MSc Thesis
Integration of Building Performance Simulation in Product Development Processes
Sandwich Panels case study
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“Integration of Building Performance Simulation in Product Development Processes- Sandwich panels case study”

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Abstract

This study develops and tests a framework for the integration of Building Performance Simulation (BPS) in product development. Several known BPS tools are used in order to answer the design questions generated at the different steps of the stage gate approach for product development. Sensitivity, uncertainty and optimization analysis were found to serve the purposes of scoping studies, concept definition and development, through providing information on comparison of research ideas, importance of design parameters and optimized values of those. The aim of the developed framework is to provide all the relevant information needed in terms of energy performance for the design and decision making team, to make educated decisions. The suggested framework is applied to a product development case of a façade manufacturer. The aim of the manufacturer is to deliver a façade element suitable for energy efficient refurbishment. In order to assist this process, information on energy performance of the design space of each stage is provided. Energy performance is measured through a suitable performance indicator. In this case it is the annual primary energy consumption expressed also in terms of energy savings. Energy saving potential of the façade element under development was found to be 7-18%. Core properties were identified as important in all the climate types while external skin properties gain significance in the case of hotter climates. Product cost, with the means of Return of Investment, was also inserted as an objective at the last stage of the project. Calculations indicate that the increase rate of energy savings was found to be lower than the one of the product cost. After the alternatives are reviewed in terms of energy savings, product cost and Return of Investment, guidelines and conclusions for the design of the product are provided. The project’s stakeholders assessed the information provided as relevant and future application of the framework to product development was decided.

1. Introduction

1.1 Background

Product development has always been a challenging task for managers and design teams [1]. Over the past decade, companies have been aware of the environmental pressures that add considerable difficulty to their task of delivering market attractive products [2]. Energy and sustainability is one of the main drives for product development, and innovation is one of the primary means by which companies can remain competitive. Successful businesses view the global environmental problems as business opportunities in the market of green and innovative products.

With the building sector accounting for 35-40% of energy consumed worldwide [3], building component manufacturing industries have sustainability high on their list of objectives for the development of products. Besides the energy efficiency measures proposed for new buildings, the refurbishment of the existing building stock proves to have potential. The gross floor space of European Building stock is
equivalent to Belgium (30.528 km$^2$) with 70-80% of these buildings constructed before the 1990s and up to 40%, depending on the region, constructed even before the 1960s [4]. These facts are an indication of the underlying potential in the renovation of the existing building stock.

The façade system, representing the skin of the building, participates to its heat exchange with the external environment and therefore contributes to the total amount of losses and gains. Multiple benefits can arise from façade refurbishment [5] [6]. New higher energy efficiency can be achieved leading also to energy costs reduction [7]. In addition façade renovation is beneficial in terms of aesthetics and increase of property value, or change of the building’s functionality and damage repair [8]. These values arising from façade renovation are among the objectives of façade manufactures, in order to deliver products attractive and competitive in the market.

For delivery of market attractive products the introduction of innovation to the product development process is necessary. Use of building simulation at the early design phase remains a challenging task for design and simulation teams. Several questions rise on how to simulate something that does not yet exist, or which are the most important parameters to be investigated and finally the most promising markets for the future product. Interaction of BPS tools with design and decision making teams at the early stages of a product design can provide information and answers to the design questions. In addition BPS tools enhance the creativity of the design team by providing them the ability of not only imagining innovations but also testing their feasibility.

One of the basic principles of the integration of BPS into product design processes is that for each of the design options the same information should be generated. As an example it could be mentioned that the generation of uniform information for the total of the design space is a clearly defined principle found in the work of P. de Wilde et al. regarding “Computational support for the selection of energy saving building components” [9]. Furthermore J.L.M Hensen et al. when describing the “Computational Innovation Steering” (CIS) method [10], for assisting the design innovation process, point out that its basic assumptions are that:

- **Design decisions should be based on a multiple of design alternatives or options**
- **The decision between alternatives has to be made on a basis of multiple criteria known as performance indicators**
- **For each design option the same performance information must be available.**

One key principle in the integration of simulations in product development would be also the clear objectives definition. It is important that the defined objectives are “translated” to a complete list of performance indicators. A complete list of performance indicators should help the design team to decompose the objectives into manageable parts [11]. In the case of energy performance objective for example this could be translated into primary energy consumption, heating and cooling loads etc.

The next step would be to generate this information for the total of the design alternatives. Literature review confirms the use BPS tools during the exploration of the so called “option space”. Sensitivity, uncertainty and optimization analysis prove to be powerful tools for option space exploration, the ranking of parameters’ influence, prototype testing and provision of assistance to the decision making process of conflicting objectives. “..*It will be very beneficial to be able to identify the most important...*
design parameters in order to develop more efficiently alternative design proposals and reach optimized solutions” [12], is stated in the work of Heiselberg et al. for the application of sensitivity analysis in the design of sustainable buildings. In addition sensitivity, uncertainty and optimization studies are integrated at the process of CIS “aiming to generate more insight and therefore useful design information” [13].

1.2 Objectives

The main objective of this research is to investigate how to assist the development of an energy saving façade element suitable for refurbishment, through the use of BPS tools. During this process information for educated decision making should be offered to the manufacturers and the design team involved in the decision making process.

The research questions as a result from the defined objective are:

- “How can building simulation tools assist the R&D development of a new product?
- “What information is required to be communicated to the design/decision making team in each step of the development process? ”

2. Methodology

A series of BPS tools were reviewed in order to choose the ones capable to answer the design questions addressed at the different phases of the product development process. The aim of the methodology section is to match suitable BPS tools to specific stages/gates of product development. The methodology part is divided in four sections. The first one is the description of the stage gate technique the second the short analysis of BPS tools, the third refers to their integration and the fourth provides some case specific information.

2.1 Stage Gate Approach

Research conducted during the past years has proven that the new product development processes are based on series of development stages interpolated by series of evaluative stages known as gates [14]. The main representative of this principle is the Stage Gate approach (Appendix A.1)

Stages are defined as the elements of the project in which research and technology development are performed in order to meet the short term objectives of each stage. The knowledge accumulated in each stage assists informed decision making at the subsequent gate and moves the process forward [14].

The evaluation points that follow each stage are known as “convergent points” or “gates”. At the gates decision making team evaluates the progress based on some pre-specified criteria and assesses whether the different tasks have been performed effectively and efficiently. Based on this information the decision is made to whether the project should go ahead, be delayed or stopped. Furthermore the plan for the next stage is defined [15].
Figure 1 demonstrates the first three stages and evaluative gates of the method. Stage 1 represents the preliminary investigation and analysis, which comprises of the generation of ideas and the identification of possible research topics. It is followed by the research project selection at Gate 1 after an approximate estimation of technical and economic merits or drawbacks of the ideas generated and competitive alternatives have been identified. Stage 2 is the concept definition of the selected research project. This means that candidate technical concepts and competitors are explored for the research approval to be made at Gate 2 in which questions for technical concept exploration and energy advantages expectations should be answered. At Stage 3, named concept development, actual technology development and prototype testing are taking place. Specific technical issues are addressed and at Gate 3 in which, after feasibility and competitiveness in the market are demonstrated, the decision on whether a scale up is feasible or not, is taken.

2.2 Building performance simulation tools

BPS tools have potential to be an optimal instrument to support decisions during the product development process, by providing detailed information and objective comparison of the various design options [9]. In the following paragraphs some common simulation tools are briefly described.

2.2.1 Building Simulation Programs

During the past 50 years several building simulation tools have been developed and are in use within the building energy community [16]. According to Crawley et al “The core tools on the building energy field are the whole-building energy simulation programs that provide users with key building performance indicators such as energy use and demand, temperature, humidity and costs”. Some known building energy software tools are: BSim, Ecotech, IES-VE, TRNSYS, SUNREL, eQUEST, ESP-r and Energy Plus [17].

2.2.2 Modeling Resolution

In cases that simulations are needed during the early design phase of a building or a building component very few information exist on the project. This lack of information can be confronted by the use of low level resolution models. The main advantage of this, is the reduction of computational time and the understanding and evaluation of the performance of the various design possibilities without spending
many resources. Nevertheless the challenging part during the development of this kind of models is the accurate introduction of assumptions and simplifications that should be adapted to the scope of the results required. The second option is the development of detailed simulation models. The main advantage of this model is that detailed simulations could be performed and accurate results also could be gained due to the more advanced definition of several building components. Also this kind of model is more representative of realistic conditions and operation of a building, since less simplifications and assumptions are made during its development. One disadvantage of this model type is its complexity. Detailed modeling increases significantly the development time and requires a high level of expertise.

2.2.3 Sensitivity Analysis
Apart from the development of “evaluation tools” described in section 2.2.1, the past decade a range of “guidance tools” have been developed, in order to facilitate decision making prior to design [18]. The first of this series of tools is sensitivity analysis (SA). Through available sampling techniques design parameters are uniformly distributed, creating the design space. SA enables the evaluation of the importance of these design parameters. In addition the assessment of the option space is supported, through the calculation of the selected performance indicators for all the design options [12], [13], [19].

2.2.4 Uncertainty analysis
The purpose of uncertainty analysis (UA) is to support the design process by providing additional information on the parameters chosen during the design of an innovative project. It is common for the design team during the design of innovations to be confronted with new ideas and limited amount of information, therefore it is useful to quantify the uncertainties. The result of UA is a number of probability distributions of the considered performance indicators [13], [20].

2.2.5 Multi-Objective Optimization
Another common technique among the simulation tools is optimization. Optimization assists the decision making when cases of conflicting objectives are encountered [13]. In multi-objective optimization with conflicting targets the aim is to define a set of Pareto solutions, through the use of suitable generic algorithms [21]. A solution is said to be Pareto optimal if and only if it is not dominated by any other solution in the decision variable space [22]. The components needed to be defined in optimizations cases are the various variables, the objective functions and the constraints related to the objectives. Through the use of optimization the innovation design reaches to optimized design alternatives.

2.3 Integration of Simulations and Product development theories
The matching of BPS tools with the stages of the stage gate approach was made on the basis of answering the design questions at each stage. The design questions of each stage are represented by the information that need to be available at the subsequent gate. Figure 2, demonstrates how these design questions were “translated” to BPS tools.

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As previously explained, the key principle for the integration of BPS tools in the stage gate approach is the generation of uniform information for the design space occurring by the objectives of each stage. Firstly, in order to generate this uniform information, design questions are converted to measurable performance indicators. Examples of performance indicators are shown in Figure 2. Secondly, the design space alters depending on the content of each stage. For example, based on the objectives of gate 2, its design space could be representative types of the selected concept, but the design space of gate 3 should represent a large possible designs database in order to evaluate and choose potential build-ups. In order to generate the selected performance indicators for the total of the designs database, suitable BPS tools are corresponded based on the knowledge acquired during their review. For example, a rough potential calculation can be performed with a low resolution model. Other issues to be taken into account during the integration are specific requirements (e.g., building regulations) and issues regarding the process. This means that the framework should be developed in such a way, regarding time or result expectations, that it would be feasible to “follow” and assist a real product development case. At section three, the integrated approach along with the simulation steps is presented.
2.4 Case Study Methodology

This section presents the case specific parameters that were defining for the direction of this research. First a short description of the background is made and then the importance of the stakeholders’ impression of the developed framework is briefly discussed.

2.4.1 Case Study Background

This study is conducted in parallel with the product development of a façade element suitable for refurbishment. The reason behind the choice of the stage gate approach as the technique in which BPS tools are integrated is that this is the product development approach used currently by the façade manufacturing company in collaboration with which the research was conducted. In addition even though the stage gate comprises of five stages and gates, only the first three of them are included in the development of the framework. The reason for that is the project timeline. Despite this background though the ambition for the developed framework is the expansion to the remaining stages and gates and its applicability in a larger scale in the future.

2.4.2 Case Study Design Team Feedback

Product development support with the use of BPS tools is an interactive process. The design team along with the other stakeholders involved in the process addresses a number of technical questions in the simulations team. The answers to these questions assist the decision to be taken at the different gates. The application of the framework will help the research to evaluate to which extent the integration of BPS tools upgraded the process. This will be done through the feedback provided from the project stakeholders to several aspects. Some critical points are the process timeline, the communication of information, its value to the decision making and the future use of simulations for product development from the manufacturer. Based on these aspects the application of the framework is evaluated at the discussion section.

3. Building Performance Simulation in the Stage Gate

3.1 Integration steps

As a result of the research conducted, a framework for the integration of building performance simulation tools to the stage gate approach has been developed. In Figure 3, an outline of this framework presents the simulation activities at every stage. In the following paragraphs all of the integration steps are discussed in more detail. In addition the information generated at each gate and the way that it assists the decision making process is analyzed as well.

![Figure 3 Integration Framework- Simulation Steps](image-url)
3.2 Introduction of Stage and Gate 0

Review on the Stage Gate approach [15] indicates that introduction of stage 0 (Figure 3) at the beginning of the process is a useful addition. Three main steps are suggested for this initial stage:

- The first one which is not related to simulations, but starts the process, is Broad market and problem definition: It comprises of a clear definition of the targeted market and the problem to be resolved, through the new product development.
- Performance clarification of manufacturer’s current product: Through the use of BPS software a low resolution model is developed and an indicative performance indicator is chosen to measure the energy performance of the current building component product.
- Performance clarification of the leader on the defined market on the selected performance indicator and comparison with current product performance identified on the previous step.

The results delivered from the suggested steps provide a number of information at the, subsequently called, gate 0 at which decision for the initiation of the process is made. The information generated regarding the problem and market definition leads to solution oriented research. In addition, the in depth understanding of current product and its comparison with the market leader, through simulations, helps to identify its strengths and weakness and the issues to be addressed at the new product development. Finally the introduction of this additional stage should be evaluated from the perspective of improvement of the product development process itself and not only as a simulations strategy.

3.3 BPS in Stage and Gate 1

The objective of stage 1 is the identification of research topics with potential to correspond to the targets set in the previous stage. Furthermore an understanding of potential future benefits-energy, financial etc- of the identified research topics should be gained. In this scoping studies phase the simulations team should be the “interface between the design process and the building performance simulation tools” [23]. Simulations for this stage should be based on the following directions:

- Identification of the analysis activities that are needed in order to evaluate the research topics. That would mean that for the several candidate concepts specific software requirements and tools should be chosen, modeling techniques and simulation times, suitable performance indicators and interesting simulation cases. These activities are also known as scoping studies and have been used in several studies during the early design phases [24], [25], [26].
- Qualitative comparison of variant solutions with a low resolution model. At this conceptual design phase simulations of potential solutions can be performed, for a rough potential estimation rather than the assessment of a single case. The extent to which these calculations are conducted depends on the resources available, the number of potential solutions and the time allocated for that stage.

For the selection of the research topic, taking place at gate 1, information regarding technical issues, knowledge gaps, and comparison with competing technologies, possible energy savings, timing and costs for the project should be identified. The simulation plan identified provides this information, by
delivering simulations schedule for all the possible solutions and a rough energy saving potential estimation calculation through a low resolution level model.

3.4 BPS in Stage and Gate 2

At this stage, after research project selection, the objective is concept definition. Activities focus on the thorough understanding and description of the technology and its capabilities. In addition preliminary technical concepts have to be defined. The work from the simulation team includes the next three steps:

- Like in stage 0 an initial non-simulation step is required. This is market research on common practices and market representative types of the selected technology: In this way the design and simulation team gain knowledge on possible product buildups. Different kind of concepts for various applications can be identified and evaluated. As part of this step the most representative solutions are chosen to be simulated.
- Performance evaluation of selected concepts: The effect of the selected concepts on a building’s energy performance is estimated. For that the model developed in stage 0 and the same performance indicator are used.
- Comparison with results generated in Stage 0: The performance of the interesting concepts defined is compared with the one of the current company product and its main market competitor simulated in stage 0.

Technical questions raised during this research approval gate refer to technical specifications of the concept, its expected performance, estimates regarding energy or other benefits and performance of competing technologies. The answer of these questions comes from the suggested simulation work. Design team becomes familiar with possible product structures, based on the ones identified, and is provided with information regarding their energy saving potential. The simulation of common market solutions offers a benchmarking of expectations for the new product. Finally the technologies comparison provides indicates the strengths and weaknesses of each concept.

3.5 BPS in Stage and Gate 3

During this stage, research, development and testing of prototype technology are conducted. Predictive simulation work is suggested in this stage and proof of technical feasibility should be demonstrated at the end of it. The simulation work includes the next four steps:

- Assessment of importance of the product properties: During this set of simulations the tool of sensitivity analysis is used in order to evaluate the importance of the effect of the various product properties, to the selected performance indicator. The reason sensitivity analysis is used here, instead of uncertainty is that the objective is to quantify the relative effect of the design parameters on the outcome rather than assess the probability of occurrence of this outcome [27].
- Prototype testing through simulations: A large build-ups database is created during the previous step. Attractive solutions could be separately simulated and contrasted with Stage 2 results.
- Optimization of important product parameters: Parameters identified as important, from the outcome of the sensitivity analysis, are selected for optimization in respect to the objectives.
• Guidelines for potential build-ups and regulations: Based on optimization results, guidelines for potential product build-ups are extracted. Possible build-ups are also evaluated from the perspective of current building regulations.

The information required at Gate 3 includes results on prototype testing, modeling and experimental results, able to demonstrate technical feasibility. Simulation work performed, enables the team to answer these questions. Sensitivity and optimization analysis not only assess and improve the effect of design parameters but also calculate the performance of a large design space. In this way prototype testing is actually performed without construction of prototype.

Furthermore information from simulations at this Gate 3 can lead to decision of possible product build-ups and evaluation of their performance.

4. Case study application- Sandwich panels development

In this section the framework is implemented and its effect on the process is assessed. The aim of that is to evaluate the use of the developed methodology though use in a product development case. In each stage the steps along with case specific information are described and the results are presented at a separate section together with the decision made at each gate. At the first stage the specifications of the model used are also given and at the third stage simulation results of each step are separately presented. Strengths and weaknesses of the framework are identified during the discussion section.

4.1 Introduction of Stage and Gate 0

The objective of this stage is the project’s broad scope definition and the acquisition of knowledge regarding strengths and weaknesses of the company product in comparison with the leading product in the defined market. Integration steps are applied as described in section 3.2.

• Broad market and problem definition: Energy is high in the objectives list for the manufacturers of building components. This has its origin in the new legislation regarding energy efficiency of buildings. Apart though from the construction of new buildings, there is a high energy saving potential in the refurbishment of the existing ones. Among the European building stock 70%-80% of the existing buildings was found to be constructed before 1990’s and 40% of these buildings were constructed even before 1960’s. Countries that posses the larger components of old buildings are: Denmark, Sweden, France, Czech Republic and Bulgaria [4]. Therefore the market identified is the renovation market within Europe and the objective is to deliver an energy saving façade component suitable for renovation. High energy saving potential, easiness of installation and aesthetics are among the priorities, since they also represent popular refurbishment motives.

• Performance clarification of manufacturer’s current product: In this case the current manufacturer’s product is a ventilated façade system. A ventilated cavity is created between the insulation applied externally on the structural wall and the laminate panel in the front used for reasons of aesthetics and protection of the insulation (Appendix A.2). The panel is applied through wooden or aluminum fixing systems.

• Performance clarification of the leader on the defined market on the selected performance indicator and comparison with current product performance: Through marketing research the leading
renovation strategy was found to be the External Thermal Insulation Composite Systems, also known as ETICS (see Appendix A.3). Insulation is directly applied on the existing structural wall with a layer of render finish that acts as protection and decoration. The main advantages of this solution are its low cost, compared to the other façade renovation strategies, and the easy and economical installation compared to manufacturer’s product.

4.1.1 Model specifications and simulation settings

In order to clarify the performance of the described technologies building performance simulations were used. The simulations were carried out using the program ESP-r [28]. Annual simulations with a time step of one hour were executed. Furthermore simulations were performed for four different climates representative of the various climatic “zones” within Europe. Based on their HDD (Heating Degree Days) the selected climates are the ones of Copenhagen, Brussels, Madrid and Palermo. The chosen performance indicator is primary energy consumption in kWh/m$^2$ annually, and its percentage reduction among the base case and the ones after the façade renovation [29].

The energy performance of the two compared façade technologies was assessed through the use of a one zone model, representing a zone of an office building. The main dimensions are indicated in Figure 4. The window has a height of 1.5m and consists of double glazing (U value 2.78 W/m$^2$K). The south façade orientation is the one exposed to external environmental conditions. The façades in other orientations are set to be exposed in a similar environment, as well as the roof and the floor.

<table>
<thead>
<tr>
<th>Technology</th>
<th>U value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base case</td>
<td>3.19</td>
</tr>
<tr>
<td>Ventilated façade</td>
<td>0.28</td>
</tr>
<tr>
<td>ETICS</td>
<td>0.25</td>
</tr>
</tbody>
</table>

Figure 4 ESP-r Representation of a zone of an office building and façade U-value of simulated cases

Representing part of an office building, zone’s occupancy hours are from 7 to 19h and the internal gains during that time correspond to 30 W/m$^2$. Infiltration rate is 0.2 ACH and during occupancy hours there is also ventilation of 2 ACH. In addition HVAC system has unlimited capacity to meet the set points for heating and cooling which correspond to 21°C and 24°C for occupancy hours and 10°C and 40°C during non-occupied hours, as an anti-frost and over-heating protection. The COP for cooling system is assumed to be 4 and the efficiency of the heating system is 0.8.
For modeling purposes the cavity of the ventilated façade is represented by two separate zones, one above and one below the window of the south façade. The air flow network of each cavity zone is modeled with three nodes, two externals and one internal. The thickness of the cavity is 34 mm.

In both of the façade technologies simulated, the same level of mineral wool insulation was used. This means 140 mm for the case of the ETICS and 130mm in the case of the ventilated façade, in order also to represent thermal bridging due to the fixing systems (Figure 4).

### 4.1.2 Simulation Results and Information at Gate 0

The energy saving potential of the two façade technologies under comparison is measured as the percentage reduction of the primary energy of the renovated case when compared with the base case (Figure 4). It is identified to vary from 3-20% depending on the climate. The effect of the two technologies as refurbishment strategies is similar due to the use of the same level of insulation (Figure 5). This is also confirmed by generating the south façade energy balance of gains and losses for both the ETICS and the ventilated façade. Figure 5, demonstrates that in the case of ventilated façade, the panel is protecting the cavity and acts as weather barrier for the insulation. It reduces convective losses, reducing at the same time the solar gains, preventing solar irradiation from entering the cavity. The result is that the overall balance of both technologies is within the same range. That explains their similar effect as refurbishment strategies. It is also worth mentioning, that the cooling load, especially in hotter climates, is increasing because of the addition of external insulation. This is explained by the increase of thermal resistance and the absence of night-time ventilation that could cool down the surfaces that store heat during summer or hot days.

Finally through the generation of the zone energy balance for the case of the ETICS it was found that the opaque façade part, the one façade manufacturers can affect, accounts for 10-12% of the total zone losses.

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**Figure 5 Façade technologies comparison and south facade energy balance, Copenhagen**
After this first simulation set, information was gained regarding the energy performance of manufacturer’s current product and the main market competitor. The potential reduction of primary energy consumption after refurbishment was identified and in addition it was found to be dependant of the climate. Finally the energy saving potential of the opaque façade part is a piece of information that acts as a benchmarking of expectations and targets within the design team.

After evaluation of the information provided, initiation of research on new products suitable for refurbishment was decided. The focus was decided to be on potential improvements of the current product and on new products that would provide similar or higher energy benefits along with easiness of installation, which is a critical issue for the manufacturer.

4.2 BPS Stage and Gate 1

At Stage 1 after the initiation of the research project, all the stakeholders involved contribute to the idea generation. In respect to the identified market a number of ideas and innovations are generated. In the case of refurbishment a list of innovations was created from the design team. The forty generated ideas include concepts that either save or produce energy through the opaque façade part. Some examples of ideas are the Phase Change Materials (PCMs), application of thermotropic or photochromic coatings, improved infrared reflectivity, integration of photovoltaic, heat conductive and sandwich panels. The computational assessment of this large number of ideas requires allocation of resources and time therefore restrictions may occur due to limitations in these two factors. The “simulation team” in general should act as the interface between the ideas generated and the building simulation tools available. This would involve the following:

- **Identification of the analysis activities needed in order to evaluate the research topics.** At this initial stage of the project in order to assist decision making the first information to be provided to the design team and decision makers is the analysis of simulation activities, required for each of the innovations listed as potential products. A great amount of the ideas generated are still not available in large scale in the market and there is still research to be conducted until they become commercially available products. This also affects the simulation work to be conducted for their technical assessment. The question that rises is “How to simulate something that does not exist” [30]. Another obstacle also is the adaption of current programs to simulate future developments. A representative example is the case of thermotropic and electrochromic coatings and phase change materials. Current programs do not have the ability to simulate variable surface or material properties. Therefore an adaptation of their source code is often needed for the simulation of innovative materials or concepts. This source code modification can be a complex and time consuming process. As a result at this gate the simulation team should generate a plan of all the required activities of the scoping studies to be conducted. Define all the required software programs and modifications that these may need the timeline and interesting simulation cases for the potential identification.

As an example the case of thermotropic coatings is going to be mentioned. Application of thermotropic coatings on the building surface is based on the concept of response of solar absorptance to the change of surface temperature. In order to simulate these coatings a source code modification of ESP-r would be necessary. Furthermore in order to assess the potential savings in heating and cooling load several
building types and climates should be included in the simulations. Besides the potential identification this also would help to identify attractive markets for this type of products. A second example of this kind of scoping studies is the research conducted for the manufacturer regarding the concept of improved IR reflectivity [24].

- **Qualitative comparison of potential solutions with a low resolution model.** The second level of information necessary in order to assist the process move forwards is a rough energy saving potential calculation for the ideas that this is possible. The main focus at this stage is the relevant comparison of ideas.

Demonstrating again the example of thermotropic coatings, and for purposes of potential calculation, two annual simulations were performed, with different solar absorptance value in order to approximate their dynamic behavior as a function of surface temperature, through post-processing of the results. Furthermore differences in panel’s temperature were calculated as an indication of the effect of thermotropic coatings. The performance of ventilated façade was assessed with and without the application of thermotropic coatings (Appendix B1).

### 4.2.1 Simulation Results and Information at Gate 1

The extent, to which the scoping studies are performed, as previously described, depends on the time and resources available. Technical information delivered at this gate include rough calculation of energy saving potential, like in the case of thermotropics or infrared reflective coatings, analysis of strengths and weaknesses of the listed ideas and simulation schedules.

After the collection of this information the decision for the selection of the research project is made at this gate. Calculations of energy performance through simulations or the schedule of the simulation activities are not the only parameters to form the final decision. The decision making team, taking into consideration the information delivered from design team, simulations and marketing, reaches to the selection of the most promising idea, based on multiple criteria.

At the end of gate 1 the choice of the decision making team initiated the research on the concept of sandwich insulative panels for use in refurbishment of existing buildings.

### 4.3 BPS Stage and Gate 2

The idea selected to proceed with at stage 2, also known as concept definition stage, is this of sandwich panels. A rectangular sandwich panel comprises of two skins and insulating material, such as foam, sandwiched in between two structural surfaces [31]. These surfaces usually have a steel core that is protected from several layers of substrate coatings (Appendix A.4).

The steps defined in section 3.4 were applied in this case.

- Prior to simulations a Market research on common practices and market leaders for this technology was conducted. In collaboration with marketing team two representative types of sandwich panels, available in the market, were identified. The main differences between these two sandwich panel types are the insulation level, which is higher in type 1, and the fixing system. Application of these two types of sandwich panels on the base case leads to a U-value (W/m²K) of 0.28 for type one and of 1.01 for type two. Regarding the fixing system Sandwich panel type 1 is applied to the structural
wall with the use of a frame and type 2 through fixing systems and a closed air cavity of 20mm (Appendix A.5).

- **Energy performance evaluation of selected concepts**: The energy performance evaluation of the two types of sandwich panels was conducted with annual simulations as described in stage 0. In addition the same model was used at this stage as well.
- **Comparison with results generated in stage 0**: The performance of the interesting concepts defined is compared with the one of the current company product and its main market competitor simulated in Stage 0.

### 4.3.1 Simulation Results and Information at Gate 2

Figure 6, demonstrates the results from the simulations performed at this stage for the climate of Copenhagen. Results for the rest of the climates can be found in Appendix B.

![Figure 6 Facade technologies comparison and south facade energy balance, Copenhagen.](image)

Through these simulations, knowledge is gained on the energy saving potential of the sandwich panels as a refurbishment strategy. Furthermore this potential is compared with the one of ETICS and ventilated façade system. South façade energy balance assists the understanding of the comparison and verifies its validity.

Therefore at the end of this stage, it is found that the sandwich panels available in the market have an energy saving potential of 7-18% depending on the climate. Additionally useful information includes the higher energy saving potential of sandwich panel 1 in comparison to sandwich panel type 2, leading to its better performance in colder climates. The performance of sandwich panel type 1 is at the same levels as ETICS and ventilated façade. This is explained by the similarity of the U-value when ventilated façade, ETICS and sandwich panel type one are used as renovation strategy. U value of the total construction in the case of second sandwich panel type is more than three times higher. This as it can be
seem in Figure 6, leads to higher losses from the opaque façade part, leading therefore to higher heating consumption. In hot climates on the other hand this is an advantage, preventing the cooling consumption increase.

In general solar gains in the case of sandwich panels were found to be less than in the case of ETICS. This is justified by the fact that their skin comprises of metallic materials with lower solar absorptivity values than the one of the skin of ETICS.

At gate 2 the continuation of the project was decided. Potential build ups were sufficiently explored for technical merits and drawbacks and their energy performance (saving potential of 7-18%) was within the expectations, as these were defined in stage 0.

4.4 BPS Stage and Gate 3

The main objective of Stage 3, also known as concept development stage, is through predictive simulation work to examine the technical feasibility of the selected concept. The steps discussed in section 3.5 are applied in order to assist the development of sandwich panel façade elements.

- **Assessment of importance of the product properties**: The properties of the various layers that form a sandwich panel could affect in a different way and to a different extent the goal of lowering the primary energy consumption of the office building. For that reason a sensitivity analysis was conducted. The various properties and ranges investigated for every panel layer, are presented in Table 1. The sensitivity analysis was performed for four different climates, the ones examined so far: Copenhagen, Brussels, Madrid and Palermo. In addition, for every climate a separate sensitivity analysis was performed for every orientation. The results are analyzed with the use of Spearman correlation coefficient.

- **Prototype testing through simulations**: A large build-ups database is created during the previous step. The performance of this design space is also calculated through simulations conducting in that way the testing of a number of product prototypes.

- **Optimization of important product parameters**: Parameters identified as important, from the outcome of the sensitivity analysis, are selected for optimization in respect to the objectives. Lowering product cost is also inserted as an objective at this phase of the project. Product return of investment is the chosen performance indicator.

- **Guidelines for potential build-ups and regulations**: Based on optimization results, guidelines on potential combination of materials for final product build-ups are provided. These guidelines are given on the basis on satisfying the two conflicting objectives. Furthermore regulatory issues are also inserted as a parameter in order to narrow the option space.
4.4.1 Simulation Results – Sensitivity analysis

Figure 7 demonstrates the results of the sensitivity analysis for the two extreme climates of Copenhagen and Palermo. In the cold climate of Copenhagen properties of the core prove to be the ones of importance. Properties of the external skin gain increased importance in the case of Palermo. This trend is not limited among different climates. It can be observed for different façade orientations of the same climate as well. Skin properties gain increased importance in the south façade in Copenhagen climate as it can be seen in Figure 7.

<table>
<thead>
<tr>
<th>Panel elements</th>
<th>Property</th>
<th>Low limit (material)</th>
<th>High limit (material)</th>
<th>Unit</th>
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<th>High</th>
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<tr>
<td>Outer skin</td>
<td>Absorptivity</td>
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<td>Black coat</td>
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<td>0.2</td>
<td>0.35</td>
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<td></td>
<td>Thermal conductivity</td>
<td>PolyCarbonate</td>
<td>Aluminum</td>
<td>W/(m.K)</td>
<td>0.2</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
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<td>na</td>
<td>mm</td>
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<td>3</td>
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<tr>
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<tr>
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<td></td>
<td>Thermal conductivity</td>
<td>PolyCarbonate</td>
<td>Aluminum</td>
<td>W/(m.K)</td>
<td>0.2</td>
<td>230</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
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<td>na</td>
<td>mm</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Fixing system</td>
<td>Air gap thickness</td>
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<td>na</td>
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<td>Concrete</td>
<td>cm</td>
<td>50</td>
<td>200</td>
</tr>
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</table>

Table 1 Sensitivity analysis, properties and ranges

Figure 7 Spearman correlation coefficient – Primary energy consumption
In a more general note, it could be said that the ratio between heating and cooling, either among climates or orientations modifies the rank of the parameters, since the influence parameters have different rank in terms of heating and cooling. The heating and cooling ratio can also be affected by the efficiency of heating and cooling system, since the results are presented in terms of primary energy. Another parameter that proves to be significant, in almost all the climates (see Appendix B.3.1) is the thickness of the structural wall behind the sandwich panel.

Furthermore in order to assess the relative importance of the coefficients the percentage of losses and gains due to the opaque façade part, during heating and cooling months, was calculated in every climate and every orientation. In the Table 2 the façade orientations with the highest contribution in gains and losses for every climate are presented.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Maximum opaque façade fraction of total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Losses-Heating Season</td>
</tr>
<tr>
<td>Copenhagen</td>
<td>North (12.5%)</td>
</tr>
<tr>
<td>Brussels</td>
<td>North (12%)</td>
</tr>
<tr>
<td>Madrid</td>
<td>North (11%)</td>
</tr>
<tr>
<td>Palermo</td>
<td>North (10%)</td>
</tr>
</tbody>
</table>

Table 2 Orientations with highest potential per climate

The information gained from this study to be provided at the design team is:

- The energy performance of a considerable design space through the elaboration of 1600 annual simulations
- The importance of core thickness and conductivity mainly for colder climates like Brussels and Copenhagen
- The importance of skin properties as skin conductivity and solar absorptance for moderate and hot climates as Madrid and Palermo.
- Properties for further research and directives on suitable values for lower ranking parameters.

4.4.2 Simulation Results-High ranking product parameters optimization

The behavior of the parameters identified as important from the outcome of the sensitivity analysis are also the ones of interest for the design team to further investigate. At this point, close to decision making, energy reduction is no longer the only objective. The second objective that was introduced to the process is the product cost. The parameter highly associated with both of the objectives is the thermal conductivity of the core, meaning the core material. Therefore the target of this research is to identify materials that could serve energy savings and cost reduction in the best possible way. Energy savings are presented in means of reduction in the primary energy consumption and cost of the product is associated with insulation cost and is presented in the form of return of investment.
Initially a list of six possible materials representative of a range of thermal conductivity values available in the market is developed (Figure 8). Also based on the results of the sensitivity analysis and constraints for the weight of the panel, relevant to the fixing systems, two insulation thicknesses are chosen, the ones of 30 and 50 mm. The properties of the skin, due their weak association with the cost objective are set to values suitable for each climate category based on the guidelines extracted from the sensitivity analysis (Appendix B.4.1). In addition two different cases for the structural wall were investigated. The first one represents the non-insulated construction (U value=3.19 W/m²K) used so far as base case. At the second one the U-value of the structural wall was adjusted to 1.1 W/m²K in one of the cases, which was found to be representative for renovation cases constructed between 1970s' and 90s' [32].

At this stage of the project, some modifications were introduced to the model in order to reach a more realistic representation of an office building. Night time ventilation of 1ACH per hour was introduced during the summer months, and shading devices are activated when solar irradiation in vertical place overcomes the threshold of 200 W/m².

Annual simulations were performed for all the four climates, six insulation materials, 30 and 50mm of insulation, the façade orientations with the higher identified potentials -south and north-, a case in which all façade orientations are exposed to external conditions and two different U values for the structural wall.

In Figure 9 the energy savings, due to the application of sandwich panels, with different core insulation materials, as a function of the insulation cost are presented. These are the results generated for the case of structural wall with a U-value of 1.1 W/m²K, representative of a refurbishment building case between 70s-90s.

The first remarks to be made after observation of Figure 9 are:

- For both orientations the energy savings, for the same insulation thickness are higher in colder climates.
• Colder and moderate climates have higher energy savings with the use of insulation of lower thermal conductivity value leading also to higher insulation costs.
• Colder and moderate climates have higher energy savings with the use of 50 mm of insulation (Appendix B.4.2)
• Energy savings in all of the cases are smaller in the south façade orientation (Appendix B.4.3)
• In the case of Palermo north façade orientation small energy savings are noticed which decrease with the increase of insulation cost. In the south façade the addition of insulation leads to increase of primary energy consumption in comparison with the initial case

These information gain added value for the design team when also combined with the information for the return of investment of each possible solution.

Figure 9 Energy savings and Insulation cost, structural wall 1.1 W/m²K
In Figure 10 the calculation for the return of investment in years for each of the solutions included in the option space are presented. Please make a note of the different scale in the horizontal axis of the four climate cases. Some first general comments from this figure are:

- In all four climates the ROI time is within the same range for the first four materials (mineral wool, polystyrene, polyurethane and polyisocyanurate) and increases for both aerogels and VIP. That is explained by Figure 9, in which it is observed that rate of increase of the energy savings does not follow the rate of increase of the insulation material cost.
- The ROI is in most of the cases shorter for the thickness of 30 mm. This is justified by the lower insulation prices leading to lower product prices for the case of 30mm of thickness.
- North façade orientation presents faster return of investment than south since the energy savings obtained with the same investment are higher compared to south façade orientation.
- ROI time is shorter in colder climates again due to higher energy savings in comparison with the ones of milder climates.

![Figure 10 Design Space Return of Investment](image-url)
4.4.3 Design Directives

Combining the information generated from simulations and results’ post processing, directives for the suitable core material(s) in each climate type, are given.

In the case of Copenhagen, as it can be seen in Figure 9, energy savings continue to increase while the core’s thermal conductivity decreases. This is the case for both the north and south façade. The increase rate though in the case of the north façade is higher. In addition in this climate the 50 mm insulation thickness leads to further rise of the energy savings. In terms of energy savings therefore, the best option is the VIP material with 50mm of insulation. Combination of this information though with the ones from the ROI calculation provides a different perspective. Best design in terms of ROI is the mineral wool in a thickness of 50mm. As already concluded earlier the rate of increase of energy savings and insulation cost are not similar, since insulation cost after the first four materials presents an increase not proportional to the one of energy savings. That is represented also from the return of investment. In that sense polyisocyanurate with 50mm proves to be an attractive solution since it belongs to the materials group with the shortest ROI previously identified. Aerogels follow with 1.5-3 kWh/m² higher energy savings, depending on the thickness, and 5-8 years longer ROI time. Finally VIP are excluded as a possibility due their ROI which varies from 26-38 years (Figure 10).

The conclusions in the case of Brussels climate are similar in terms of energy savings. They follow the same trend, but as expected, in a lower range. Therefore VIP present to be the optimal solution from the perspective of energy. The situation is different in terms of return of investment with most of the ROI times being almost double when compared to the ones of Copenhagen as seen in Figure 10. The reason for that, besides the lower energy savings with the same cost, is the price of energy [33]. Energy prices in the case of Brussels are approximately 50% lower than in the case of Copenhagen. Mineral wool of 50mm is again the best solution regarding the ROI time. Trying to combine both objectives in the best possible way, polysterenef of 50mm with ROI among 15 and 24 years is a fair trade among the two objectives since further increase of the product cost does not lead to higher energy savings.

For Madrid in Figure 9 though, it can be seen that the rate of increase of the energy savings is lower than in the cases of Copenhagen and Brussels. Despite that the best solution in terms of energy is again VIP with 50mm thickness. It is rather easy to observe though that the energy savings increase rate is much smaller in comparison with the previous climates and almost non-existent in the case of the south façade. Based on the ROI calculations, for both orientations mineral wool of 30mm is the optimal design solution. Even in that case though the ROI years vary from 29-32 years, which is high. This is justified by the reduced savings (compared to other climates) and the low energy cost. A fair trade among the two conflicting objectives is obtained with the use of polysterenef of 30mm thickness for both the orientations with ROI time 35-40 years. Figures 9 and 10 demonstrate that in the case of Madrid, and especially the south orientation, further decrease of material’s thermal conductivity does not pay off neither in energy savings or in return of investment.

In the case of Palermo the decrease of thermal conductivity value, followed by the obvious increase in the insulation cost, leads to the opposite effect of reduction of energy savings. This can be justified by the fact that the larger amount of energy consumption in the climate of Palermo regardless the orientation, corresponds to cooling energy. It is worth noticing that in the case of the south façade all
the application of external insulation, through the sandwich panels, leads to the rise of primary energy consumption compared to the initial case. This is the reason why in Figure 10 ROI time is not present for the case of the south façade orientation. Therefore it can be concluded that in climate types like the one of Palermo, in which cooling is the main contributor to primary energy consumption, the addition of insulation to the south façade should be avoided. In the case of the north façade though, mineral wool with 30mm of thickness was found to lead to the largest energy savings among the various options. It is also the solution with the shortest return of investment, which is though close to 30 years.

As a final general guideline it should be mentioned that the decision is highly dependent on the prior to refurbishment U-value of the building’s façade. The simulations conducted with an initial U-value of 3.10 W/m²K instead of 1.1 W/m²K show that ROI time in that case is much shorter due to higher primary energy consumption of the base case that leads also to higher energy savings after façade renovation. Figure 11 gives an example of the magnitude of differences that can occur in the ROI.

![ROI comparison graph](image)

**Figure 11 Comparison of ROI –Copenhagen North-30mm**

### 4.4.4 Building Regulations

Another perspective to process the results and assist the decision making process is their association with the current building regulations, within the European Union. Existing regulations in every country provide directives on the U-value of the various building constructions [34]. Information for these values were compared with the final U-value obtained after the application of the various design options. This information are presented in the following graph.

From Figure 12, it can be concluded that all of the design options can meet the regulatory requirements of Brussels, Madrid and Palermo. In the case of Copenhagen the regulatory space varies from 0.2 to 0.4 W/m²K, which means that the solutions that are feasible are polyurethane and polyisocyanurate with 50 mm of thickness and both aerogels and VIP.
Besides compliance with each country’s directives, additional points could be gained in certification schemes like BREEAM and LEED. In BREEAM for instance up to 3 credits can be gained by the use of materials with low environmental impact on the external walls, taking into account the full life-cycle of the material, and up to 6 credits can be earned by the responsible sourcing of materials in key elements of the building [35].

4.4.5 Information at Gate 3

During this stage a great amount of information was generated in order to assist the decision making at gate 3. The decision to be made at this gate, after first the design team decides on the possible product build-ups, is whether the project is going to move to the next scale up stage or not. Some directives are given based on the previous section

- Core properties were identified as important in all climate types and more on the colder ones
- In hotter climates properties of the skin gain increased significance
- Optimization for core material selection indicates that VIP panels lead to the highest energy savings in all climates and orientations besides Palermo. In Palermo, south façade does not require additional orientation and north façade has the higher energy savings with mineral wool. In addition mineral wool has the shortest ROI in all the previous cases.
- Combination of both objectives indicates as attractive solutions polyisocyanurate of 50mm for Copenhagen followed by aerogels, polystyrene of 50mm for Brussels and 30mm for Madrid and 30mm of mineral wool for Palermo north façade.
- In the case of Palermo and south façade orientation, no additional insulation was found to be required.

This information will be evaluated and along with other criteria a decision has to be made on the potential product build-ups. The simulations team will evaluate the energy performance of these chosen build-ups by comparing it with the energy performance of previously simulated façade technologies in stages 0 and 2. At the end the decision for the further technology development shall be made.
5. Discussion

The scope of this research project was the development of a framework of standard steps for the integration of BPS into the stage gate product development approach. The development of this framework was based on research conducted initially on the basic principles of the stage gate approach and after on the work in the field of guidance of design and innovation processes with the use of simulations. The developed framework was afterwards applied in a real product development case of a façade element, the sandwich panels.

As a first general remark it could be stated that the application of the framework managed to provide the required information at each stage of the process. The key objective, set from the beginning was the provision of information in terms of relevant comparison of the existing design space at each stage. That was implement by the comparison of existing technologies at the initiation of the project to identify their strengths and weaknesses, the simulation and comparison of main market representatives of sandwich panels at stage 2 and the large designs’ database simulations during stage 3. Through the framework application in the sandwich panels case study it was verified that the qualitative assessment of a series of alternatives, at the early design stages, provides more relevant information to facilitate educated decisions than a single case in depth analysis. In that sense the need of moving energy simulations at the beginning of the design process seems to offer multiple benefits. One of them, besides the option space exploration, is the enhancement of creativity, since BPS tools like SA are able to facilitate the generation of design alternatives that did not occur to the design team. This was also done in the case of sandwich panels’ development through the uniform sampling of the design parameters and the generation of a number of designs.

The feedback of project’s stakeholders confirms the previous findings. The design and decision making team of the project concluded that integration of building performance simulations provided information that was not possible to acquire before or in a different way. This information also proved to be necessary since energy was among the main objectives of the project. The information was gained without construction of prototypes and within the timeline of the project. The difference is though that technical issues were addressed earlier than usual and with smaller resources allocation. Finally the manufacturer decided the application of the developed framework in future product development processes as well.

The issue that also rises from that decision though, is whether or not a wide framework application would be possible. Potential wide use of the developed framework would mean that further research should be conducted and the framework should also be expanded in order to define simulation activities for the next stages of the stage gate approach, which for timeline reasons, were not a part of this project. Additionally the framework large scale application to product development should be done in an incremental way, taking also into consideration the separate needs of each specific case. Simulation consultants should constantly try to translate design questions into simulations. Furthermore the suitable BPS tools to conduct the planned simulation work might be different from one case to other. For instance in the case study of sandwich panels, sensitivity analysis was identified as the one that will provided the required level of information, in other cases uncertainty analysis or a combination of the two might be more suitable. Another remark also is the optimization analysis for which the data were
processed without the need of use of Pareto techniques, since only one parameter is optimized for both the objectives, which might be necessary in other conflicting objectives problems. Therefore what is suggested as beneficial scale up for the manufacturers is the introduction of innovation to their processes in order to include innovation at the end-product as well.

A point identified to be in need of more attention during the application of the process is the research of how building parameters or building typology affects the performance of the façade element under development. Besides the different climate types and orientations, different building typologies should be investigated as well. This could be done through the use of sensitivity analysis, in order to identify which building parameters are the most influential ones and to which direction. In the principle of simulations at the early design phase this could be part of stage 3 as well, or even stage 2 during the market research. Besides product development this kind of studies would be of interest for marketing purposes as well.

Finally the differentiating factor of this process, compared to similar ones found in the literature, is the fact that it is part of a specific product development process, rather than a separate stand alone set of simulations. Research was focused on improving the process itself with the use of simulations. An example of that is the introduction of stage 0. The main objective is to assist the process, by providing the relevant technical information in the field of energy, and not guide it since, as it was also concluded by the case study there many different and controversial issues to be taken into account in a real product development.

6. Conclusions

This research has focused on the development of a framework for the integration of Building Performance Simulation tools in product development processes organized with the principles of Stage Gate approach and the application of this framework in a real case. The real case is concerned with the development of new façade element suitable for refurbishment that would lead to improved energy performance. Conclusions therefore are divided in two parts. The first one refers to the conclusions regarding the integration of BPS to the stage gate and the second part to the results of the case study.

Regarding the framework:

- Introduction of stage zero in the stage gate approach was found to be required in order to guarantee a solution oriented initiation of the project
- The framework provides the required information, including simulation results and post-processing calculations, at each stage for the evaluation of the design space according to the opinion of the stakeholders involved in the process
- The key principle of the generated information is the relative comparison of the design alternatives of each stage which was found to answer the addressed design questions.
- Research on the remaining stages is required in the case of wide framework application in stage gate product development processes

Regarding the Sandwich panels’ case study:
• Energy saving potential of the ventilated façade system is in the same level with the one of external thermal composite systems (current product and market leader) varying from 3-20% depending on the climate
• Assessment of façade element under development (sandwich panel) typical build-ups shows that their energy saving potential varies from 7-18%, benchmarking the expectations in that way
• Properties of the core of the façade element identified as important in all climate types. External skin properties gained increased importance in hot climates and south façade orientation of more severe ones
• Optimization indicated that the rate of increase of energy savings is lower than the rate of increase of the product cost. That means that even though the extreme solutions are better based on a single objective view (primary energy or return of investment), a multi-criteria processing of results gives a different perspective on the choice of suitable materials.
7. Acknowledgments

This research is conducted as my master thesis for my studies in the MSc “Sustainable Energy Technology”. Here I would like to acknowledge my supervisors who have helped me during my internship and graduation project. I would like to thank prof.dr.ir. Jan Hensen, dr.Daniel Costola and my external supervisor Miss Isabel Macedo for their guidance and support. I would also like to thank all my colleagues and academic staff of the Building Performance Simulation for their suggestions and comments during the monthly progress meetings. Finally I want to thank my family and friends for their support during the course of my studies.
8. References


9. Appendices

A. Schematics

A.1 Stage Gate Approach

A.2 Ventilated facade system, cross section

A.3 External Thermal Insulation Composite Systems (ETICS)

A.4 Sandwich panel, structure schematic
A.5 Sandwich panel, build-ups of common market solutions
B. Simulation Results

B.1 Thermotropic coatings, preliminary assessment

Effect of absorptivity change on panel temperature and cooling energy consumption

Panel temperature $\alpha=0.6$

Panel temperature $\alpha=0.9$

Cooling primary energy consumption

5.7% reduction
B.2.1 Simulations Stage 2 - Technology Comparison - South Facade

Copenhagen

Brussels

Madrid

Palermo
B.2.2 Simulations Stage 2-Opaque façade potential

![Diagram of causal energy breakdown - KWhrs February-Copenhagen and July-Copenhagen]

B.3.1 Sensitivity analysis-Primary energy consumption Spearman correlation

![Bar charts for Copenhagen, Brussels, Madrid, and Palermo showing Spearman correlation coefficient – Primary energy consumption]
B.3.1.1 Spearman correlation coefficient for heating and cooling - Copenhagen

B.3.1.2 Spearman correlation coefficient for heating and cooling - Brussels
B.3.1.3 Spearman correlation coefficient for heating and cooling- Madrid

B.3.1.4 Spearman correlation coefficient for heating and cooling- Palermo
B.3.1.5 Comparison of design space minimum with Sandwich panel 2

![Graph](image1.png)

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<th>Location</th>
<th>Standard market Sandwich panel</th>
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B.3.1.6 Mode frontier model SA

![Diagram](image2.png)
B.4.1 Properties values for optimization

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<th>Panel elements</th>
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<tr>
<td>Core</td>
<td>Thermal conductivity</td>
<td>W/(m.K)</td>
<td>0.04</td>
<td>0.004</td>
<td>Variable</td>
<td>variable</td>
</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>mm</td>
<td>50</td>
<td>10</td>
<td>30/50mm</td>
<td>30/50mm</td>
</tr>
<tr>
<td>Inner skin</td>
<td>Emissivity (if air gap)</td>
<td>na</td>
<td>0.95</td>
<td>0.1</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Thermal conductivity</td>
<td>W/(m.K)</td>
<td>230</td>
<td>0.2</td>
<td>0.2</td>
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</tr>
<tr>
<td></td>
<td>Thickness</td>
<td>mm</td>
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</tbody>
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B.4.2.1 Difference in energy savings for 30 and 50mm

Energy savings difference for 30 & 50 mm-North

![Energy savings difference for 30 & 50 mm-North](image)
B.4.2.2 Energy savings for 30 and 50mm-Copenhagen

B.4.5 Energy Savings and Orientation