features present and fully described in Vester (2007):

- ✓ **Holistic capture:** the complex system should be captured with its socio-economic-ecological environment as a biocybernetic whole;
- ✓ **No more floods of data:** instead of a large amount of data, the sensitivity model works with a manageable number of representative actuating variables thanks to its process to reduce the variables to the minimum;
- ✓ **Fuzzy logic as foundation:** with the sensitivity model it’s possible to draw connections between data of lesser relevance and through them reach conclusions about system functions;
- ✓ **Interactive operation:** the user can find himself in constant open dialogue between the computerized and manual parts of the proceeding;
- ✓ **Permanent working tool:** this feature is due to sensitivity model recursive structure, every step remains open until the end and capable of being updated;
- ✓ **Argumentation aid:** didactically innovative methods of simulation, interpretation, and appraisal provide useful political and material aids to decision-making for the future development of a system;
- ✓ **New kinds of solution:** interpreting the system behavior in the light of its “sensitivity” will bring new kinds of potential solution and opportunities that spring from the better understanding of the system;
- ✓ **More scope for action:** the biocybernetic view of things offer solutions that vary from system to system and are not standard. As a result scope for action is not restricted to a single fixed goal but will be greatly expanded;
- ✓ **An end to forecasts that make no sense:** sensitivity model will help the user to recognise the qualities and development potential of the system and using the ‘what if’ forecasts about how the system will behave treat those qualities and potential in such way that the system can cope better.

3.2.3. Areas of use

The Sensitivity Model can be used in practically unlimited areas thanks to its open structure, already explained in 3.2.1, and it is useful everywhere where the complexity of the problem can no longer be tackled by customary methods (Vester, 2007). The most common areas of use are:

- ✓ Corporate strategic planning;
- ✓ Technology assessment;
- ✓ Developmental aid projects;
- ✓ Examination of economic sectors;
- ✓ City, regional and environmental planning;
- ✓ Traffic planning;
- ✓ Insurance and risk management;
- ✓ Financial services;
- ✓ Research and training.

3.2.4. Sensitivity modelling in building analysis

As observed above, the construction area is not mentioned however, as explained before, the Sensitivity Model has a large range of applications in many areas. After an extensive research it was found some applications in buildings area. Several studies in thermal and energy performance of buildings were carried out using this method. The aim of those studies is analyze the building behavior to achieve specific targets like reducing energy consumption, reducing environmental impacts or improving indoor thermal environment (Nguyen and Reiter, 2015).

4
APPLICATION OF SENSITIVITY MODEL - CASE OF STUDY

4.1. SYSTEM DESCRIPTION

4.1.1. INTRODUCTION

The first step to system analysis consists in describing the system. The initial description of the system is very subjective: different entities present different visions and opinions of the same system. The author calls it a brainstorming session. Record all opinions, views and ideas, is essential to create a structured system model. Here is where the model mediation capacity is visible.

This step is the basis for building the model, here, the users will for the first time get to know relationships and connections. System boundaries will be defined, problems will be found and the partial goals will be set. However, setting goals in so earlier stage brings as consequence errors but, since the model structure is open, other goals will arise from the analysis carried out.

At this step, a system map will be drawn. This tool is very useful to see relationships and connections that would not have occurred before.

4.1.2. FACTS AND DATA

The system related to this work is a seven storeys multi-family dwelling with 28 habitations located in the city of Maia, Portugal.

The building structure is in frame reinforced concrete supported by shallow foundations. The slabs are voided and flat slabs which loads are supported by horizontal beams and then vertical columns until the foundations. The exterior and interior walls are in brick masonry, being the first double walls with interior insulation in polystyrene extruded (XPS) and the second simple walls. The building has, as bracing system, two lift shafts and stairwells.

The basement is entirely for parking, the ground floor is for parking and habitations entrance and the others are entirely for habitation.

This building, under construction until 2017, is located in a rich place of the city provided of good infrastructures and services such as schools, markets and also recreation spaces as city gardens.

4.1.2.1. Building details

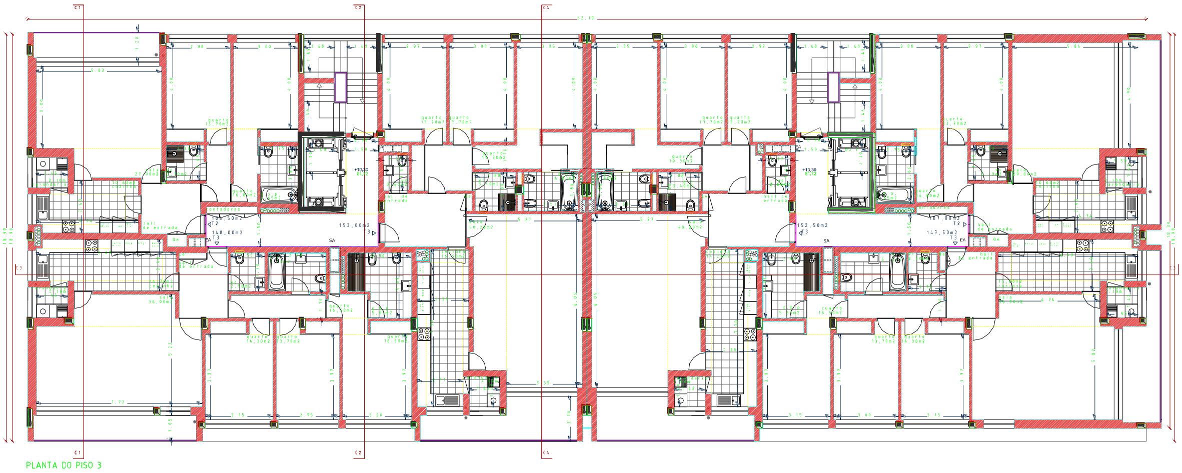


Figure 4.1 – Floor architectural plan (CIVI4, 2015).

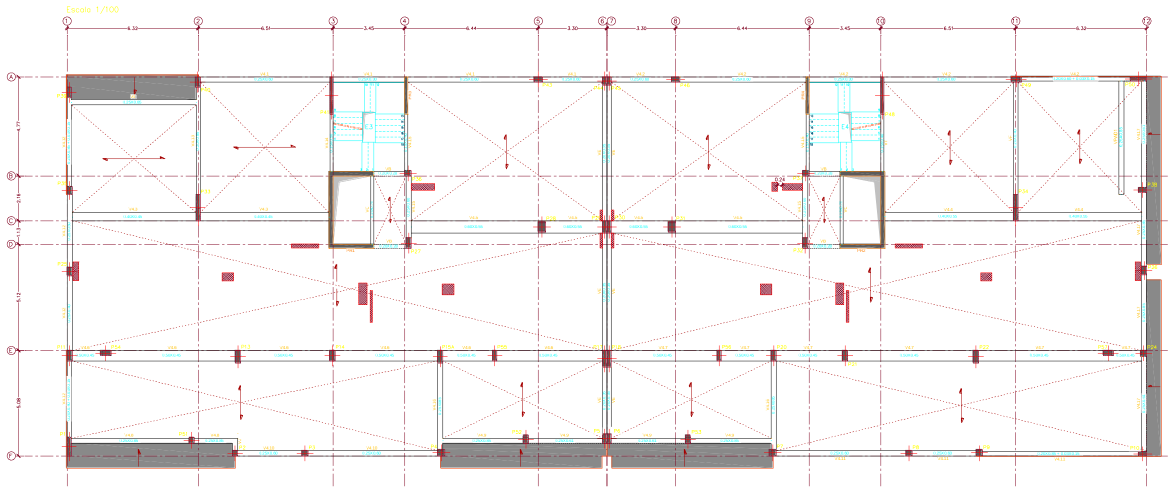


Figure 4.2 – Floor structural plan (CIVI4, 2015).

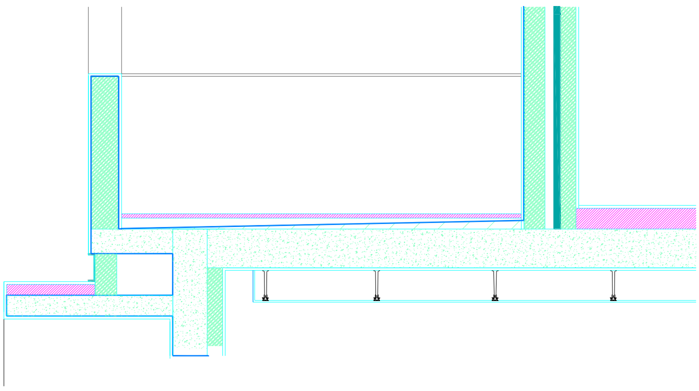


Figure 4.3 – Balcony with outside wall detail (CIVI4, 2015).

Figure 4.4 – West (at left) and East (at right) building facades (Prumocerto, 2015).

4.1.2.2. Building characteristics

In table 4.1 are gathered some characteristics about the study building withdrew from the building project. This information will be furthest useful.

Table 4.1 – Building Parameters.

Building Parameters	Specifications
Number of floors	7 (1 parking, 1 GF + parking, 5 residential)
Total roof area	985 m^2
Total floor area	6895 m^2
Structure	Reinforced Concrete (RC)
Envelope	Brick masonry
Foundations	Shallow (RC)
Walls (interior)	Brick masonry
Walls (exterior)	Brick masonry, exterior tessellation and interior insulation (XPS)

4.1.3. Problems and goals

After understand the type of system that we are dealing with, it’s possible at first sight to find some problems in it. However, before jumping into conclusions and fix it in any final design solutions it is essential to find the problems looking to the whole system, that is to the relations and boundaries in it. That happens because those problems result from our one dimensional way of looking at things which doesn’t contribute much for a sustainable solution.

Looking to the system and thinking about all the purpose of this work, there is an existent design project of a building and we want, throughout the sensitivity modelling find new ways or change others in order to achieve a more sustainable design project. The goal here is get to know the relevant parameters that we can play in order to redesign the building for a more efficient and sustainable design.

4.1.4. SYSTEM MAP

An easy way to better understand the system is representing it through a small sketch with pictures and symbols – see fig.4.5. That way of represent it, sometimes will reveal relationships and connections not seen before. Vester (2007) ensures that this way of doing things trains our imagination and blinds our system description to reality in a quite different way of right from the start.

Moreover, here it's possible for the first time think in the networks of influence among the key variables that will be approached in the ensuing steps.

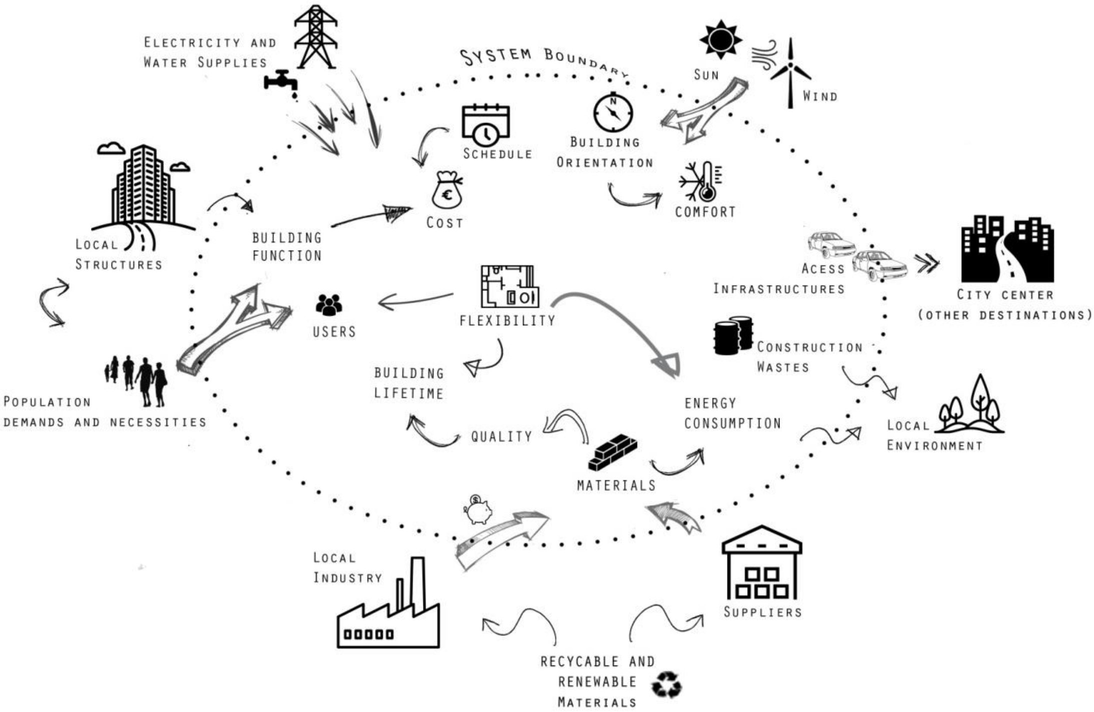


Figure 4.5 – System map (author, 2016).

4.2. THE SET OF VARIABLES

Variables (as their name implies) are quantities that can change, they should be flexible. During the course of sensitivity analysis, the interactions of each reveals show the cybernetics of the system. Cybernetics is the study of how a system control and communicate information.

In complex systems we can have many variables, most of them are components of that system, however just a few can be interesting for modelling it. In that way, sensitivity analysis is essential for model building and quality assurance. Some steps further, it will be possible to understand which variables are important to the system, most of them because of the interactions that they reveal.

Seventeen variables were identified. Most of them are based on typical parameters of a building design that can contribute for sustainability, as mentioned in fig.2.1. Others stem from the surrounding environment. In the steps above each one of them will be described and indicators will be used to represent each one of them during the run of the method.

4.2.1. Variables description

4.2.1.1. Cost

This variable includes the total cost of the whole building but including only the building design and construction phases.

4.2.1.2. Function

This variable is about the final purpose of the building design: habitation, education (ex: school) or commercial (ex: hotel). It depends on the flexibility and it could be affected by the needs of the city or society in terms of structures.

4.2.1.3. Energy Consumption

The consumption of energy in the building sector is a problem very discussed in the last years because on the one hand, energetic efficient buildings increase sustainability and on the other hand, energy consumption causes environmental impact. During the lifespan of a building, the life cycle energy (LCE) includes, among operational energy, two types of embodied energy (EE): initial embodied energy (energy consumed in manufacture, transport and construction of materials) and recurring embodied energy (energy associated to maintenance and replacement of materials during operation phase). In this way, embodied energy is the non-renewable energy required for raw materials extraction, processing, manufacture, construction, maintenance and demolition (this last one isn't always included) (Haynes, 2010). It is measured as the quantity of energy per unit of material and expressed in megajoules (MJ) or gigajoules (GJ) per unit weight (kg or tonne) or area (m^2) (Level, 2014). Embodied energy will be the indicator of this variable.

Operational energy won't be talked here because it depends on the use of the building. Operational energy is the energy consumed to maintain the internal environment and ensure system functionality during the operation/use phase of the building.

Choose certain materials properties like durability, locally sourced materials, and recycled materials can help to reduce embodied energy of building materials and also the environmental impact (Level, 2014). Fig.4.6 represents the EE cycle and how it's can be inserted in the building system. For this study only from manufacture until maintenance stages will be accounted.

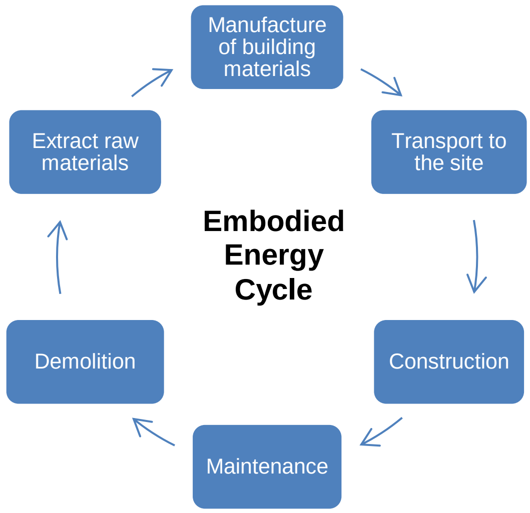


Figure 4.6 - Embodied Energy cycle (author, 2016).

4.2.1.4. Environmental Impact

During building life cycle, for all different stages, it is demanded energy to accomplish all the tasks and necessities. This amount of energy required brings as consequences the emission of greater quantities of greenhouse gas (GHG) into the air due mainly to the use of fossil fuel energy based.

This variable involves it: the impact of building design and construction phases in the environment. Since carbon dioxide (CO_2) represents around 80% of GHG, it will be the indicator of this variable. Besides GHG emissions, waste generation, soil pollution, resources consumption and effects on biodiversity represent other environmental impacts caused by building construction.

4.2.1.5. Structure Material

This variable includes the selection of different structural materials among construction industry. Selection of materials with certain properties like recyclable or reusable materials as well as materials with low EE coefficients and low environmental impact.

The materials selected to the analysis were reinforced concrete, steel and timber since they are the most common used structural materials.

4.2.1.6. Type/Quality of materials

Type and quality of structural materials used in the construction. Quality of materials can bring more costs but also more durability of the construction. For example, a study of how a change in resistance class of concrete affects variables such cost, energy, environmental impact or building lifetime. Concrete is used as example because is one of the materials used in larger quantity in the construction.

4.2.1.7. Flexibility

Flexibility is the adaptation of the space to new future changes by the users. Designing and building for variable conditions allow significant energy savings and more efficient use of resources (PennState). It can also extend the building lifespan.

4.2.1.8. Comfort

Well-being, comfort and health of the occupants are essential to improve their quality of life. In buildings, comfort is measured in thermal comfort (insulation, solar and wind exposure), visual comfort (strategic windows), air quality (ventilation, windows) and acoustic comfort (barriers and sound breaks) (Workshop).

4.2.1.9. Time

Expect time to finish the construction. It is very important that the construction be achieved in the expected time. More time involves more cost.

4.2.1.10. Slab

This variable indicator will be the length of the span. With long spans we can increase the interior spaces flexibility and reduce the number of columns. The length of the span depends on the structural material used: steel framed buildings allow longer spans than reinforced concrete frames. However, in average reinforced concrete buildings spans can measure until 8 meters. To understand better this topic let's have a look in the structural plan of the study building – see fig.4.7.

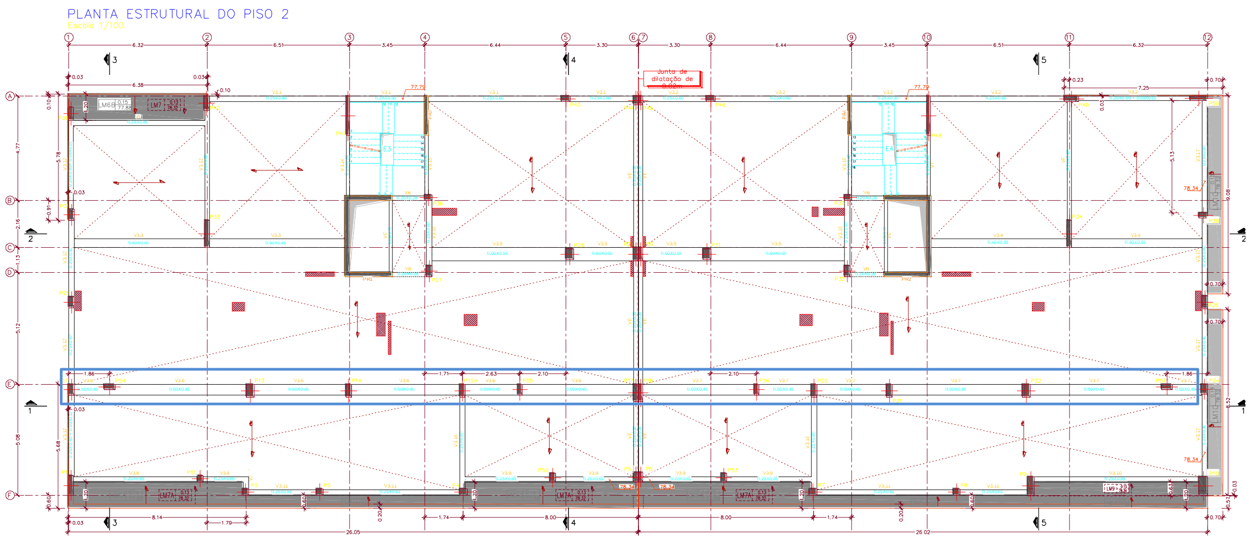


Figure 4.7 – Actual structural plan and possibility of increasing flexibility.

This plan composed by voided slab is inflexible because of its shorter spans (around 3.70m) in the bottom part of fig.4.7. To increase that span, an option would be, in the earlier design stage, remove the surrounding line of columns, increasing the span. However, for that be possible is necessary a more resistant slab, like a flat slab or higher slab thickness. As everything in construction that will bring extra costs, however, is ensured more flexibility and even a new future building function.

4.2.1.11. Building Orientation

A good orientation of the building is very important, mainly because of the sunlight and the benefits that could be taken from it. The building should be oriented to minimize summer afternoon solar heat and to maximize winter solar heat (PennState). Building orientation is measured by the azimuth angle of a surface relative to the true north (Workshop) - see fig.4.8. In fig.4.9, the actual study building orientation is represented with respective sun movements during summer and winter seasons.

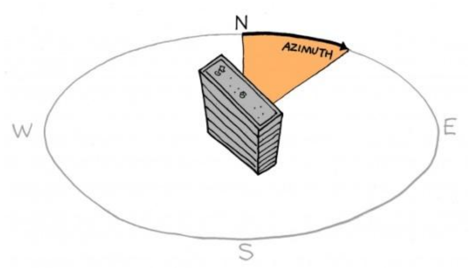


Figure 4.8 – Building orientation measure (Workshop).

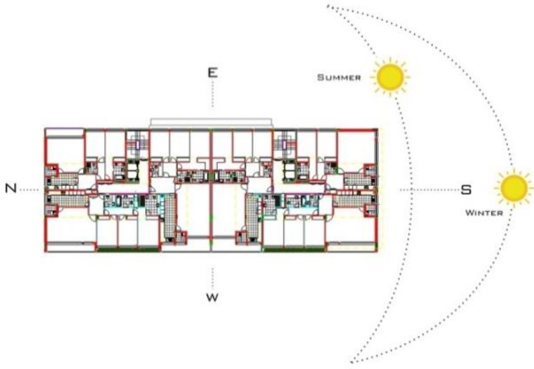


Figure 4.9- Study building orientation (author, 2016).

4.2.1.12. Insulation

This variable includes as indicators the insulation material and thickness. The effectiveness of the insulation depends on thermal resistance (R-value) of insulation material. More thickness increases the R-value, however there is a big list of materials which have different R-values among them and in this way comparing two materials with high and low values of R, the material with higher R-value needs less thickness to insulate a certain element.

Fig.4.10 shows that amongst the most common insulation materials the R-values and EE coefficients are very diverse. Assuming an insulation thickness of 100mm, the R and EE values of most common insulation materials vary as follow. – see fig.4.10.

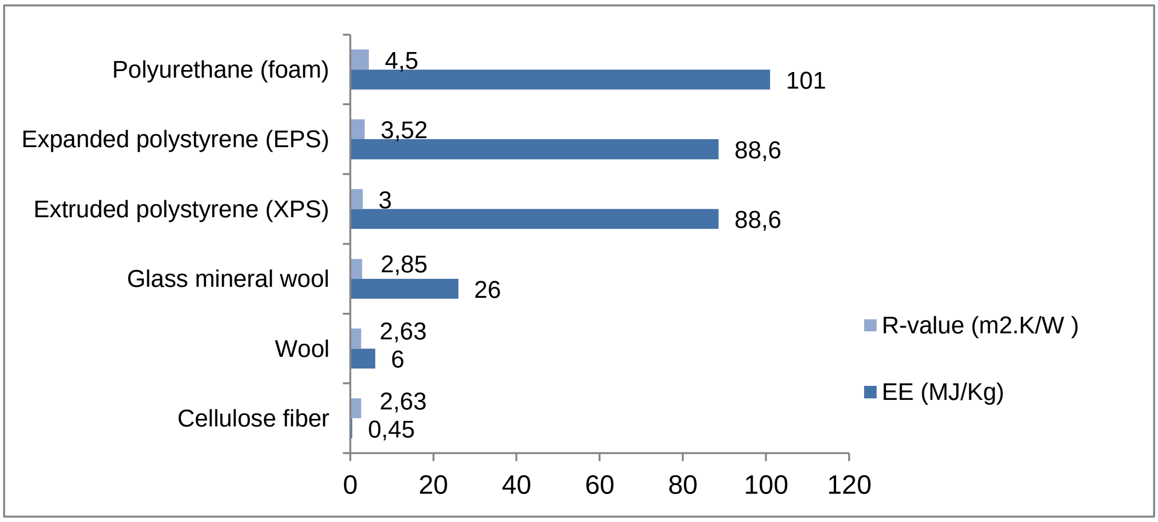


Figure 4.10 – Thermal resistance and embodied energy values of most common insulation materials (Greenspec).

In this way, chose an insulation material should be a weighted decision because, on the one hand materials with higher R-values (higher EE) lead to less thickness and on the other hand, lower R-values (lower EE) can bring to future extra costs in operational energy (e.g. for heating, cooling, etc.) because of heat losses or gains due to insufficient insulation.

4.2.1.13. Space Organization

This variable is about the plan disposal. Main living spaces like living rooms and kitchen face to south side. Bedrooms face to north side. It's related with the building orientation.

4.2.1.14. Space Division

This variable is about the division of the internal spaces inside each habitation. Walls that can be easily removed (ex: gypsum boards walls). This can be related with the flexibility of the space since that walls can be easily removed.

4.2.1.15. Attractiveness

This is about the attractiveness of the building to new users. Factors such as good location of the building and good access infrastructures are assessed. This variable is directly affected by the surrounding environment.

4.2.1.16. City/Population demands

This variable has is focus on the local city and its population. Function of the building matches with the city necessities in terms of structures. A city with too many dwellings doesn't need more. What does the city need? Social demands are a very important factor that can directly affect building durability and also new construction.

4.2.1.17. Lifetime

This variable includes the building lifetime. It's affected for many factors, mainly, economic, functional and social. If you double the life of a building and you use the same amount of resources to construct it, the building is twice as resource efficient (Lstiburek, 2006).

4.3. SYSTEM RELEVANCE

4.3.1. NATURE OF VARIABLES

After define the set of variables concerned to the system, it's important to understand the content and nature of each one in it. The set of variables should represent the 18 essential criteria of any viable system.

Within the essential criteria, there are all "spheres of life" from economic aspects to feelings and actions of those who are active in the system. Additionally, they should cover physical bases like matter, energy and information and also dynamic bases like flows of matter (e.g. power consumption, traffic, etc.), a structure rather than flow (e.g. accessibility, population densities, etc.), certain temporal dynamics (e.g. seasonal activity, climatic factors, etc.) and spatial dynamics (traffic revenue, industrial effluent, etc.). Besides, they need to be checked on their system relatedness: they can be variables that open the system by input (e.g. precipitation, dumping, etc.) or output (e.g. waste water, exports, etc.) and variables which are controllable from inside or outside (Vester, 2007, Wolf *et al.*, 2012).

All these criteria are checked for all variables with the help of the criteria matrix.

4.3.2. MATRIX OF CRITERIA

As mentioned in 3.2.2., one of the several features of SM is working with a manageable number of representative actuating variables in order to make the system model convenient to use.

Here the variables are reduced to a flexible number. That reduction is obtained through the relation between the variables with the 18 criteria mentioned before. In this way, we can reduce the variables in a secure way without omitting essential characteristics.

The matrix of criteria, represented in fig.4.11, is a useful and easy tool to relate the set of variables with the 18 essential criteria.

	Criteria →	SPHERES OF LIFE							PHYSICAL CATEGORY			DYNAMIC CATEGORY				SYSTEM RELATIONS			
●	FULLY APPLICABLE	Economy	Population	Space utilization	Human Ecology	Natural Balance	Infrastructure	Rules and laws	Matter	Energy	Information	Flow quality	Structural quality	Temporal dynamics	Spatial dynamics	Open though input	Opens though out	Influenced internally	Influenced externall
○	PARTIALY APLICABLE																		
1	Cost	●						●							○		○	○	●
2	Function			●			●				○		●	○				○	●
3	Energy Consumption	●			○	●				●		●		○	○	●		●	
4	Environmental Impact		○			●		●						○	○		●	●	
5	Structure Material	●				●			●	○		●				●	○	●	○
6	Type of material	○				○			○	○								○	●
7	Flexibility		○	○							○		○			○			●
8	Comfort	○	●		○	●							●					●	
9	Time /Schedule	○						○									●		○
10	Slab			○		○			●						●		●	●	
11	Building Orientation	●								●			○		●	●			●
12	Insulation					●				○		○	○		○	●		●	○
13	Space Ocuppation			●									●					●	
14	Space division			●									●	●				●	
15	Attractiveness		●				●				●	●	○	●	●	○	●	○	○
16	Population Demands		●					○			●	○	○	●	●	●			●
17	Building Lifetime	●	○							●			○		○	●		●	●
	Sum:	6,5	4,5	4,5	2,0	6,0	2,0	3,0	2,5	4,5	3,0	4,0	7,0	4,5	6,5	7,0	5,0	11,0	9,0

Figure 4.11 - System matrix of criteria (author, 2016).

4.4. EFFECT SYSTEM

In the previous step, the content and nature of the variables was known and, therefore, we know now the individual components of the system and the criteria that each one represents. Therefore, we are ready to build the model, i.e., analyses its effects in the systemic context.

During this step, which is divided in three different phases followed by discussion, we will get to know the system by other point of view and we will identify the relevant factors.

The three phases are: matrix of influence, index of influence and the matrix of consensus which are essential steps to the next step of the model where is known the variables cybernetic role in the system.

4.4.1. MATRIX OF INFLUENCE

The role of a variable in the system is defined through its interactions with the other components of the system and the interactions amongst themselves (Vester, 2007). The first step for a cybernetic description of the role of a variable consists in estimate in which way it influences each one of the others.

This may be achieved with the help of the influence matrix represented in fig.4.12. In this matrix the variables are arranged numerically from top to bottom (in row) and again, and in the same order, in line, from left to right. Strengths of relationships are given values of 0 to 3 (Vester, 2007):

- ✓ 0= no connection at all;
- ✓ 1 = a change in A brings about only a weak change in B;
- ✓ 2 = I need to change A a lot in order to achieve an equally big change in B;
- ✓ 3 = A changes little, but B changes a lot.

Easily, as far as the matrix is filled, we will understand on the one hand, how and in which way each variable affects the others and on the other hand, which ones are more influent in the system. This latter conclusion will be possible after all the matrix is filled through two new concepts: active and passive totals.

To the sum of the line correspondent of each variable we call active total, to the sum of the row of each variable we call passive total.

A variable which presents a high active total requires small modifications to affect significantly the system, the opposite happens if the variable has low active total. One the other hand, whether the variable presents a high passive total this means that if something happen in the system this variable is going to suffer large changes.

In this way it is possible to have an idea of the influence/importance of each variable in the system behavior.

This matrix will be a useful tool in the step 4.5 since it will help us to achieve the role played by each variable in the system.

	Influence by ↓ to →	Cost 1	Function 2	Embodied Energy 3	Environmental Impact 4	Structure Material 5	Type of materials 6	Flexibility 7	Comfort 8	Time 9	Slab 10	Building Orientation 11	Insulation 12	Space Organization 13	Space Division 14	Attractiveness 15	Population Demands 16	Durability 17	Active Sum:.	Product (P-value)
1	Cost	V1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Function	2	V2	2	2	1	1	3	2	3	1	0	0	1	1	2	0	1	22	132
3	Embodied Energy	0	0	V3	3	2	0	0	0	0	0	0	0	0	0	0	0	0	5	85
4	Environmental Impact	0	0	0	V4	2	0	2	0	0	0	0	0	0	0	0	0	0	4	100
5	Structure Material	3	0	3	3	V5	0	2	1	2	0	0	0	0	0	1	0	2	17	187
6	Type of material	3	0	2	2	3	V6	0	1	0	0	0	0	0	0	0	0	3	14	112
7	Flexibility	1	3	2	3	0	1	V7	0	0	1	0	0	0	1	1	0	3	16	288
8	Comfort	2	0	0	3	1	2	0	V8	0	0	3	3	3	0	0	0	0	17	238
9	Time /Schedule	3	0	0	0	0	0	0	0	V9	0	0	0	0	0	0	0	0	3	15
10	Slab	1	0	1	0	1	1	3	0	0	V11	0	0	0	0	0	0	1	8	24
11	Building Orientation	0	0	0	3	0	0	0	3	0	0	V12	3	3	0	0	0	0	12	36
12	Insulation	1	0	3	2	0	0	0	3	0	0	0	V13	0	0	0	0	0	9	54
13	Space Organization	0	0	0	1	0	0	0	3	0	0	0	0	V14	1	0	0	0	5	35
14	Space division	0	0	1	0	0	0	3	0	0	0	0	0	0	V15	0	0	0	4	12
15	Attractiveness	0	0	0	0	0	0	0	0	0	0	0	0	0	0	V16	0	1	1	6
16	Population Demands	0	3	0	0	0	0	2	0	0	0	0	0	0	0	0	V17	1	6	0
17	Building Lifetime	1	0	3	3	1	3	3	1	0	1	0	0	0	0	2	0	V18	18	216
	Passive Sum:.	17	6	17	25	11	8	18	14	5	3	3	6	7	3	6	0	12		
	Quocient (Q-value)	0,00	3,67	0,29	0,16	1,55	1,75	0,89	1,21	0,60	2,67	4,00	1,50	0,71	1,33	0,17	0,00	1,50		

Figure 4.12 - System influence matrix (author, 2016).

4.4.2. TABLE OF INFLUENCE STRENGTHS

Through the matrix of influences it's possible to build a table of influence strengths. This table, represented in fig. 4.13, shows at a glance which variables have a stronger effect on the system, which react strongly to it, and which perhaps do both (Vester, 2007). Furthermore, this table is an useful tool for the next steps, first of all to scale the index of influence and further for the role of variables.

In this table, variables with higher values of active and passive sum, as soon as they suffer any change, not only will assume a strong influence in the system as a whole, as well as will strongly react to changes inside it. Such behavior makes them crucial influence factors.

As fig.4.13 shows, variables like environmental impact, embodied energy and cost present a high value of passive total and building lifetime, function, flexibility, structure material and comfort a high value of active total. The first group is strongly affected by changes in the system while changes in the second affect markedly the system.

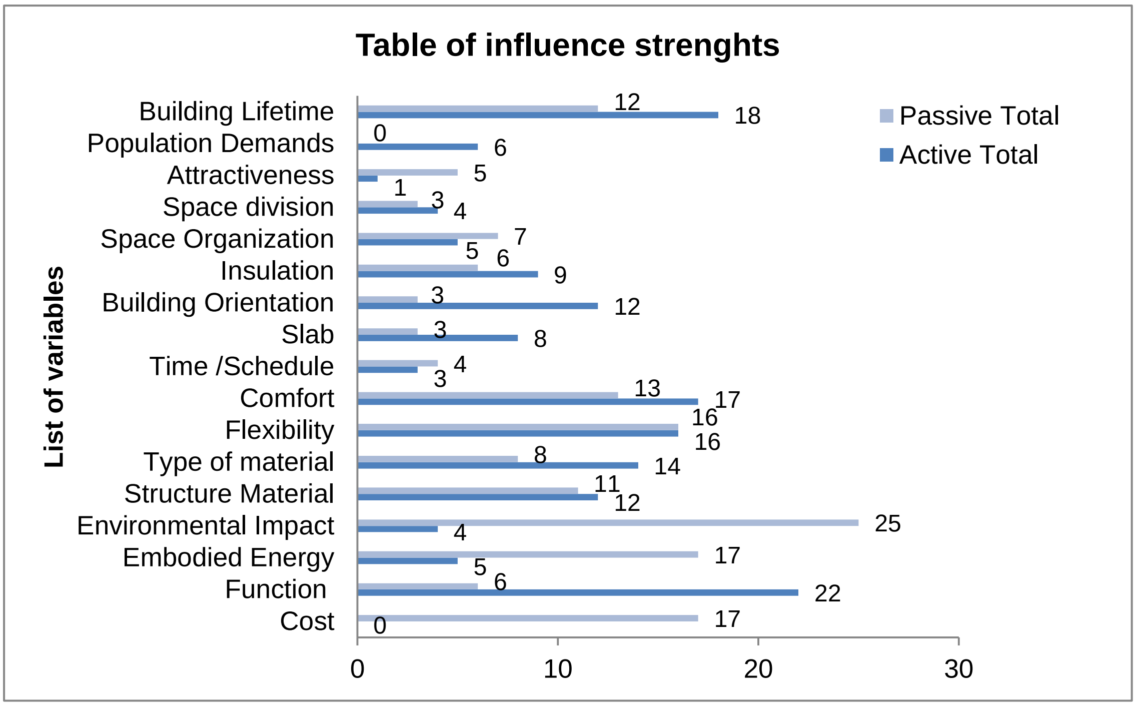


Figure 4.13 - Table of influence strengths (author, 2016).

4.4.3. INDEX OF INFLUENCE

There are questions that need to be done about the considered system. Where are the potential control levers? Which components can put the system in danger? In relation to which indicators are we doing analog improvements to threat symptoms? Which variables offer to the system a certain inertia that makes possible absorb even the great changes? To answer questions like these it's necessary go beyond active and passive totals (Vester, 2007).

Only the relation between passive and active totals, called "AT/PT quotient", reflects the active or passive variable cybernetic character. However, whether the question is until where variable plays a role in the system as a whole or how much is it involved in the events, this quotient is not enough. In this way, a second scale is needed, represented by the product (P) of each active and passive total.

Bigger that product, bigger the role and more relevant is the component in the system behavior (critical character). Fewer the product, fewer the variable role (buffering character) (Vester, 2007).

The quotients (Q) show us whether the system as something to say independently of its strength. A high quotient, even together with a low product, means that the variable in question has really something to say even that doesn't show.

In this way, the variables gain gradually a relevant position in the system. They can be active, critical, buffering or reactive, with all the intermediate stages between these four values patterns. Only the position of them in the two tension fields (between active and reactive and on the other hand between critical and buffering) will show whether and in which way the intervention in a variable, can or may be used, in the struggle with the study system (Vester, 2007). The meaning of each stage can be seen in table 4.2.

Table 4.2 – Vester's typology.

		Influenced by other factors (PS)	
		Weak	**Strong**
Influence on other factors (AS)	**Strong**	Active (Q is high)	Critical (P is high)
	Weak	Buffering (P is small)	Reactive (Q is small)

Active factors have more influence on other factors that they are influenced themselves. Passive factors are the opposite: more influenced by other factors than the influence they exert themselves. At a simple level, active factors might be potential levers of change, and passive factors measures of the system state (Vester, 2007). Buffer factors are neither influenced by the system or in turn influence it, and thus have the capacity to absorb change. Critical factors have high influence and are highly influenced by other factors as well.

Influence strengths were derived from influence matrix, fig.4.12, and the active and passive sums calculated, together with the product P = AS x PS and the quotient Q = AS / PS. These are measures of where a factor is placed on the continuum between buffering and critical (P) and between reactive and active (Q).

In the next step, role of variables, the position that each variable take in the two fields of tensions referred before, will be analyzed and interpreted in the cybernetics field of the study system.

4.5. ROLE OF VARIABLES

As mentioned before, cybernetics is the study of how a system control and communicate information. In this step the cybernetic character of each variable is revealed.

In order to easily reach this aim, Frederic Vester created a two-dimensional diagram, fig.4.14, in which it's possible to see the position of each variable among the four roles (critical, buffering, active and reactive).

The diagram is divided in quadrants, each one with a specific meaning. The location of each variable depends on the value of passive and active totals calculated in the impact matrix in 4.4.1.

Observing fig.4.14, a variable selection is made. The variables located below the first radial line are not very relevant for the system because their role is not important. Because of that, they will not be mentioned in the next steps. Our focus should be on the variables located above that line. These variables will set up the system. They show us the important interdependencies, which are the relevant controllers and the indicators. Furthermore, these variables are the primary candidates for the furthest step of partial simulation.

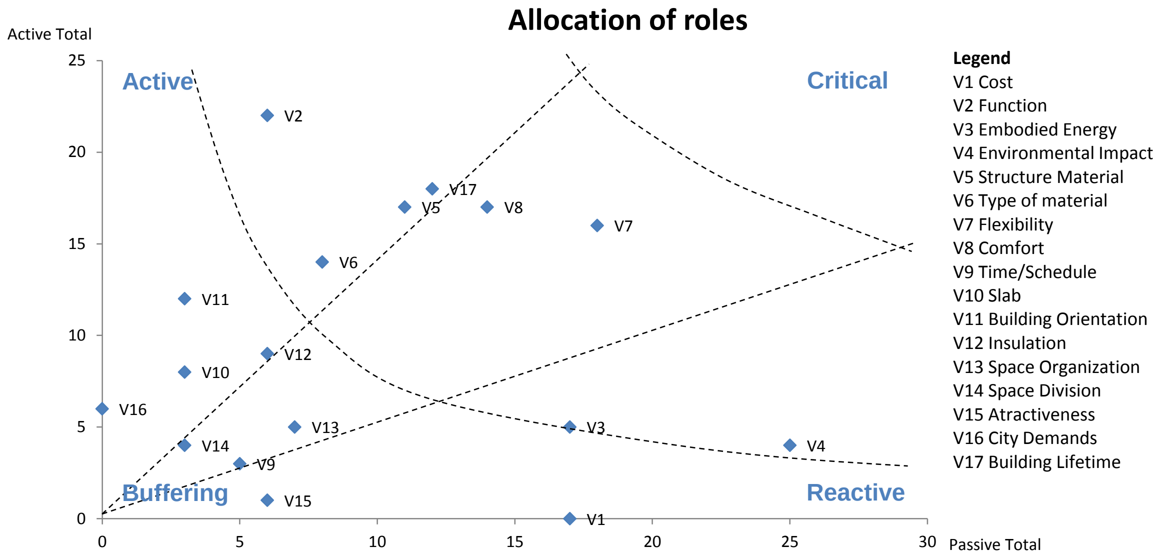


Figure 4.14 – Allocation of variables roles (author, 2016).

The diagram of roles, fig.4.14, shows:

- ✓ **Variable V1 and V3** are reactive variables. They are influenced by other variables but there isn’t influence on others. Those variables are very sensitive to changes in the set of variables and they are very good indicators of the system. Such result was expectable because on one hand the cost involved in the building is very dependent on almost all the variables of the present system and on the other hand every building component demand energy to create it.
- ✓ **Variable V4** is very reactive. This variable is strongly influenced by other and deserves a special attention since a small change in other variables can cause a large change on it.
- ✓ **Variable V2** is a highly active variable which means that it has a strong influence on other variables but it is weakly influenced by others. It is a good variable to control the system. The purpose of a building easily influences the set of variables since it has direct effect on them. If the function changes the other variables are strongly affected. **Variables V5 and V17** are also active variables and good controllers.
- ✓ The variables **V7 and V8** are also important in this analysis. Its location is in a denominated neutral area which represents the position of variables that are self-regulated, i.e., these variables don’t influence others or aren’t influenced by others, they depend on themselves.
- ✓ All the variables above the bellow radial line are important to the partial simulation;
- ✓ Active variables as V2 are good controllers of the system and reactive variables as V1, V3 and V4 are good indicators.

4.6. EFFECT STRUCTURE

4.6.1. SYSTEM INTERCONNECTEDNESS

Having reached this step, we know all the variables of the system and the role they play in it (active, reactive, buffering or critical). However, we don't know the direction of the effects that one variable has on another if a change occur. In this chapter, we will measure the effect that a change in one variable has on all other variables, in other words, a change on variable A is going to decrease, increase, improve or degrade variable B.

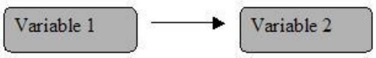
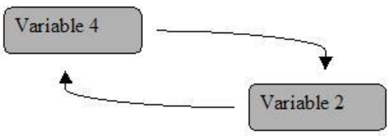
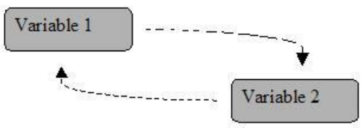
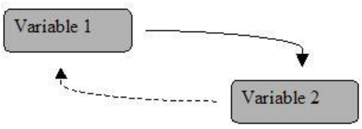
This step has something similar to the influence matrix because both represent links between variables, however here the links are examined differently like explained above. As a result of that, different links between variables can appear that we couldn't find in the matrix of influence. These links show us the system from a different perspective and it is possible to find errors that weren't observed before. In order to accomplish that it's really essential to build up the effect structure independently from the matrix of influence.

The effect structure will put the system's chains of effect and feedback loops visible, reflecting present reality in its multi-dimensional interconnectedness.

4.6.2. FEEDBACK LOOPS AND REGULATORY CYCLES

The interconnectedness is represented with feedback loops or regulatory cycles and the table 4.3 shows how are represented the basic elements of those cycles. The variables are linked not because of the influence strengths (like in matrix of influence) but for the direction that influence makes effect on others variables.

Table 4.3 – Description of the links between variables (Vester, 2007).

TYPE OF LINK	SIMBOLOLOGY		MEANING
Same direction	Continuous arrow		The more the first change the more the other change
Reverse direction	Dotted arrow		The more the first changes, fewer the other change
Same direction	Two continuous arrows	 **(Positive Feedback)**	Variables mutually reinforce each other in same direction
Reverse direction	Two dotted arrows	 **(Positive Feedback)**	A variable starts rocking at the expense of the other
Both directions	Continuous arrow plus dotted arrow	 **(Negative Feedback)**	Self-regulation. They have the property of absorbing changes or converting them into a pendulum movement.

The positive and negative feedbacks are more interesting and complex to understand under the system. The first ones are rare in living systems but the second ones are very interesting because they suggest the presence of self-regulation. It means that they have the property of absorbing changes so if the system is to remain stable in the face of disturbances, they should predominate over positive feedback loops (Vester, 2007).

Starting with individual variables links, it's possible to build all system network. Besides, we start to see that some variables defined in the beginning of this work have no connection at all with any other variable like was seen in matrix of influence. Variables like V9, V10 and V13 are a little isolate in the system since they only present an individual link.

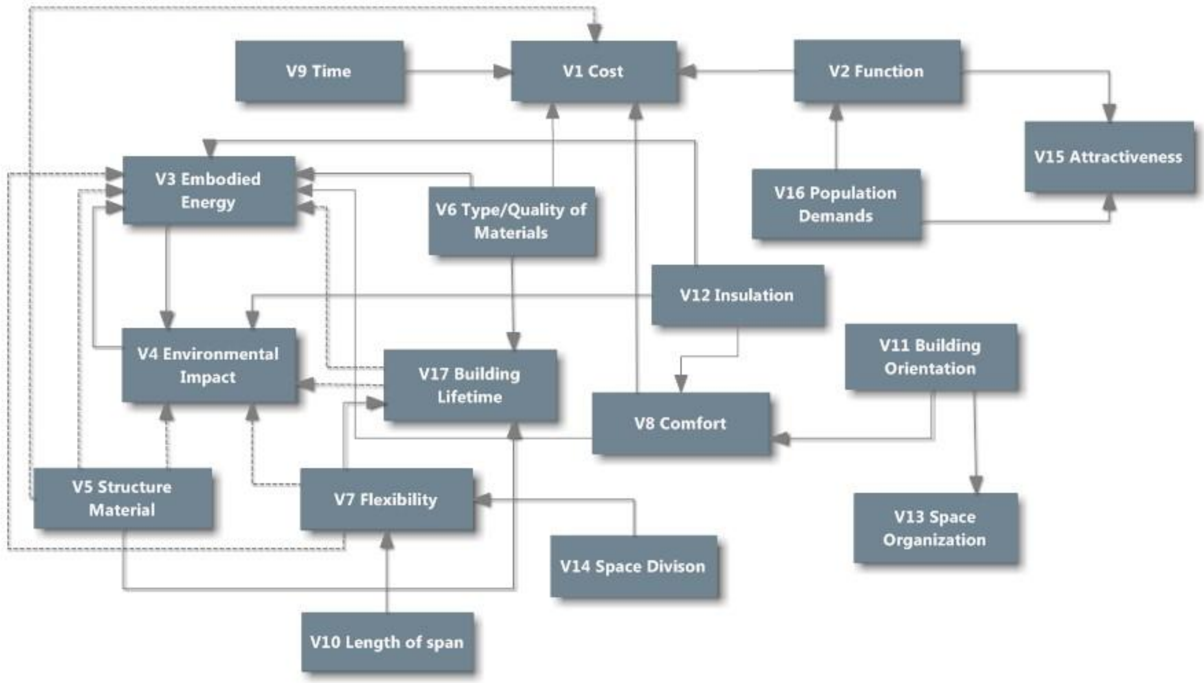


Figure 4.15 - System network developed using software *SmartDraw*.

In this network, fig.4.15, only one short positive feedback is visible. It involves Embodied Energy and Environmental Impact variables. If embodied energy demand increase, environmental impact will increase. If embodied energy decreases, environmental impact will decrease as well.

4.7. PARTIAL SCENARIOS

Partial scenarios represent a small specific part of the effect structure regarding to an issue of particular thematic interest. They should have between two and ten variables, however small partial scenarios made up of three or four variables can show often clear cybernetics functions.

The partial scenarios aim is to allow understanding the cybernetic examination of specific interesting areas of the system in a clearer way. Due to the limited time to develop this work, only a scenario was studied.

4.7.1. Partial scenario 1 – Embodied energy demand

One of the main topics to consider during the building design phase is the energy use. In this work, the energy consumption is measure in terms of embodied energy and thus this partial scenario will focus on this topic and it will show how the embodied energy demand is controlled.

Although the cost and the environmental impact may be as well important questions in design phase, the energy demand is one of the main problems and concerns at this phase, which brings consequences in terms of global greenhouse gas emissions.

So, an interesting question could be: **how can we reduce the embodied energy consumed by the building?**

For this partial scenario were selected the following variables: Embodied Energy, Structure Material, Environmental Impact and Building Lifetime.

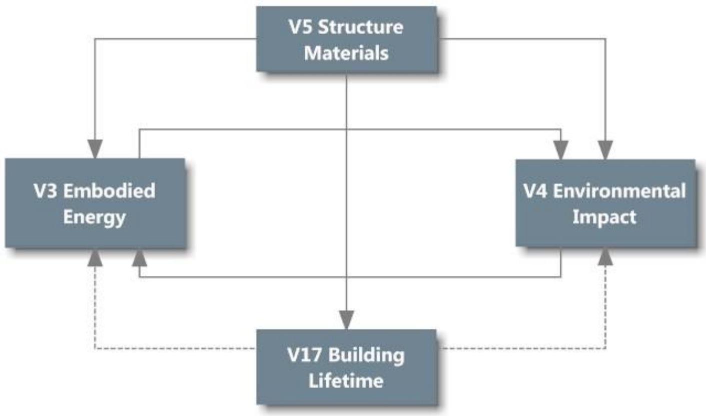


Figure 4.16 – Partial Scenario 1: How can we reduce Embodied Energy consumed by the building?

4.8. Simulation

Now that we have the partial scenario, the next step is the scenario simulation. Simulation is a tool that allows understanding the cybernetics of the system. It reveals how the system reacts, for example, to an increase or decrease in a certain variable (Vester, 2007). The basis for simulation is the partial scenario mentioned in 4.7.1.

4.8.1. Scales for variables

The way used to measure, in reality, the effect that a change in a certain variable has in other variables is through mathematical functions which represent, with satisfactory accuracy, the relation between each two variables. Accordingly to the values obtained, it is possible to build scales for each variable concerned to the partial scenario, fig.4.16, where is clear whether the scale position is ok, careful or dangerous. With these scales the model user easily understands how a change in a variable affects the other variables.

4.8.1.1. Embodied Energy – Building Lifetime

According to (Cole and Kernan, 1996, Ramesh *et al.*, 2010), life cycle energy (LCE) demand (embodied and operational energy) of residential buildings is in the range of 150-400 KWh/m^2 per year. Furthermore, according to the same article the percentage of embodied energy consumed by a building is 10-20% of total LCE and thus the embodied energy consumption per year in residential buildings, during its lifespan, is about 15-40 KWh/m^2 (0.054-0.144 GJ/m^2).

As mentioned in 4.2.1.3., embodied energy includes both initial and recurring embodied energy. In this study, the initial embodied energy is the energy consumed by building materials manufacture and construction, the transport to the site will be excluded since there isn't data about it.

Since in this study there is a lack of information about building materials quantities used in the construction it was assumed, based on a value of a similar building studied in Talakonukula *et al.* (2013), a total initial embodied energy value of 48,891.6 GJ (7.09GJ/m^2).

Furthermore, in the 1-10 years period it was assumed that none of the materials were replaced which means that no recurring energy was demanded, and thus the value for 10 years corresponds to the initial embodied energy value over the 10 years. For year zero, the value corresponds to the total initial EE over two years, normal period to conclude construction works.

The remaining values include both initial and recurring EE and were obtained through the same relation observed among the embodied energy values of case of study by Rauf and Crawford (2015) for different building lifetimes over a period of 150 years.

The values of EE per year for each building lifetime were obtained through the expression (2.1).

$$EE = \frac{Energy\ demand\ for\ each\ lifetime}{Total\ floor\ area \times Years\ of\ lifetime}, GJ/(m^2.year) \quad (2.1)$$

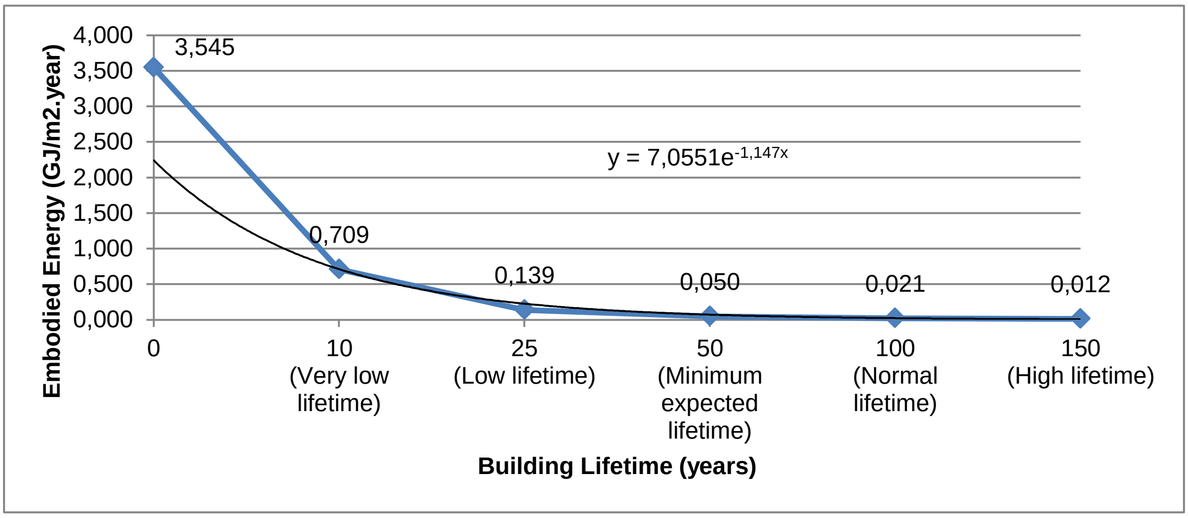


Figure 4.17 - Embodied energy demand according to each different building lifetime.

The fig.4.17 shows the demand of EE during building lifetime and respective mathematical relation between these two variables using Excel. However, as we can see the tendency curve is a bit lagged from the original curve, especially between 0-10 year's period. To prevent future errors, it was used MATLAB software in order to obtain better results at this level. As represented in fig.4.18, the function obtained is much more adjusted to the real values as shows the coefficient of determination (R^2) close to 1.

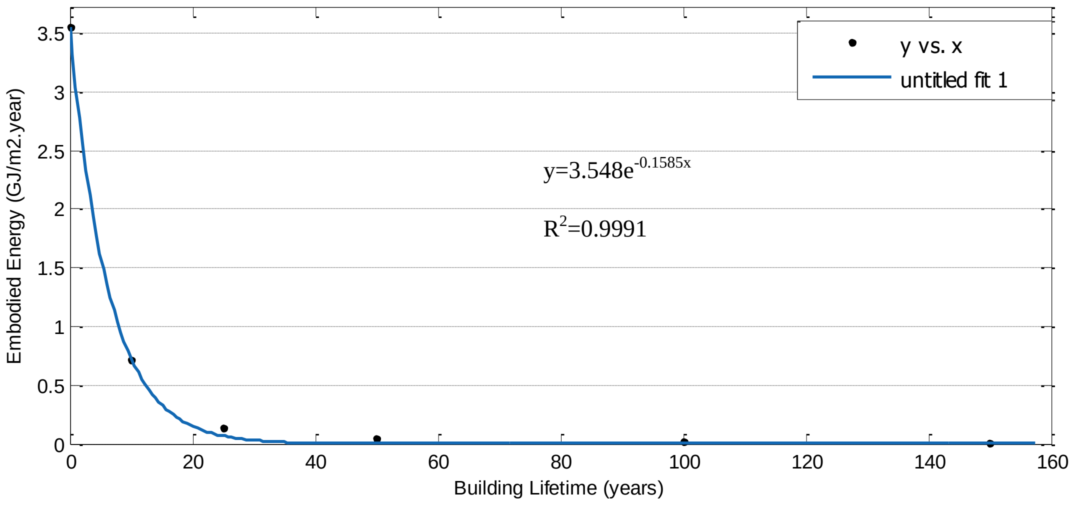


Figure 4.18 – Embodied Energy demand according to each different building lifetime using MATLAB.

According to Rauf and Crawford (2015) the values of embodied energy decrease with the lifetime of the building, the longer the building lasts, the lower its annual life cycle embodied energy demand. Such fact can be explained by the decreasing of initial embodied energy over the years and the increase of recurrent energy after some years of lifetime. However, the demand of recurrent embodied energy is much lower than the initial embodied energy demand. In the first it's the energy demand to build a whole building, and in the second the energy consumed for occasional repairs.

4.8.1.2. Environmental Impact - Embodied Energy

The link between these two variables, observed in fig.4.16, is called positive feedback which means that the two variables mutually reinforce each other, and in this case, in the same direction (Vester, 2007). Every stage of building requires energy input and lead to GHG emissions output, mainly CO_2 emissions, as represented in fig.4.19. Therefore, the environmental impact variable will be measured in terms of CO_2 emissions and it will be explained how an input of energy in the system leads to CO_2 emissions output.

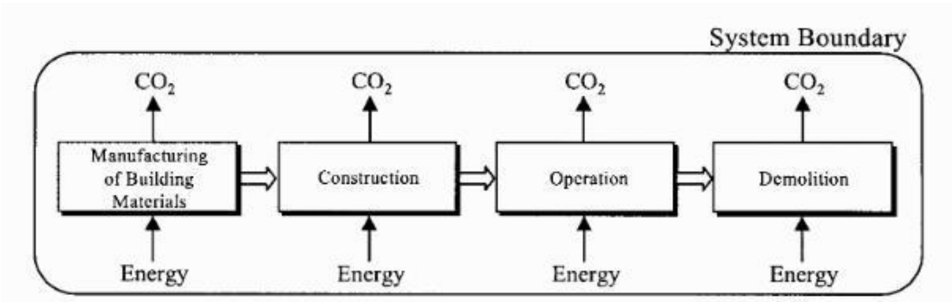


Figure 4.19 - Energy and CO2 relation in the system (Seo and Hwang, 2001).

To reduce CO_2 emissions from building phases, there are two options: reduce the energy input or make that energy cleaner, i.e., replace fossil-fuel energy based for energy derived from renewable sources as hydroelectric, wind and solar energy. With regard to energy reduction, it means reduce the embodied energy input since it's the only energy approached in this study.

However, this relation is a bit complex since a correct evaluation of the environmental impact of a building should go beyond the building initial phases where only EE is accounted. Many studies reveal that the operational energy, which corresponds to 80-90% of building LCE, is the one responsible for the greater quantities of CO_2 emitted by buildings (Ramesh *et al.*, 2010, Seo and Hwang, 2001). Such fact can be explained on the one hand because is the longer phase of the building where users use energy to maintain their quality of life, and on the other hand the main operational energy sources are fossil fuels (coal, gas etc.).

However, in this study only EE is approached and so only the relation of it with CO_2 emissions will be explained.

In several studies (Hammond and Jones, 2008, Jeong *et al.*, 2012), it was found some data that relates embodied energy demand and CO_2 emissions by construction. In table 4.4, it's presented some values of each parameter for those studies and the percentage relation between them.

Table 4.4 - Embodied energy and CO_2 emissions by different buildings.

Area (m^2)	Embodied energy (GJ/m^2)	CO_2 emission ($KgCO_2/m^2$)	Relation (%)	Ref.
84.9	5.82	531.21	1.09	(Jeong *et al.*, 2012)
102.5	6.58	602.93	1.09	(Jeong *et al.*, 2012)
149.5	6.05	557.19	1.08	(Jeong *et al.*, 2012)
several cases	5.34 (average value)	403 (average value)	1.32	(Hammond and Jones, 2008)

Looking at table 4.4, EE demanded by a building corresponds to 1.15% (average value) of CO_2 emissions by that building. This percentage is applicable to manufacture of construction materials only.

In order to scale EE, as mentioned in 4.8.1.1., the embodied energy in a building corresponds to a 10-20% of total LCE, hence it was considered 10% a conventional low EE value and 20% a conventional high EE value. Conventional means, in this case, conventional construction from reinforced concrete structure. So, if the initial value of 48,891.6 GJ (3.55 GJ/m^2.year) used in 4.8.1.1 corresponds to 11% of LCE, for 10% is 3.22 GJ/m^2 per year and 20% is equal to 6.45 GJ/m^2 per year. An average value corresponds to 4.83 GJ/m^2.year, i.e., 15% of LCE. These values are applicable to manufacture and construction phases and are represented in fig.4.20.

The CO_2 emissions values correspondents to each EE value were obtained through the relation above of 1.15%.

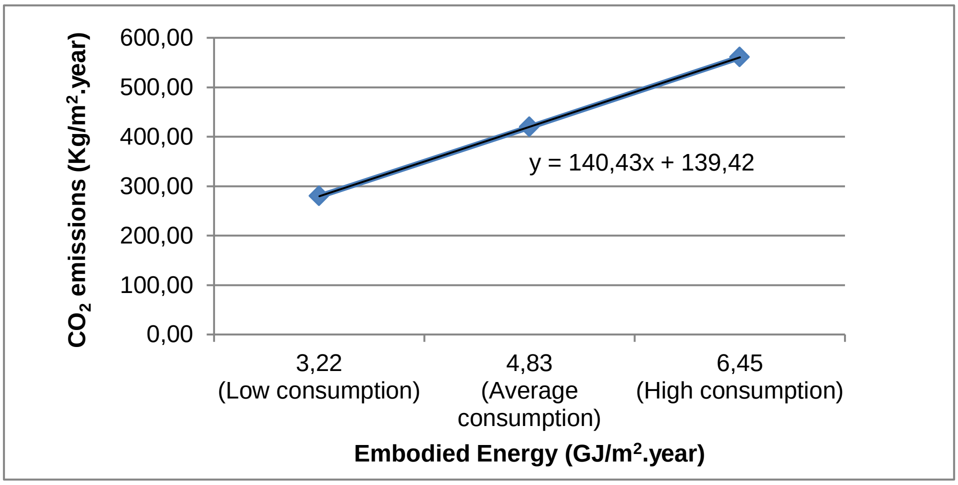


Figure 4.20 –CO_2 emissions according to Embodied Energy demand.

The reduction of EE can be achieved through the use of mixture of materials instead of use conventional materials. Example of it is the use of concrete with recycled materials like fly ash or blast furnace slag, the substitution of aluminum for timber pieces and a lot of other options which can reduce significantly the EE of the entire building and consequently the CO_2 emissions.

After understanding how EE demand affects CO_2 emissions in a building it's important to understand how the opposite happens. As before, less CO_2 emissions include less EE consumed. Some articles (Cho and Chae, 2016, González and Navarro, 2006) explained the life cycle of carbon emissions (manufacturing and construction) in low carbon buildings (column B) and how it differs from conventional buildings (column A) – see table 4.5.

Table 4.5 - Difference of CO_2 emissions in conventional and low carbon buildings.

Area (m^2)	**A CO_2 emission (Kg/m^2)**	**B CO_2 emission (Kg/m^2)**	**Emissions of B in relation with A (%)**	**Ref.**
526	268.057	195.975	- 27	(González and Navarro, 2006)
1078	480.1	369.3	- 23	(Cho and Chae, 2016)

Looking at table 4.5, it's possible to assume a relation of less 25% (average value) emissions between conventional and low carbon buildings. Conventional buildings are buildings built with traditional methods of construction, in this case, brick masonry envelope. Taking into account Peng and Wu (2015), where a similar building was studied, it was assumed for this case of study a value of CO_2 emissions due manufacture and construction of 4298.78 tonnes (311.73 KgCO_2/m^2.year). Assuming that value as an average value of CO_2 emissions in a conventional building, the value of 233.8 KgCO_2/m^2.year can be assumed for a low carbon building. The variation of embodied energy according to each CO_2 emissions quantities is represented in fig.4.21.

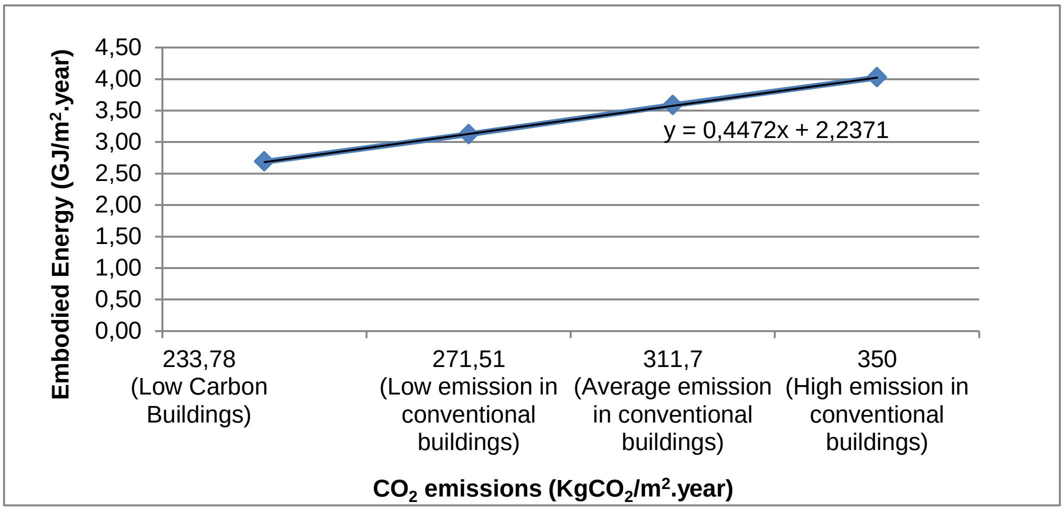


Figure 4.21 – Embodied Energy demand according to CO_2 emissions.

As explained in Haynes (2010) independently of embodied energy and CO_2 emissions being different aspects they are dependent of each other and so they evolve in the same way.

4.8.1.3. Environmental Impact – Building Lifetime

According to Seo and Hwang (2001) the range of values for CO2 emissions in residential buildings resulting from construction (including manufacture) are 38.11-62.01 Kg-C/m^2 per year. To measure the relation between these two variables, two approaches were made. The first one, as mentioned in 4.8.1.2., for the study building it was assumed the value of 4298.78 tonnes (311.73 KgCO_2/m^2.year) for manufacturing and construction stages, i.e., for year 0 (over 2 years) and for year 10 (over 10 years) using the expression 2.2.

Analogously to expression 2.1, the quantity of CO2 emissions per area per year (C) were calculated through expression (2.2):

$$C = \frac{Total\ emissions\ per\ phase\,(Kg)}{Total\ \ floor\ area \times Years\ of\ \ lifetime}, Kg/(m^2.year) \quad (2.2)$$

The remaining values were obtained using the percentages of 49% and 35% of initial 4298.78 tonnes of CO_2 for 25 and 50 years respectively, and 84% and 71% of 50 years emissions value for 100 and 150 years observed in Rauf and Crawford (2015). The second approach was to use the relation of 1.15% between EE and CO_2 emissions observed in 4.8.1.2 combined with the EE values of 4.8.1.1. It was observed that both results were similar, however to keep the consistency the second approach was used and it is presented in fig.4.22.

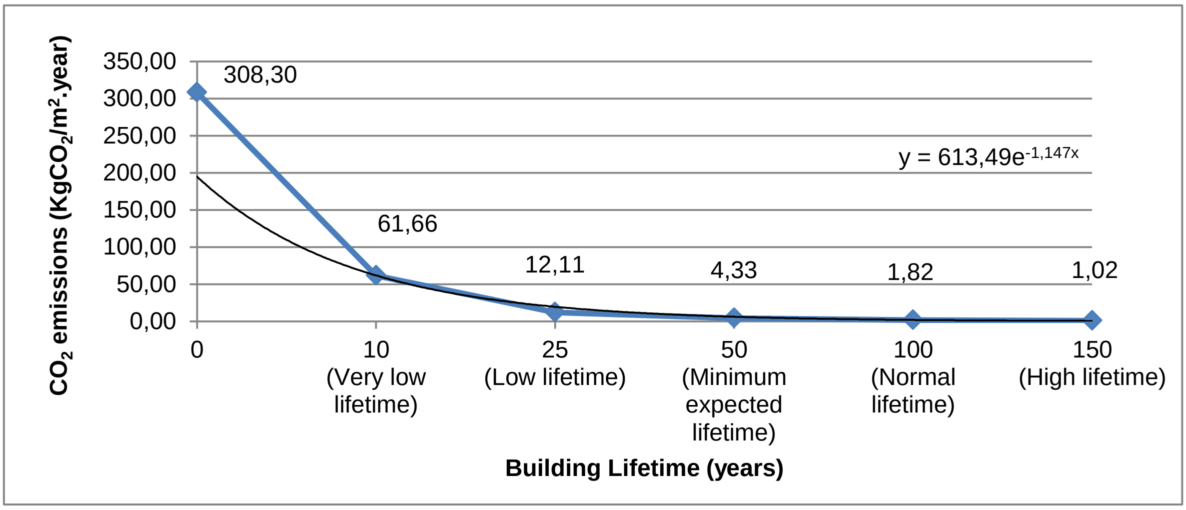


Figure 4.22 – CO_2 emissions according to each different building lifetime.

Observing fig.4.22, it's noticeable that the mathematical relation between the two variables presented is not close from the real values what can lead to bad results. To correct that it was used the software MATLAB to find a better curve for this relation – see fig.4.23.

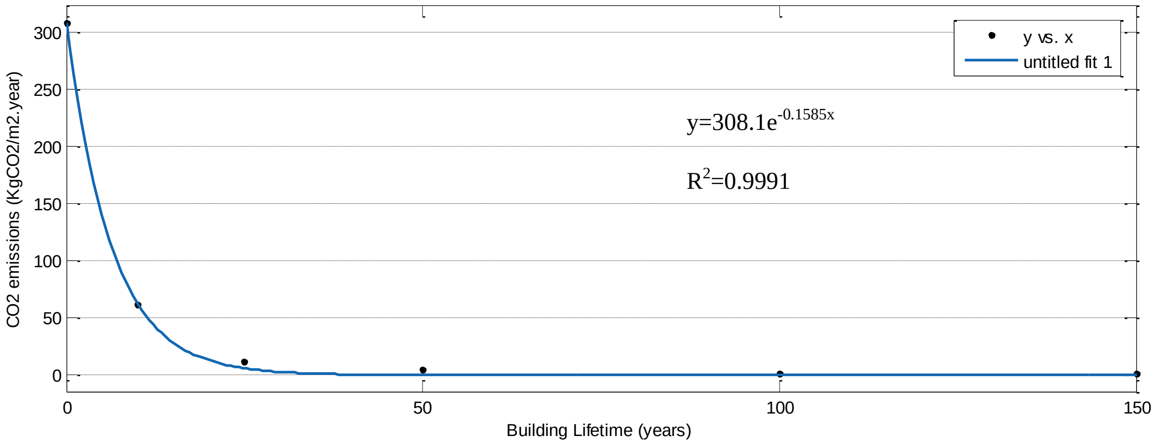


Figure 4.23 – CO_2 emissions according to each different lifetime using MATLAB.

As expected, see fig. 4.23, increasing the lifetime of the building the CO_2 emissions will decrease, mainly because if a building lasts more it means that the building materials present good properties, such long lifespan, which means that less changes will be required and thus less energy demands and consequently less CO_2 emissions.

4.8.1.4. Structure Material – Environmental Impact

The choice of the structural material for the building frame is one of the most important to reduce energy demands, environmental impacts and even building costs (Kim *et al.*, 2013).

In some studies which show that among all the parts that form a building, the structural system is the one that more contribute for energy demands and environmental impacts (Perez Fernandez, 2008).

Concrete can be considered the most used material in construction. However, its production causes great environmental problems, mainly due to the GHG emissions. This fact can be explained because cement is one of its main components and its production use fossil fuels energy based which are the main responsible for these GHG emissions during its combustion (Kuruscu and Girgin).

A wood structure is not so common in Portugal although is a very good option in terms of GHG emissions, embodied energy demand and energy efficiency. Furthermore, at the end of building service life, wood can be recycled or reused and it's also a renewable material fig.4.26. However, for that be true it's essential that the wood comes from a sustainable source with the respective certification. In that way it's guaranteed no deforestation of green reserves and ensured replanting (Papakosta, 2016). The taller wood framed buildings, fig.4.25, are nowadays possible because of the technology of "mass timber", which includes products such as Cross Laminated Timber (CLT), Laminated Strand Lumber (LSL) and Laminated Veneer Lumber (LVL). These products composed with thin layers of wood, fig.4.24, that are not only stronger than conventional timber, but thanks to their uniformity and straightness, are also simpler to design and build with (Arstechnica, 2012).

Figure 4.24 – CLT panel disposition (Ebnesajjad, 2016).

Figure 4.25 – "The Cube", tallest CLT building in Europe (London) (BKStructures).

The steel is considered environment-friendly due to its recycling potential (93%) however, the production of it leads to great CO_2 emissions and energy demand for the same reason of cement production.

Figure 4.26 allows us to better understand the end-of-life scenarios of each one of the structure materials.

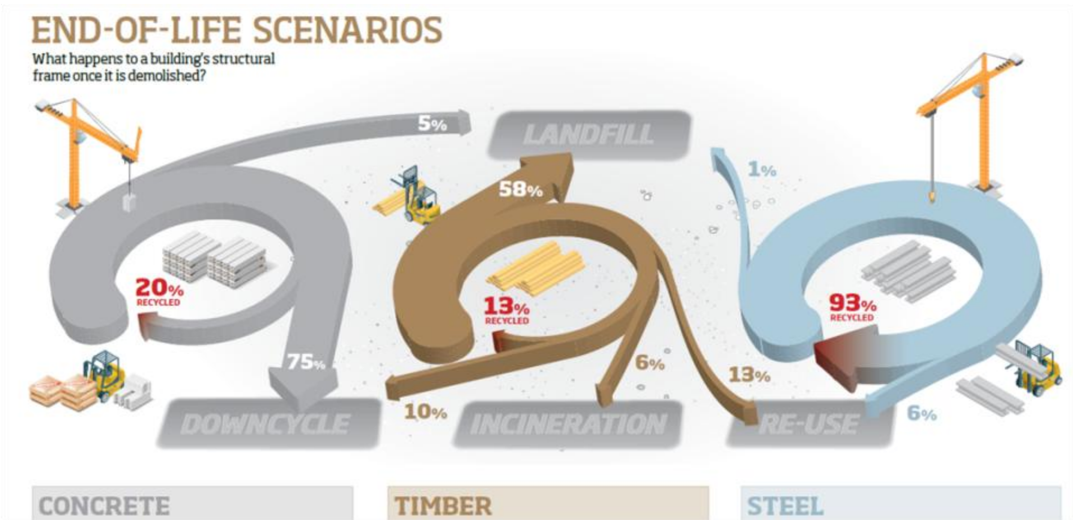


Figure 4.26 – End-of-life of different structural materials (Construction).

Like in 4.8.1.2, the environmental impact variable will be measured in terms of CO_2 emissions, and in this case resulting from the use of different structure materials (wood, concrete and steel). For the wood structure was chosen a CLT structure since it is more realistic for this study due to its common use in medium and high rise buildings.

Accessing some studies about the use of different structure materials amongst steel, concrete and wood, it was gathered some information presented in table 4.6.

Table 4.6 – Differences of CO2 emissions among structural materials.

Area (m^2)	Material	CO2 emission (Tonnes of CO2)	Concrete relation (%)	Ref.
19,027.78	Steel	10,461.34	135	(Kim *et al.*, 2013)
18,861.61	Concrete	7,731.55		
51,076.63	Steel	27,249.08	138	(Kim *et al.*, 2013)
50,959.81	Concrete	19,774.08		
14,127.58	Wood (CLT)	2,370	40	(Chen, 2012)
14,127.58	Concrete	5,980		
4,154	Wood (CLT)	655	39	(Darby *et al.*, 2013)
4,154	Concrete	1661		

As table 4.6 shows, steel and wood structures were correlated with concrete structures in terms of CO2 emissions. In fig.4.27 was used the average percentage of each relation with reinforced concrete structure, 137% for steel structure and 40% for timber structure.

The values of fig.4.27 include CO_2 emission due to construction stage, assuming 2 years for this stage.

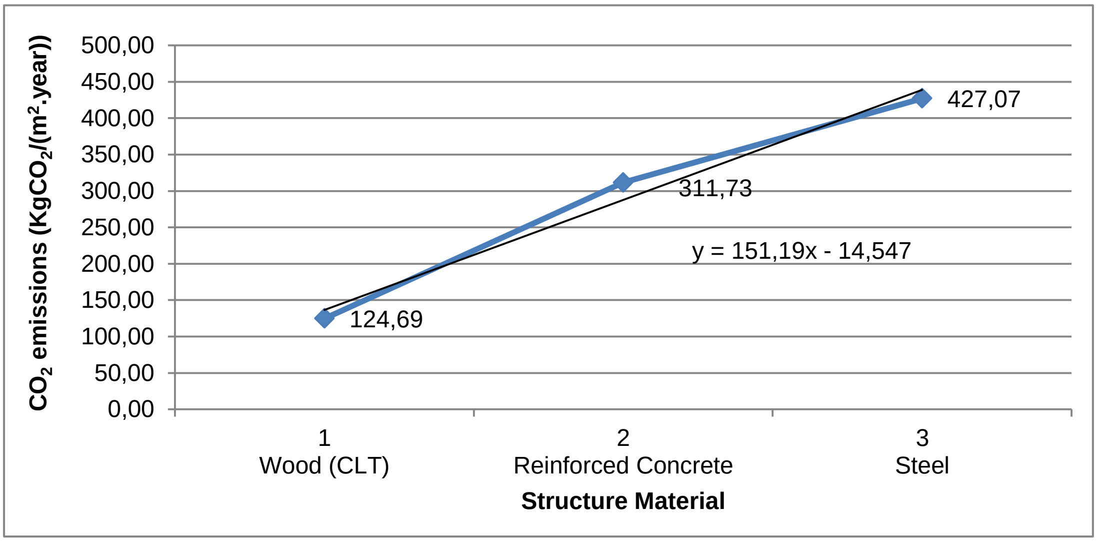


Figure 4.27 – CO2 emissions by different structure materials.

As expected, a wood framed option is the more environment-friendly. Such fact can be explained by the fact that wood, besides release less CO_2 during its manufacture, also the trees have during its life the capacity of carbon sequestration which sometimes is represented by negative CO_2 emissions (Darby *et al.*, 2013).

4.8.1.5. Structure Material – Embodied Energy

According to Griffin *et al.* (2010), the structure of a building should be a primary target for reducing the embodied energy of a building. Depending on the material, it is also sustainable and economically favorable. In this way, it's essential that, in the building design phase, the designers consider this issue and choose materials also durables but environment-friendly, to replace the conventional materials and thus reduce the energy demand and hence the environmental impacts.

Cole and Kernan (1996) developed a study with different structural systems among wood, concrete and steel, where they found out the differences of each structural option in the life cycle energy of the building.

In present case of study, for the concrete structure, was used the previous EE value of 3.55 GJ/m^2 per year. For the remaining materials, the EE values were withdrawn from different articles, represented in table 4.7, where was conclude that a steel structure requires more 4% of EE than a concrete structure and CLT structure requires less 18% than concrete one.

Table 4.7 – Embodied Energy for different structure materials.

Area (m^2)	Structure	Embodied Energy (GJ/m^2) Structure	Non Structure	Total	Concrete relation	Ref
4,620	Concrete	1.17	3.62	11.24	-	(Cole and Kernan, 1996)
4,620	Wood	0.92	3.62	10.86	0.97	(Cole and Kernan, 1996)
4,620	Steel	1.48	3.65	11.69	1.04	(Cole and Kernan, 1996)
14,127.58	Concrete	-	-	3.42	-	(Chen, 2012)
14,127.58	Wood (CLT)	-	-	2.80	0.82	(Chen, 2012)

The values presented in table 4.7, refers only to the total initial embodied energy. Recurring embodied energy is not accounted at this point because that energy is associated with the maintenance and replacement of building materials and it is directly affected by different materials life cycle (Rauf and Crawford, 2014) which is very difficult to estimate.

In the values accessed from Cole and Kernan (1996) it is clear the difference of energy demand for different types of structures, since the energy required for non-structure materials is almost the same in the three cases – see table 4.7.

Thus, based on table 4.5 relation values, for the study building the total initial embodied energy demand per year, assuming 2 years for construction stage, vary as the fig.4.28 shows:

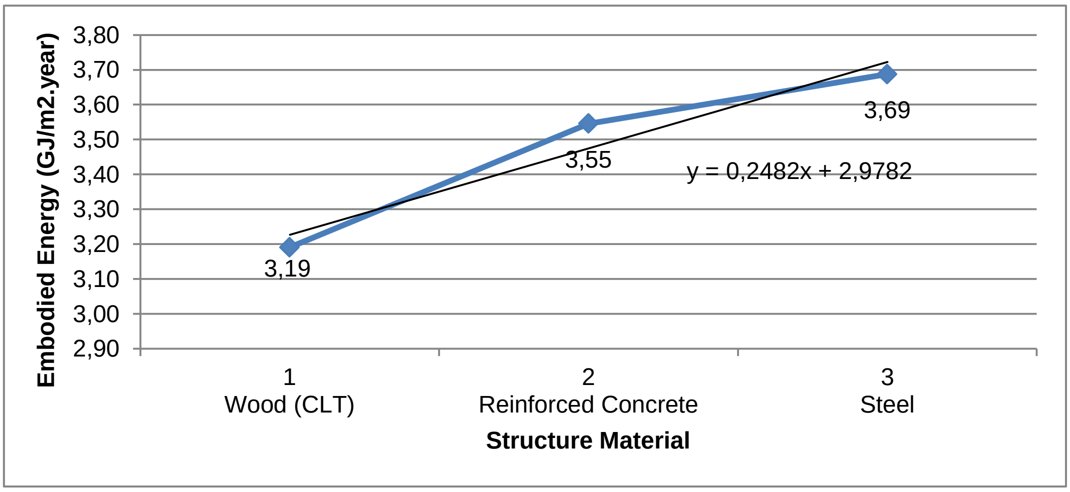


Figure 4.28– Embodied Energy for each structural material.

One more time, a wood-framed building plays a favorable role in terms of EE demand and CO2 emissions than the other two options. The manufacture of wood products requires less energy than other materials and its residues can be used as energy supply for other industries (Gustavsson *et al.*, 2006). With regard to the relation between concrete and steel structures, the concrete structure seem to be a better choice as well as in other several articles, however according to Griffin *et al.* (2010) a simulation with a special tool revealed the opposite. In this way, this relation above will be used here but may not be reliable.

4.8.1.6. Structure Material – Building Lifetime

The lifetime of a building depends on a few factors among economic, social and functional. The economic problem arises from a building when maintenance costs are no more viable comparing with the demolition costs. The social problem is related with the function of the building and the local city development, and the last one is related with the condition of the building, structurally, i.e., if it remains serviceable. However, in the majority of cases, the main reason for building end of life is not due to structural problems but economy and building function no more suitable.

In EN (1992) a concrete structure is generally dimensioned for 50 years in good conditions however, most of them can start to deteriorate after 20 to 30 years due to lack of maintenance. Furthermore, there is a lack of research about this topic, since it's a question that depends on other many factors.

If it's assumed a correct maintenance of the building, a building structure can last more than 100 years regardless of the material that compose it. Some years ago, state something like that about a timber structure could have been ignored, although if we think about Pombalina downtown, in Lisbon, there it is possible to find wood structures with more than a century and in very good conditions.

Since this is a matter where many factors are involved, it was decided, for this work, do not consider this relation and, in this way, avoid future discussions and disagreements.

4.8.2. Assumptions and uncertainties

Over the developing of subchapter 4.8.1, due to lack of data and differences of information among consulted articles some assumptions were made and thus uncertainties in data will be inevitable.

Variables such as embodied energy and environmental impact are very difficult to estimate. EE is obtained through the product between the quantity of specific material and it correspondent EE coefficient per unit. The problem here is that there are a lot of databases that present different EE coefficients among them for the same material. According to Hammond and Jones (2008), there are some reasons to explain these differences such as use of different methodologies to calculate EE, boundary conditions and general assumptions. The same happens when calculating CO2 emissions by buildings.

Furthermore, on this work, since there wasn't data about quantities of building materials it was assumed, based in structurally similar buildings, the values of embodied energy demand and CO2 emissions. Such assumption brings even more uncertainties in the results. In some relations only the initial EE was accounted because recurring embodied energy is difficult to estimate over the long term since the non-renewable energy contents of replacement materials, components or systems are difficult to predict (Canadian Architect) and this is also directly related with materials and components lifespan which are not known.

When analyzing building lifetime due to different structural materials, it was neglected the possibility of lack of maintenance, so it was assumed an adequate maintenance of the building. However, this is not predictable and so the failure could be derived from lack of it or improper use of the building.

Another important aspect is about the energy source used during the different building stages studied here, it was assumed fossil fuel energy based and hence the EE and CO2 emissions values are assumed based on that.

4.8.3. Partial scenario 1: simulation

After defined all the mathematical relations between partial scenario variables, we are now able to start the simulation. The simulation of a sensitivity model helps us to better understand the cybernetics of the system. It shows how the system reacts to a change in a certain variable and how a relation between two linked variables changes over time.

To build the model, fig.4.29, it was used a software called *Simulink* developed by MathWorks used for modelling, simulation and dynamic systems analysis. As we can see, the partial scenario of fig.4.16 is the basis of this model.

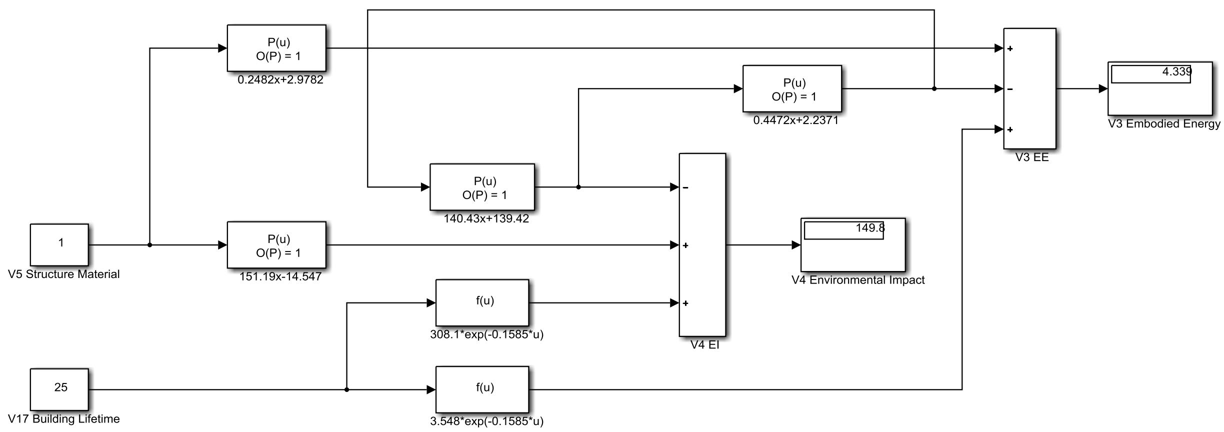


Figure 4.29 – System model in Simulink (author, 2016).

The simulation occurs round by round where some variables are changed in order to see the consequent effects that those changes have in the entire partial structure. That process is called “policy test”. Besides that, those changes over the time, round by round, are represent by effect flows which show the evolution of the variables during the simulation.

In this partial scenario simulation, variables Structure Material and Building Lifetime are both active variables, as explained in 4.5 and good controllers as well. In this way, this simulation was controlled by different inputs of those variables and the effects of it in the other two variables of the partial structure were recorded. As a result of this simulation, the effect flows are presented in the graph bellow – see fig.4.30.

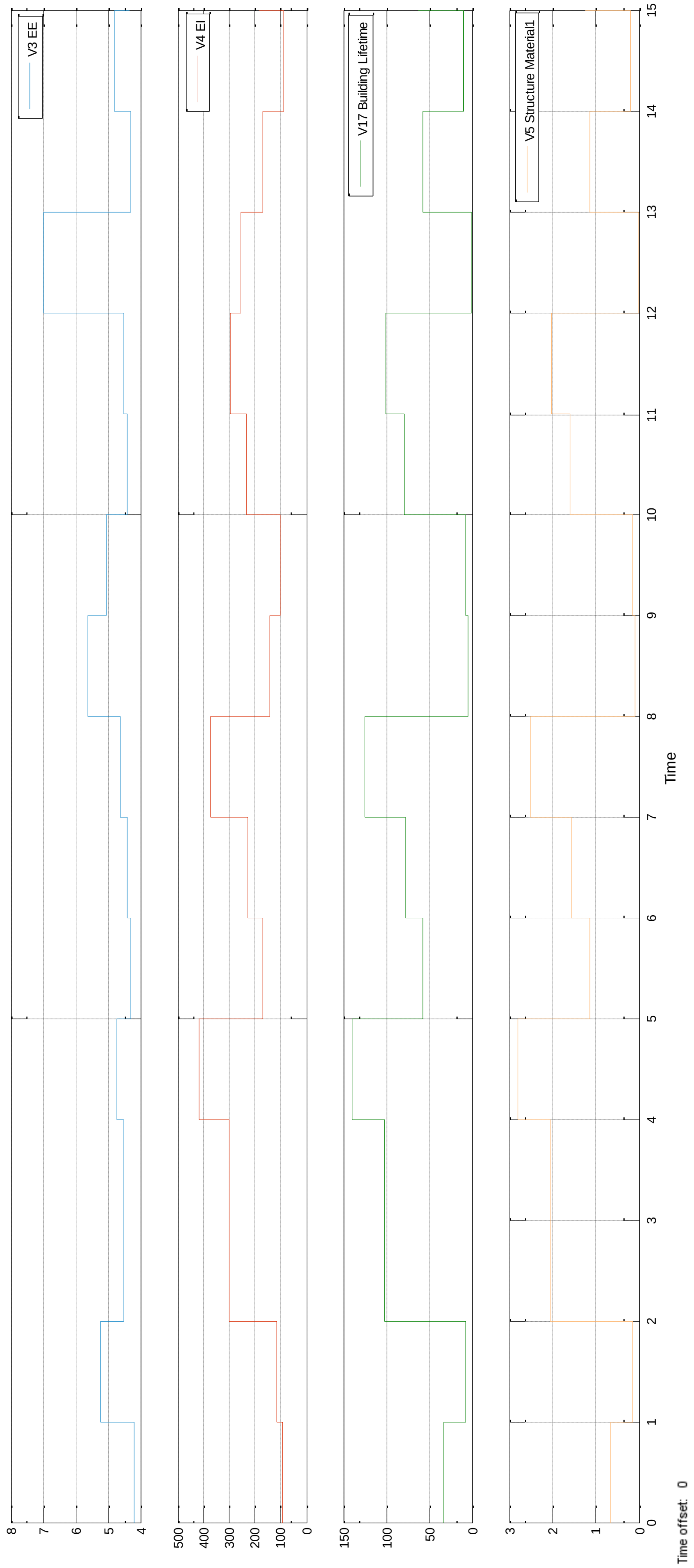


Figure 4.30 – Development of variables during simulation.

Fig.4.30 represents the effect flow resulting from the simulation of the partial scenario. Observing “environmental impact” variable it’s possible to understand that design of buildings for few years of lifetime is not a good solution in terms of CO_2 emissions. The values observed in fig.4.30 are decreasing with the increase of lifetime. It’s environment friendly a building design for many years.

Besides, the maximum values of this variable are related with the use of steel framed design. In terms of this variable, an optimal solution to reduce CO_2 emissions building would be a design for long lifetime (100 years) when concrete is the main structural material or the use of wood/timber in structure solutions combined with shorter lifetimes (25, 50 years). The steel frame design is not recommended because increases a lot the CO_2 emissions even for long building lifetimes.

Looking at “Embodied Energy” variable, as well as “environmental impact” it also decreases with the increase of “building lifetime” variable however in a subtle way. A strategy for low EE consumption building is a concrete based design for 100 years of lifetime or a wood based design for lower building lifetimes. Again, steel frame revealed not be a good option in reducing EE demands.

The understanding of the simulation effect flow for these variables, help us to control the system: whether a certain variable is too high or too low we know how to proceed to change it for a better solution.

4.9. SYSTEM EVALUATION

The last step of the SM procedure is the system evaluation. It consists in evaluate the system according to the eight basic rules of the bio-cybernetics. They reflect how a system should function in order to be long-term sustainable. Taking them into account brings new ideas which are essential helping to solve problems within the system.

The eight basic rules are followed described (Vester, 2007):

i. **Self-regulation:** Negative feedback must dominate over positive feedback. Positive feedback sets things in motion through self-reinforcement, while negative feedback ensures stability against disruptions and excesses.
   To explain this criterion, Vester (2007) uses the example of a predator (wolf) and its prey (hare), where body weight, running speed and kill frequency form a feedback loop. The faster the wolf runs, the more hares is capable to catch. The more hares it catches, the fatter it becomes, ergo the slower it becomes, the fewer hares it can catch, and the thinner it becomes again, ergo the faster it is able to run again and so on and so forth.
   As fig.4.15 shows, in the study system the negative feedback exceed the positive ones. However, we can’t say that the system is totally self-regulated. For example the variables “structure material” and “building lifetime” aren’t, in reality, directly interlinked because the building lifetime not only depends on the structure material, it depends in many factors and in the way buildings are used and maintained as well.

ii. **Independence of growth:** the system’s function must be independent of quantitative growth. A system mustn’t growth beyond its limits. An uninterrupted growth and a greater degree of interconnectedness can lead to a chaos reducing stability. To apply this rule, the function of the system should be clear otherwise it’s impossible to evaluate if the function could be realized in a different manner (with less energy, less raw materials, etc.) than done today (Wolf *et al.*, 2012).
   Design for habitation is the function of the study system. It is boosted by the necessity of building quality (more quality, more durability and more attractive) and the growing

preoccupation in environmental problems. To improve building design it's necessary reduce energy and water demands and when possible the cost. To reduce energy demand by the building, a strategic choice of materials should be done as well as a design for a long lifetime.
As the environmental exigency grows, the building design needs to be more and more efficient and innovative. This is not a strategy of quantitative growth.

iii. **Orientation of functions:** The system must operate in a function-oriented, not a product-oriented manner. The system and its product are interlinked, if the product ceases to exist so the system providing it. On the other hand, systems that provide a function are more flexible and viable.
Individual buildings are designed to satisfy specific requirements of clients in the light of specific conditions of the site, such as its area and shape, flexibility of the ground, climate of the area, surrounding environment, including surrounding buildings and infrastructures (Co-operation and Development, 2003). The building function is also an important factor for the design. In this way, building design is both product-oriented and function-oriented.
However, it should be capable to overcome the challenge of being more attractive than the other buildings with the same function.

iv. **Jiu-Jitsu Principle:** In the context of a system, the developments and trends impact society, companies and people on many different levels. They can be seen by companies as threats to them position in the market or they can be seen as a chance to develop new products, services, etc. According to this, companies can adopt two sides: they can fight against the developments and conserve its status-quo using what is called the "boxing principle", or they can incorporate those developments in their business and gain a larger market and more profits by manipulating existing forces to their own good (Wolf *et al.*, 2012). This position is called the "Jiu-jitsu Principle".
The construction sector, including design engineers, has been confronted with the necessity to reduce energy use and environmental impacts with more efficient and effective building designs. To use the "jiu-jitsu principle" in the building design, it should be developed according to some sustainable design strategies like use of recyclable materials, take advantage of the sunlight, etc. in order to diminish the environmental issues.
Furthermore, as people become more informed and more aware about the environmental problems caused by inefficient building designs or simple construction negligence, they will be more critics about the "product" that they are buying or living in and more sensitive to this issue.

v. **Multiple Use:** no single product or process should be used in isolation but rather in conjunction with others. Multiple uses reduces throughput, enhances interconnectedness, and cuts expenditure of energy, materials and information.
The study system only allows a single use: habitation. However, it can change with the existence of flexibility in the plan. Other uses such as education (e.g. school) or commercial (e.g. hotel) can be possible in a flexible building structure.

vi. **Recycling:** The cycle of materials should be closed where waste products can be reincorporated in the life cycle of the system involved. Furthermore, industries from different sectors should join together and find ways to exchange their waste products in order to make a sustainable use of materials. This last issue leads us to the seventh rule.
One of the problems of the construction industry is the large waste generation. However, only developed countries have had the preoccupation of reutilize those waste materials and minimize the construction wastes. The building design phase is where the selection of building materials is made. The decision of use certain materials like recyclable, reusable or recycled

materials is at this stage. Some building materials used in great quantities can be recycled like steel (with 93% of recycling power), concrete and wood – see fig.4.26.

Besides, the construction industry also takes advantage of wastes from other industries like steel production (e.g. blast furnace slag), thermoelectric centrals (e.g. coal combustion fly ash) and from municipal waste ashes (Cabeza *et al.*, 2013). Those materials are combined with concrete reducing the cement quantity and thus the environmental impact.

vii. **Symbiosis:** symbiosis is the closes coexistence of different species for mutual benefit. The building appears in symbiosis with other systems like the population that need a home, the construction materials industry that depends on the construction sector etc.

The construction industry is linked with a few other industries which their existence also depends on the construction sector. Different building materials and equipment's companies, service companies (e.g. architecture, engineering, consulting, etc.) and further furniture companies and other services companies (e.g. legal services, decoration, etc.) are directly affected by construction sector. If the last is bad the others will suffer economic impacts.

viii. **Biological Design:** products, services and methods should be designed in way to not harm natural structures and functions and people's health. Although all the appeals from different environmental organizations in reducing the environmental problems resulting from construction sector, some countries continue to neglect this issue. Even that a new green materials appeared to solve or reduce some of those problems, the larger quantity of construction materials continue to be produced with fossil-fuel based energies. The consequence of that are the continuous emissions of greenhouse gas into the atmosphere which affect even more the climate.

Considering all the rules above mentioned and how the system includes them, it was built the following estimation of the total system – see fig.4.31.

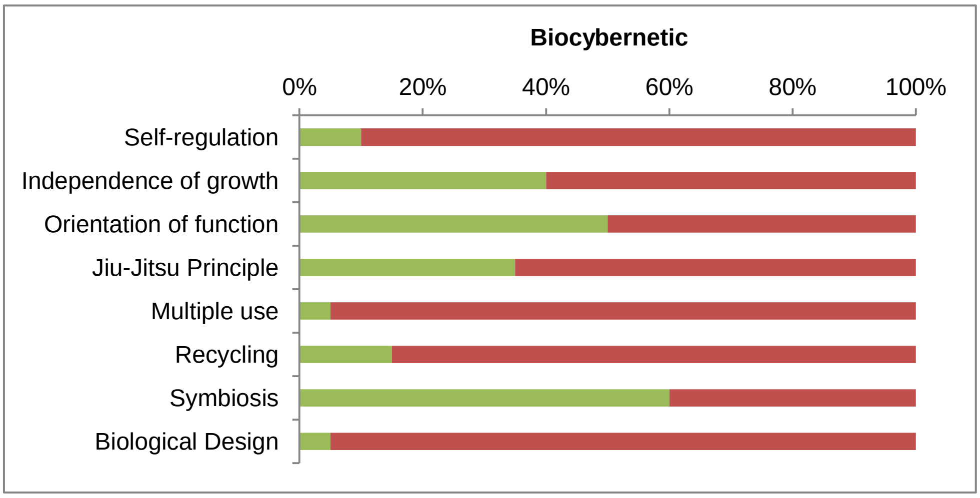


Figure 4.31 – System's Evaluation (author, 2016).

The green bars represent the extent of the rule that is regarded by the system. On the other hand, the red bars represent what needs to be done in order to fulfil that rule. This evaluation helps us to understand where the system is strong and where it needs to be improved.

According to fig.4.31, the larger problems in the system are in the multiple use and biological design criteria. The first one can be improved by a flexible building design, capable to adapt to changes in the building users and functions easily. The second problem is more complicated: even thought, in Portugal, there are preoccupations in more sustainable building designs, the use of concrete and steel as primary structural materials will continue for a long time and thus the environmental problems that came with it. The inherent properties of these materials make them dominant choices for building design. However, new materials should be explored as alternatives for these two: wood for example, in Portugal, there are a lot of wood constructions which last centuries. Self-regulation is also a weakness in this system however the chances of improvement are very limited.

The strongest criteria are orientation of function and symbiosis. The design of a building is totally dependent of its function. Whether function is a hospital, a school, a shopping or a habitation the design process is always different. Each function has its particularities and need to fill in some requisites. An improvement of this criterion in the future may not be relevant since a system should be function-oriented and it happens in the analyzed system. Contrary to the previous criterion, symbiosis can be improved. A necessity of find new materials and technics demanded by more sustainable designs can create new links with other companies, benefiting each other.

Besides these changes, recycling and biological design also have potential to be enhanced. The future environmental demands for new building materials, which can be mixed or replace the old environmental harmful materials will bring an improvement in these both criteria. On the one hand, the use of mixed materials like concrete combined with fly ash or blast furnace slag will grow and thus the other industries wastes exploitation. On the other hand those new materials are more environment-friendly contributing to the environmental impacts reduction.

Gathering all these possibilities of criteria improvement in the future, a new evaluation results – see fig.4.32.

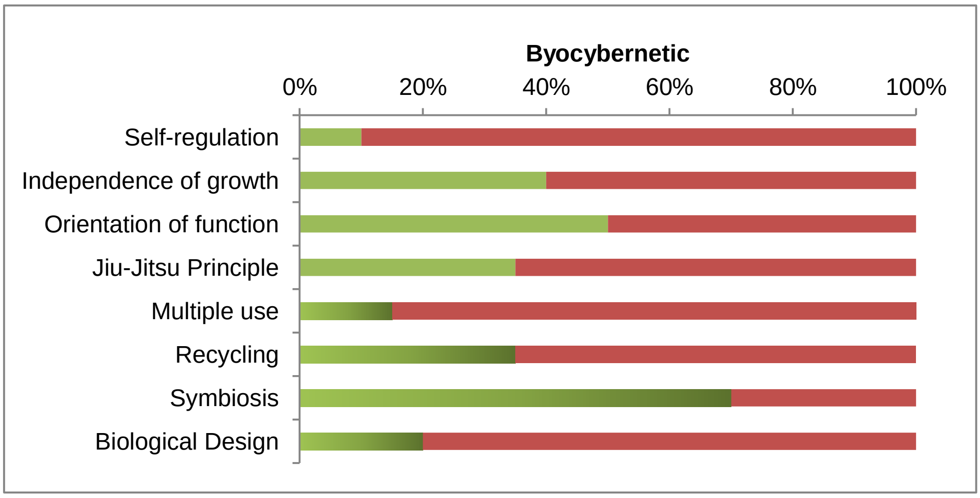


Figure 4.32- Possibilities of future enhancement (author, 2016).

The gradient bars show the possibility of enhancement of the selected criteria in the future. However, this is not completely correct. It is based on this study and in the author opinion which is not an expert on the area. The more important here, is that this evaluation gives an idea of the potential for change.

The structure of the model ends here. However, as explained before, this structure is recursive and thus it still open until the end. In this last step it is possible to re-examine the way that the system was originally described – step 4.1.

5
FINAL CONSIDERATIONS

5.1. DESIGN RECOMMENDATIONS

During the development of this work, some recommendations and hints were already mentioned. As referred before, the building design phase is the most important and decisive phase to take decisions about sustainable practices.

To help in that task, the use of management tools striving for sustainability is the ideal to achieve successful solutions in design of buildings. The possibility of simulate a solution before the construction increases the success of the project as well as designers productivity and imagination. Although all the qualities of the Sensitivity Model, this method may not be the ideal method for this analysis. It requires time and the involvement of all the stakeholders in constant meetings and discussions. Since there is little time during the earlier stages of design process maybe it is more adequate a more effective tool.

In this work was analyzed only one partial scenario, composed by four variables. It doesn't reveal enough to achieve interesting conclusions. Maybe one or two more variables should reveal better results. Variables like cost and flexibility would be very interesting to study here but due to the lack of time, it wasn't possible. Cost is one of the main barriers to overcome. Sustainable designs are seen as more expensive than traditional designs since they may require specialized professionals, advanced simulation and analysis, higher construction standards, additional construction precautions and even the use of new materials. Even that there are several studies that show the opposite, the effort to minimize costs combined with the lack of education and appropriate knowledge in this field doesn't allow to take these approaches (Miller and Doh, 2015). With regard to flexibility variable, the importance of this in the increase of sustainability was already discussed in this work.

Regarding the partial scenario studied, the wood as main structural material revealed several advantages in terms of embodied energy and CO_2 emissions. However, in Portugal, the conventional construction keeps being associated to concrete and brick masonry structures. The fact is that the wood industry in Portugal is very successful but mainly due to the paper and furniture industry and not because construction industry. Many countries from north of Europe use wood framed buildings since long time, why doesn't Portugal increase the use of this material? It is an issue that should be more discussed since 35.4% of the portuguese territory is occupied by forest. In order to conclude this issue, also the cork industry is very famous in Portugal. Cork is not a structural material however is a very ecologic insulation material and could be more used in this function.

As mentioned several times during this work, the lack of skilled professionals in this area is a serious problem and barrier for more sustainable projects. In this way, it would be really important a greater investment from universities to approach more and deeper this concept. The today students are the tomorrow's future professionals and it is really important that they can be more aware of this thematic.

From the parameters studied in this work, some showed more relevance than the others.

5.2. CONCLUSIONS

5.2.1. THE SENSITIVITY MODEL

The sensitivity model can be applied to almost all areas of study due to its open structure. Through this, it is possible to visualize the system through a bigger perspective than we are used too. In this way, it is allowed an improvement in the decisions taken since a deeper analysis from the total system is made and not only from small parts of it.

To achieve better results with this model, the participation of a large number of different stakeholders involved in the system would be essential. However, the author of this work was the only person involved, which has severely reduced the information introduced in the model.

Another problem found during the development of this work was the fact that this model is very "fuzzy" since the earlier steps, which has complicated the use of it, especially for inexperienced users. However, this "fuzzy" property is part of the system and it is clearly explained in Vester (2007).

Furthermore, a design of a building is a complex issue which has made this system very difficult to study and it brought some challenges during the application of the method. As such, some difficulties found during some steps of the SM will be following described.

5.2.1.1. Set of variables

At this point, the user needed to gather a list of variables concerned to the system. Since building design is a multidisciplinary task which complies a large number of decisions in numerous aspects such energy, materials, water use, etc., select a list of variables was not an easy task. In this way, due to the light knowledge of the user, only seventeen variables were reunited, which is not a small number, however the relevance of them may not be great. The participation of an expert, or many experts, could bring other variables interesting to study.

5.2.1.2. Effect System

Here, the bigger obstacle was filling the matrix of influence. To decide the degree of influence of each pair of variables was a slow process since this step would be essential for the following step where the cybernetic character of each variable in the system is revealed. Besides, it is important to understand that the decisions about the degree of interconnectedness between variables can change from one user to the other, and thus the decisions taken in this work may not be the best. A different person could obtain different roles for the same variables studied here resulting from different decisions taken in this step.

5.2.1.3. Simulation

Simulation was by far the most difficult step in this work. It took the majority of the work's time.

First of all, the definition of the variables scales was very complicated due to the lack of some data about the case of study building and the lack of information about the variables chosen for the simulation. About the lack of data related to the case of study, it refers, in the main, the quantity of some building materials used. It was essential to evaluate embodied energy and environmental impact variables. Instead of calculate the real embodied energy used (quantity of material times material embodied energy coefficient), it was used values from structurally similar buildings. Such assumptions bring errors in the final results. The same can be used for the environmental impact variable. The indicator used for this variable, CO_2 emissions, can be achieved in the same way as EE, quantity of material times its embodied carbon coefficient. However, as embodied energy, the CO_2 emissions were assumed from other similar buildings.

The mathematical relations obtained between building lifetime and embodied energy variable as well as the first and environmental impact variable is not totally adjusted to the real values which causes a large discrepancy between the real values and the values of the function. That happens, after the 10 years of lifetime, the values for bigger lifetimes are very lagged from the reality.

Besides, the relation between building lifetime and structure materials was not used since it wasn't found acceptable information that could be used. The building lifetime depends in many factors, including location, materials, construction methods, and the way buildings are used and maintained (Co-operation and Development, 2003). There are buildings that last long than others mainly due to its adequate maintenance and preservation and not because of the structural material. In this way, this topic is a very complex issue that can bring a lot of discussion and thus it was neglected.

For all these reasons, the results obtained in this step may not be the best which has influenced the steps further.

5.2.2. CASE OF STUDY

With regard to the case of study, the possibility of reduction of embodied energy demand was studied. It was conclude that such fact would be possible taking into account two different approaches: replacing the structure material for timber or keeping the actual structure (concrete and brick masonry envelope) but increasing the lifetime to 100 years. This last option can be easily reached however, it's essential a good structure project, which means respecting all the regulations, and combined with an adequate use and maintenance during use phase. Although the adequate use and maintenance is not designer's responsibility, it is their responsibility the development of a maintenance plan during the earlier stages of design process to prevent a needless demolition. On the other hand, replacing the structure for timber, e.g. CLT structure, is not as easy as the second option. Although in Portugal there are some companies dedicated to implement wood as main structural material, it still not being a common practice. First of all because those companies only work with low rise habitations and second because conventional construction has conquered this industry which can be explained by the fact that the cement industry occupy an important position in portuguese economy. Whereas exist this barrier about wood structures derived from the lack of information/education about this material, the construction in Portugal will continue to be the conventional and little sustainable. This is from particular interest since Portugal has a very large forest territory.

With regard to the two approaches for EE reduction mentioned above, they are not innovative, which once again emphasize the necessity to go further into this study. Bigger partial scenarios, more variables involved are some of the paths that can be followed in a future research. Besides, the selected case of study building, even following the conventional construction method, is very recent and it already incorporates some sustainable practices that have been demanded to building designers.

Last but not least, this study allowed the author to be more aware of the importance of sustainable practices as future structural engineer and it also intends to warn the readers for this thematic and how important would be to make this theme part of the future engineer's education.

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