POLITECNICO DI TORINO

Master's degree in
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Master Thesis

Strategic Selection of Retrofit Measures by Portfolio Decision Analysis: an application on a manufacturing facility

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To my father,
Who has always believed in me.

Acknowledgments

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Contents

Abstract

In a framework of growing attention towards the research of innovative tools to support the buildings' retrofit, this work proposes a methodological approach to sustain a strategic renovation of an industrial manufacturing facility through investigation from technical, social, comfort and organizational perspectives involving many disciplines. The key factors influencing the analysis are the need of energy efficiency measures, the contrasting contents behind retrofit investment criteria and the transparency of decisional process through an industrial organization, where conflicts among individuals and departments with different knowledges and targets compromise the optimal resource allocation for collective benefits.

The thesis work is structured in three parts: firstly the auditing phase, executed by pre-retrofit survey to managers and occupants, will lead to the facility's diagnosis and the definition of available improvement options. Then, within the perimeter of the local market and favored supplier, the measures will be analysed by feasibility studies, supported by a devoted chapter to describe the design methodologies, to understand the real benefits and risks filling a conspicuous database containing the impact of each project on considered criteria. The retrofit program, before the commissioning, will end with the strategic prioritization of projects by the use of an innovative Interactive Multi-Objective Optimization of Portfolio Decision Analysis discipline based on mathematical dominance, to select the best set of alternatives among the proposed.

The results of the study, driven by preferences of Decision Makers, show that a transparent decisional process of prioritization, even though only few criteria are considered, supports the centralization of power achieving a budget sharing among departments, favoring however low cost investments in energy efficiency and the relief of maintenance operations. Overall, this methodology has proved to be powerful for the variety of measures that can be considered for an industrial user and for the interactive simplicity with which the decisors are invited to participate to the decisions, thus providing a rational basis for possible building improvement plans to be commissioned.

Keywords:

Industrial Building Retrofit · Industrial Energy Efficiency · Retrofitting Strategy Selection · Facility Diagnosis and Auditing · Portfolio Decision Analysis · Building Energy Information Modelling · Transparent Prioritization · Investment Decision Making · Resource Allocation

Introduction

The problem of building's strategic retrofit arises different issues that require a deep analysis in order to determine, implement and apply the most cost-effective solution to achieve enhanced energy performance while maintaining satisfactory service and comfort levels, under a given set of operating constraints [1]. This anticipation elicits that the conflictual nature of the whole renovation process, especially for an industrial environment, requires an investigation from technical, social, comfort and organizational perspectives involving many disciplines as engineering, management, operative research and decision theory. Many the remarkable challenges such as handling uncertainties on human behavior, propose both affordable and efficient technical solutions, fitting the governmental policy on sustainability requirements, client expectations and satisfy investment criteria and prioritization.

Scientific literature points with the terms "refurbishment" the modifications to be done to take the facility back to the original state [2] or to improve the functional aspects [3] from a single repair simply for aesthetic purposes to a more complete plan that improves the building's quality and service life, like a reinforcement of its envelope or even a radical modification of its areas and spaces [4]. Whereas the words "retrofit" or "renovation" include the measures that can raise building energy performances to comply regulations hence obtain related economic benefits, improve the indoor environment, correct the environmental impact or enhance profitability with a new layout [2, 5].

Considering the vastity of aims, constraints and options, a complete project of sustainable retrofit shall be divided in five main steps as suggested by Ma et al. in the paper [1] and illustrated in Figure 1:

1. Project setup and Pre-retrofit survey: that is a moment when the building owners point the target of the renovation and a survey is compiled in order to collect operational problems and main concerns of occupants;
2. Diagnosis/auditing phase: when the real condition of the buildings, the needs and limitations are detected, including the energy data;
3. Identification of alternative scenarios: the possible measures of the retrofit are analyzed by feasibility studies according to client's choice, technician's experience or from previous similar retrofit works;
4. Assessment phase: site implementation and commissioning of the selected retrofit interventions.
5. Validation and verification: basing on the results and commissioning, energy savings are measured, and a post occupancy survey can additional aid to understand whether the satisfaction levels are reached.

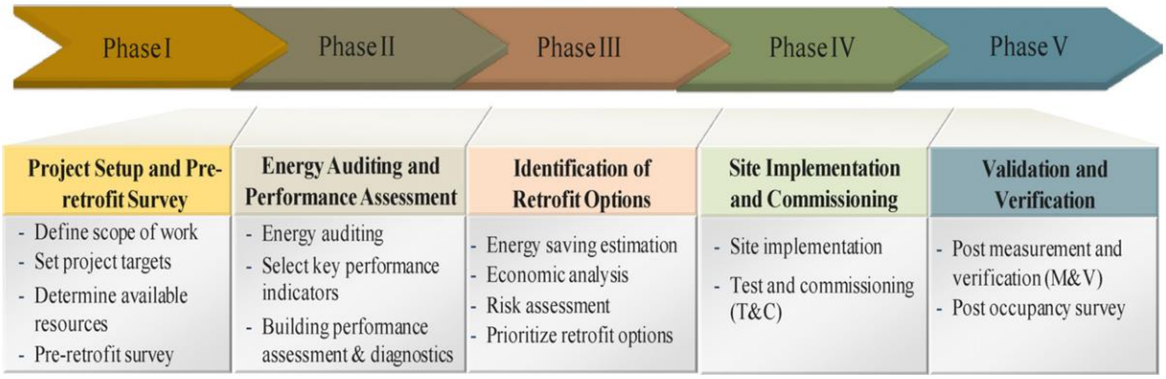


Figure 1 – Steps in a sustainable building retrofit program from [1]

The success of the whole path depicted above is strongly addressed by barriers (e.g. economic, behavioral, organizational [6]) that, particularly for energy aspects, limit the exploration of interactions. Their effects, on the decision-making process, are influenced by many elements such as legislations on performance standards, client resources and expectations, setting of the project goals, availability of technologies in the local market, building's state of the art and operational assets, comfort and occupancy regimes [1] forcing the analysis to consider the whole building to predict every measure's influence [7].

The scientific community studies the problem of building renovation targeting mostly the residential sector, offices and commercial buildings [7, 8] where a larger quantity of real applications is expected. the state-of-the-art of industrial facilities, differently, is reclaimed only under the energy retrofit perspective of the thermal envelope [9] or for the installation of technical services such as for heating [10] and ventilation [11] or for the management of old ex-industrial facilities in the context of redeveloping for housing [12] or mixed-use [13]. Although the issue of prioritizing retrofit measures grants a different importance according to the client and the type of building involved, researchers are elaborating innovative schemes and application for the decision support process, identifying three main branches of approach available [14]:

- "Discrete decision problem approaches" where a finite and not too wide group of alternatives is considered. Relevant bibliographic works about these approaches [14, 15] reveal that the methods of Multi-Criteria Decision Analysis (MCDA) are the most appreciated because they discretize the problem using criteria and weights to evaluate discrete alternatives.
- "Continuous or mixed decision problem approaches (CMDPA)" that use the multi-objective programming to account a bigger group of alternatives, often using genetic algorithms.
- "On-line approaches" that rip the boundary of retrofit, because they improve the efficiency of a building choosing in real time operation the best parameters to optimize the energy management and the indoor comfort by modern control systems connected via web.

The goal of this thesis is to apply an innovative procedure to suggest a strategic retrofit program for a manufacturing facility. All the aspects above mentioned will be translated in concrete issues and a proposed solution will be offered by engineering (for the technical aspects concerning the retrofit's measures) and by math regarding the choice of the best alternatives among the projects proposed. Three main motivations, that raise the importance of the application contents of this work, emerge as key factors of analysis, which actually are already a source of widespread scientific and engineering investigation.

The first point is, of course, the energy aspect related to a manufacturing plant and in the general framework of sustainability, affronted in the last decades, to allow the European Union the compliance of the Kyoto Protocol and so maintain the global temperature rise below 2°C achieving the objective of reducing by 20% the energy consumption and greenhouse gas emissions, together with the rise of 20% of Renewable Energy Sources (RES) utilization with reference to the levels of the year 1990 [16]. In many industrial activities, the energy investments are considered not-strategic, so not fully appreciated, because the energy expenditures are often less than 5% of the total production costs [17] even though the energy consumption is relevant: the Italian industry sector required almost the 21% of overall national energy requirements in 2016 [18], whereas for Europe this share is stable from 2012 to the 25% [19] and worldwide to the 37% [20], being the manufacturing the largest CO_2 emitter [21]. These values highlight large consumptions and emission but even potential saving from the efficiency measures and corresponding benefits as the increase of the industrial competitiveness, new job opportunities and more investments in innovative technologies: the energy saving is estimated to be 25% for European manufacturing enterprises [22] and particularly the 15% for the gas consumption deriving only from car manufacturing sector [23]. Whilst worldwide, International Energy Agency (IEA) states that manufacturing can reduce energy consumption by between 13% and 29%, with a saving of 15 EJ per year and reducing CO_2 emissions of 1.3 Gt per year [21].

The energy efficiency plan introduces for industrial users, whose sector is the largest contributor with a saving of 41% up to 2006 [21], energy audits, referring to a methodological and exhaustive procedure that aims to analyze the energy consumption of each carrier and to study the main cost-effective energy saving possibilities [24]. The corresponding figure of the auditor, chosen internally or externally [23] to the plant, has to conduct retrofit plans to improve performances conveying towards new energy models of building such as nearly-Zero Energy Buildings [16, 22]. The second measure taken is the introduction of ISO 50001 as international standardization of energy management policy, continual improvement and monitoring performance indices [25]: a survey of 2015 shows that in Europe, Germany was the most intensive country for its application, whereas in Italy the share was only 14% over 3000 enterprises with energy intensive processes, though more than 38% of companies obtained an energy saving above 5% with the nouvelle policy [26].

The second motivation, that makes the analysis interesting, is the strong contrasting content in an optimization procedure of retrofit's planning investments from the implementation of support tools point of view. Bibliographic reviews show that in general the energy efficiency and financial aspects are the most attracting objectives even though they are in contrast with thermal comfort, artificial lighting, indoor environmental quality, CO_2 reduction: the direction of the optimization procedure will be marked according to the weights assigned to such criteria, being MCDA type the most studied approach [1, 2, 14].

The last motivation is the transparency of decisional processes for retrofit's investment behind enterprise's organization and resource allocation, that might represent a barrier to the adoption of energy-efficient technologies and might be considered a system with relationships and conflicts among individuals and departments with different knowledges

[27]. In particular, energy issues and investments, usually assigned to engineering or maintenance departments, are considered peripheral and not-strategic. An investment is considered strategic if it contributes to create, maintain and develop sustainable competitive advantage: the more strategic the decision is, the more it contributes to competitive advantage, so a project characterized as non-strategic will most probably lose the competition and will be excluded from the decisional stream [17, 27]. The paper [28] lists the five types of problems faced by the managers of organizations during problems of prioritization and resources allocations where a multi-choice is possible or the preference of more strategic alternatives (e.g. on the products or on the production process):

1. Benefits are typically characterized by multiple objectives, which often are in conflict for any kind of organization (private and public sector and voluntary);
2. Decision makers (DMs) are not sufficiently informed about the details of many alternatives;
3. The choices of collective units intra-organization cannot make the best use of the total resource allocation. The individual optimal is rarely collective optimal;
4. The decisional flow passes through many hands without an exhaustive control, revealing a potential competition;
5. If the projects implemented touch the activities of workers who disagree with the choice, this can easily lead to the formation of small teams badly invested personally in the organization welfare.

To these problems, many others add where one deals with decision-making on investments, among these: the verticality of average-conspicuous organization's structure, the investment characteristics, the cyclicity of the decisional process, human factors and managers' personal pre-existing knowledge [1, 17, 28].

The counter-measures to tackle and achieve great effectiveness in investment planning and especially for not-strategic investment, like retrofit's projects, resides in managers that must be skilled at reading organization's life, remaining open and flexible in the power operations, the medium through which conflicts of interests get resolved [27]. Such attributes will drive towards a new model of investment where decision making can be considered as a process influenced by intra-organizational context and outer actors, involving many and different figures adopting new tools and approaches supporting the choice during the evaluation step [17]. One of the most addressed tools is the discipline of Decision Analysis (DA), seen as a mean to balance cost and benefits, to construct portfolios of investments across different areas collecting multiple advantages and to consult the right people coherently throughout the decisional flow [27].

The thesis work is structured in six chapters. The first describe the manufacturing facility object of the retrofit process exploring the structural data, technological process, logistic workflow, energy systems, occupancy and service utility. Such information were collected during the interactive auditing and diagnosis phase with building's occupants, content of the second chapter, where the main problems and un-satisfactions allow the detection of possible counter-measures and the sensibility towards the most accredited criteria. The third chapter depicts the modelling techniques and design methodologies used for the completion of feasibility studies of renovation projects: energy consumption and products chain are analyzed to build assumptions on routines. The fourth section collects the retrofit projects, in perspective of above mentioned criteria setting, considered separately together with the supplier analysis of the local market. The fifth chapter is bibliographic and explores, in its first part, the field of DA and Portfolio Decision Analysis (PDA) to show their historical developments and usefulness for the scope proposed; the second part of the chapter, instead, proposes the interactive method used to support the decisions of the real application case, adapting the original paper of reference. The following chapter shows the outputs of the algorithm highlighting how preferences on criteria drive the decisional process towards a clear convergence, while the conclusions discuss the results achieved throughout the retrofit's workflow.

1 Description of the model area

In the following chapter a general description of the building investigated in the thesis is offered: there will be first an introduction to the geometrical aspects accompanied with drawings and schemes, and after a characterization of technological processes occurring within. The objective of this chapter is to aid into the definition of peculiarities and to highlight a priori where a possible renovation can take part, and in which limits one can incur.

The perimeter of the model area will be addressed with an exhaustive illustration because, for most of the modelling structure used during the retrofit horizon, it strongly influences the expectation and profitability of requalification measures. With the same importance, the productive cycle (and its materials and products‘ chain) will be described so that a quantitative and/or qualitative impact of each change can be detected on actors for the manufacturing workflow.

In addition, scope of this part of the thesis is to justify the choice of temporal assumptions for the modelling section, in fact the production storyline will be studied to select the best approximation as compromise between accuracy for future previsions and necessity of clear data.

The information and data reported in this chapter, and partially hidden, were attained and collected by the author throughout a period of internship by interaction with the personnel and rulers of the unit or by non disclosable reports.

1.1 Industrial framework

The FCA[1] Plant, based in Turin, is divided in three main productive sites covering an overall area of about 2 km^2: Mechanics, Presses and Car Body.

The Plant which contains the model area is "Car Body" (whose planimetry is reported in Figure 2) constituted mainly of the following three units:

- "Lastratura" (referred as Body Shop)
- "Montaggio" (referred as Assembly Shop)
- "Verniciatura" (referred as Paint Shop)

The Car Body site dates back to the 40s: there is a main building (called "Fabbricato Principale") which extends for a surface of about 0.4 km^2 (over the 1 km^2 of Car Body plant) and additional facilities, each one with their own dedicated function to the manufacturing process. It can be noted that the paintwork processes are in the central nucleus, but it had three main extensions in the mid of 1950s, in the early 60s and in the 70s, where Bumper Paint Shop (BPS) facility was built.

[1] FIAT Chrysler Automobiles. Fabbrica Italiana Automobili Torino was an Italian automotive company founded in 1899 and leading financial Italian group in the XX century [40] that joined with the american enterprise, Chrysler.

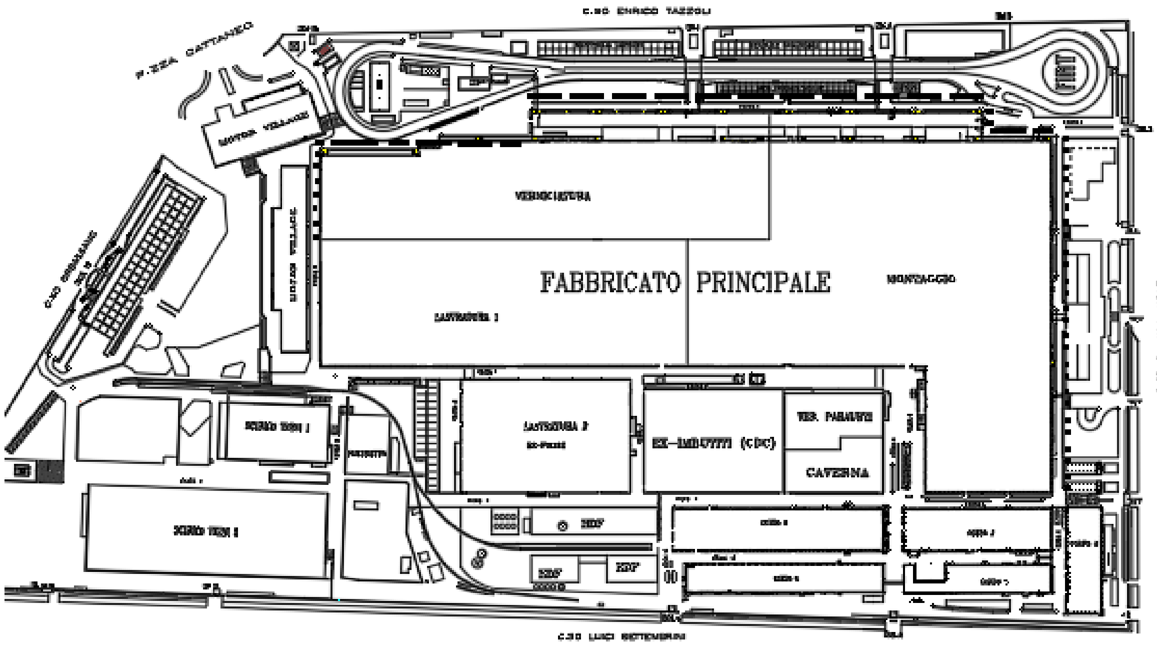


Figure 2 - General Planimetry of Car Body [29]

The most relevant final products manufactured at the Plant are Alfa Romeo Mito (from year 2010) and Maserati Levante introduced just in 2016, both shown in Figure 3.

Figure 3 - Alfa Romeo Mito (on the left) and Maserati Levante (on the right) [30]

Maserati Levante is the driven product since an almost complete re-setup of Mirafiori Plant was assessed when it was launched and most of the areas are devoted to its production.

1.2 History and geometry

The facility chosen for this analysis is part of Paint Body plant and separated from “Fabbricato Principale” only by “Strada 5”.

From Figure 4 it is clear that the model area is not an isolated building but surrounded by:

- on the west side by “Ex-Imbutiti” or “CDC” which is a warehouse with a full time occupancy. This local contains not only a stock of products recalled during the assembly stage, but even a station for the electrical charge of internal handling machines and some offices. This is conditioned with a new thermo-strip heating system (installed few years ago) and divided from BPS with a bearing wall with no additional passages or openings.

- on the south side by “La Caverna” that is a warehouse used as stock of different raw material and as garage for group’s cars to be shown in company events. It is not heated and strongly connected to the productive workflow of BPS. The two locals are joined with a combination of two fast doorways in series.
- on the east and north side by “Strada 8” and “Strada 5” respectively.

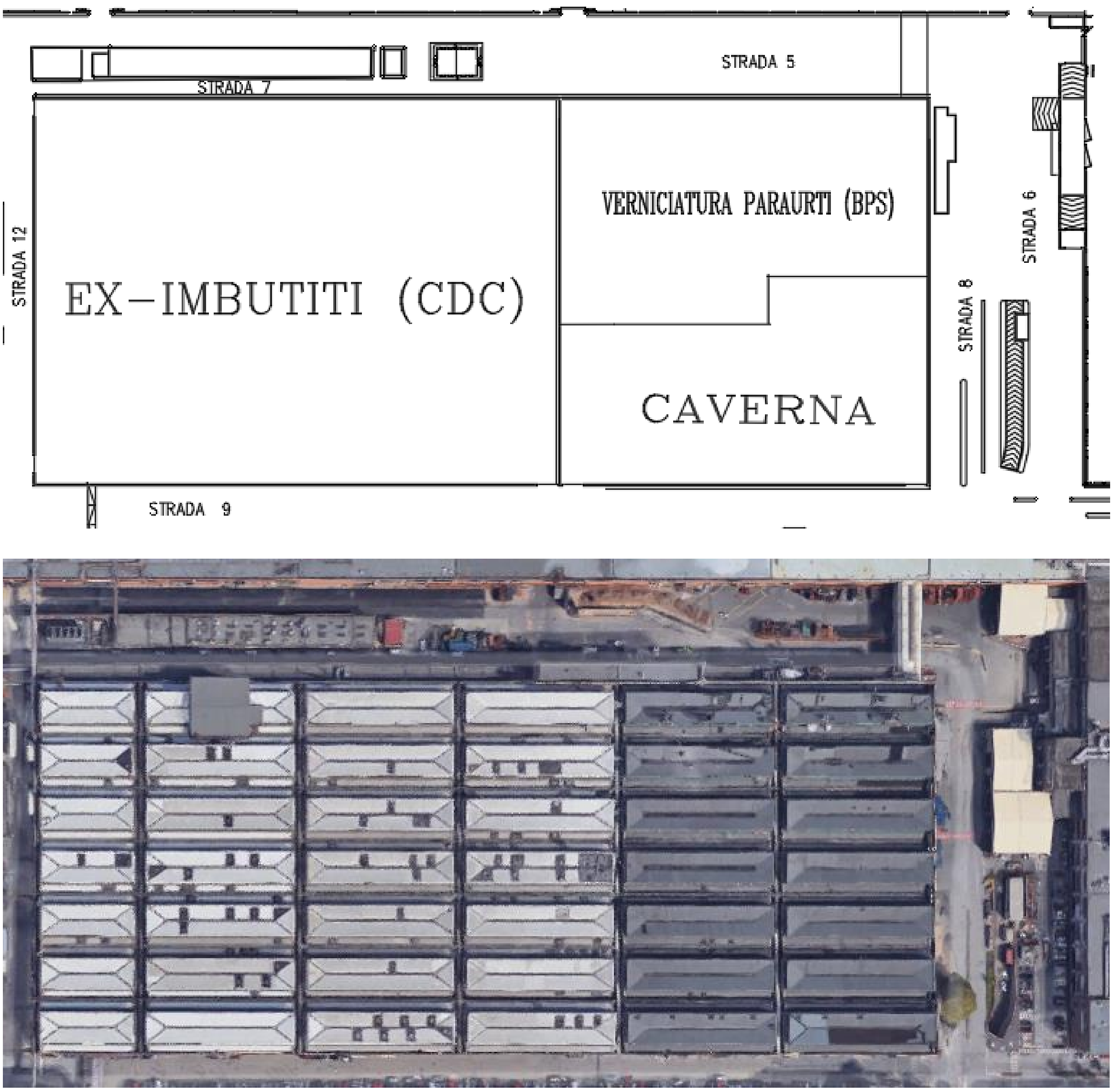


Figure 4 - Top view of BPS, above from [29] and below from Google Maps [31] (north is up)

The space of the building devoted to the BPS extends for 140 m in length and a variable width from a minimum of 67 m to a maximum of 85 m occupying an area of approximately 11’500 m^2. The height of the building varies from 8 up to 15 meters because of the historical development of the structure.

The building, in fact, is made up of a central single body, the **Workshop**, a pre-existing construction of 70s, with a height of about 12 m, with partially concrete bearing structure armed and partially in steel. Afterwards two additional bodies, that will be referred as **Paint Center** and **Dressing rooms**, were joined to the first (along their length) and are constituted by a reinforced concrete structure (see Figure 5 for details).

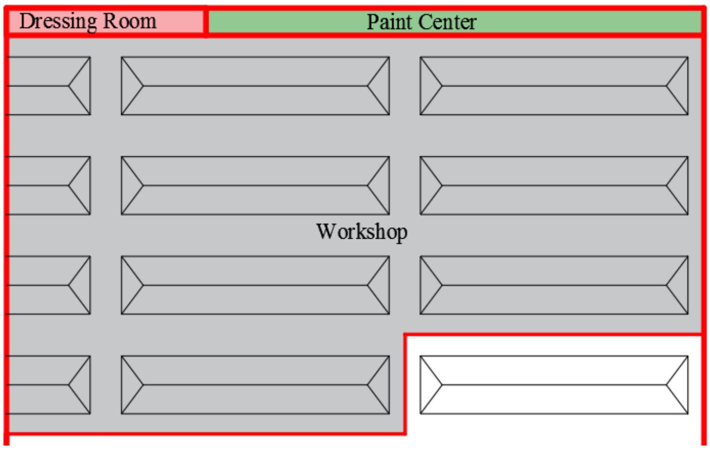


Figure 5 - Top view of the three areas of BPS

This space volume of BPS is so spread over three floors and contains:

- Workshop (constituted by a single floor), where the most relevant activities of the process take part and populated constantly by most of the workers of this unit;
- Paint Center and warehouse storage paint (constituted by a single floor) where paints are prepared for the next processes;
- Dressing rooms body, that presents on the ground floor Offices, Men's changing room at the first floor and at the second floor Women's Closet.

The geometrical information about the building are summarized in Table 1, whereas two graphical illustrations are offered in Figure 6.

Table 1 - Summary about geometrical infos of bodies constituting BPS

	Workshop	**Paint Center**	**Dressing Rooms**	**BPS**
Floor surface (m^2)	9’945	550	227	10’722
Building height (m)	12	8	15	-
Storeys	1	1	2	-
Gross Volume[2] (m^3)	-	-	-	151’025
Net volume (m^3)	119’340	4’400	3’405	127’145
Surface/Volume ratio	0.083	0.125	0.067	0.084

[2] The gross volume is achieved by reports of the FCA about the facility and construction but will not be used in further work. The net volume is calculated as product between the floor area and the height of the building, both reported in Table 1.

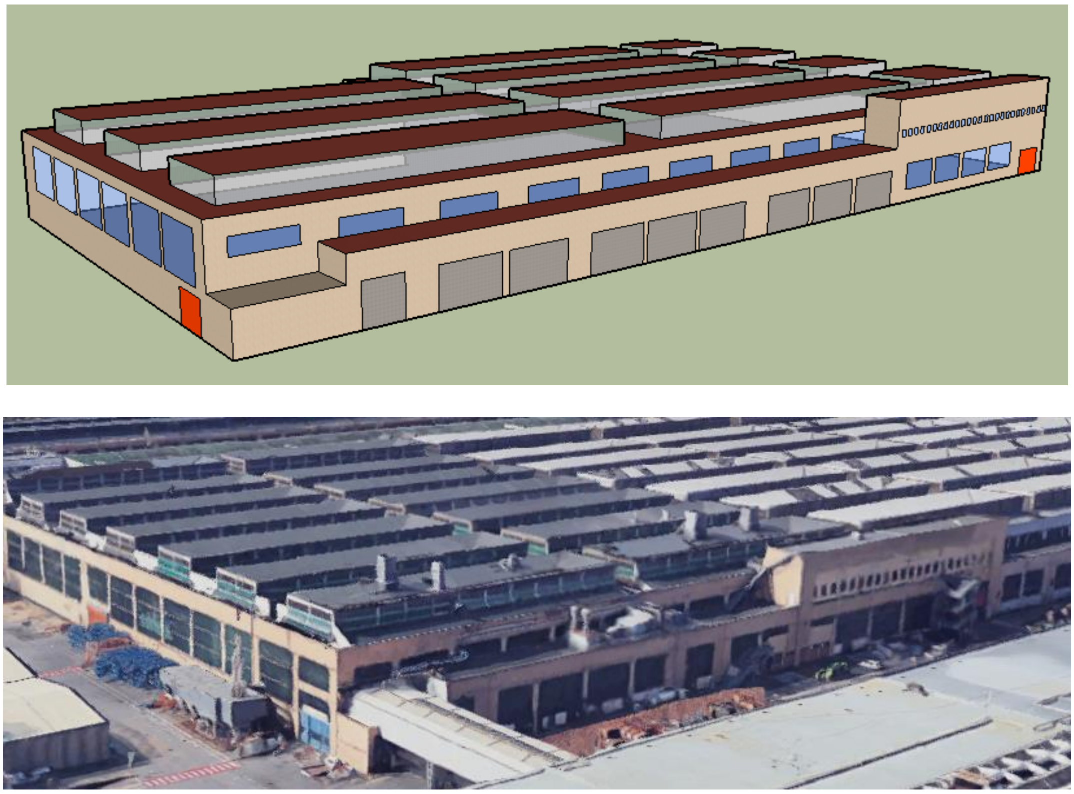


Figure 6 - Isometric views of BPS: above a SketchtUp© model, below a picture from Google Maps [31]

1.2.1 Focus on perimetric envelope

With the aid of the SketchUp© model, that will be built for considerations of paragraph 3.3.1, more words are spent in this paragraph to explain the characterization of elements constituting the perimetric walls of the building, whilst the roof will be analyzed later.

Figure 7 - Detailed photos of outdoor and indoor plastering

The outer envelope, shown in Figure 7, is essentially made with two different solutions:

- reinforced, non-insulated concrete plastering, plastered internally and externally;
- double full brick tampons, with non-insulated inner chamber, internally plastered.

In the early 1990s, modernization interventions were carried out following reconversion of the production activity, which in part led to improvements in performance: the renovation interested mainly the aluminum windows and part of technologies for the production processes.

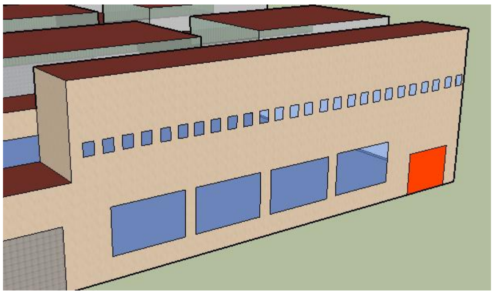


Figure 8 - Focus on Dressing rooms from SketchUp© model

In the first picture (Figure 8) it is possible to observe the higher body of BPS, constituted by the dressing rooms (for males and females at the 1st and 2nd floor respectively) while at the ground floor there are some offices: all this rooms are accessible to the workers by the workshop and the entrance from outdoor is close to the orange doorway.

The doorway (orange), from now referred as "north doorway" is a combination of two doorways in series (with a high opening speed), connecting the outer road with the workshop: this solution allows a rapid exportation of finished bumpers to the next process lines and for this it is often a busy aperture.

All the fenestration of the perimetric envelope was changed in the 90s from an iron frame to an aluminum one, while the surfaces of the wall are not interesting in this analysis, because the volume covered inside is closed and limited.

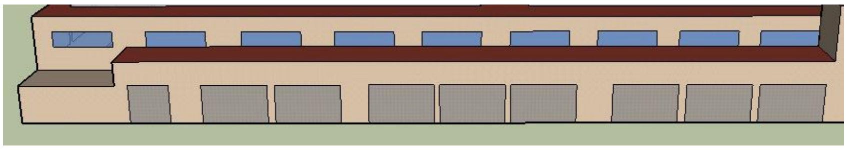


Figure 9 - Paint Center from SketchUp© model

The Paint Center presents a lower and dedicated roof (see Figure 9) because this body, as previously said, was added later to the main body. On the left, where the ceiling presents a sort of step, there is a hanging construction that was previously used in the transportation of some materials off BPS. Now it is closed and will not be modelled.

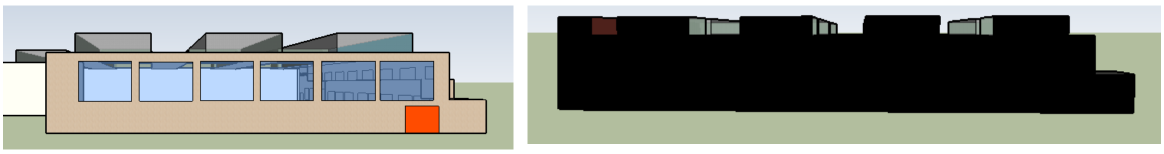


Figure 10 - Est side (on the left) and west side (on the right) of BPS

The east side (in Figure 10) of the building has an additional rapid doorway, but not congested since it is used only for service vehicles, while the west side (an inner boundary) is an entire block that separate BPS from CDC with no opening.

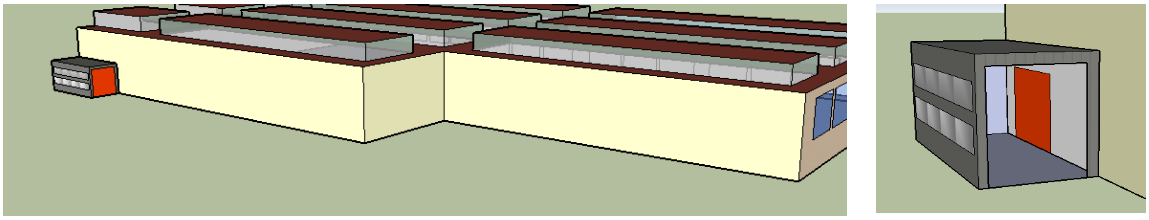


Figure 11 - South side: confining wall with La Caverna and zoom on the doorway series

Finally, the south side (reported in Figure 11) is a simple inner wall in concrete, with a series of two rapid doorways closed in an aluminium structure. This opening represents a very interesting actor in the logistic flow of the productive areas, since it connects the warehouse La Caverna with the production line of BPS.

1.2.2 Focus on roof geometry

The roof of BPS, as all the other roofs of Mirafiori Plant, is constituted by sheds (for at least one quarter of total area) which are constructions to enhance daylight entrance, through skylights, and simultaneously a waterproof raincoat and resistant to snow load.

The tilt angle of the roof's surfaces was recovered by [29] and shown in Figure 12, it is equal for all the 4 faces constituting the main body of the skylight and necessary for above mentioned functions.

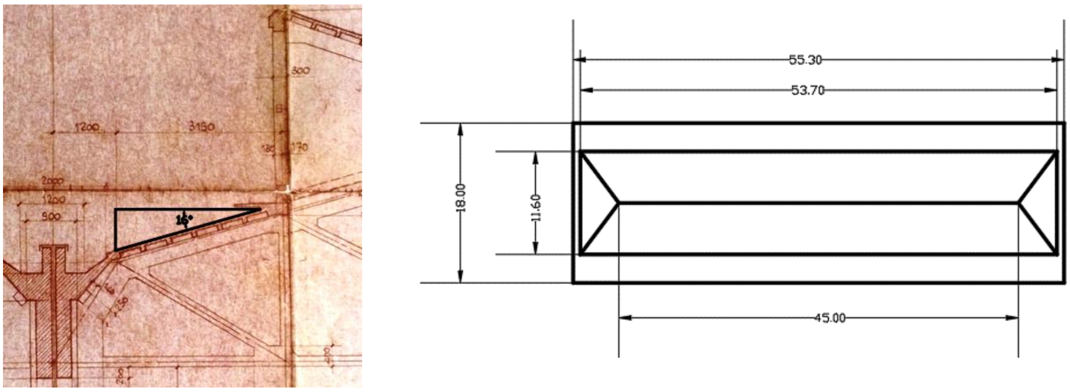


Figure 12 - Surface roof tilt angle on the left [29] and roof with share on the right

Then, assessing that for the rainwater drainage, a tilted area between two sheds (called area B in Figure 13) is considered, while the remaining sloped areas are C and D[3]. The

[3] Area B, C, and D are all sloped with a tilt angle of 16°

following Equations are used to determine, with the data reported in Table 2, the partial area of the shed.

$$A_B = x_B \cdot \frac{y_B}{\cos(16°)} \tag{1}$$

$$A_C = \frac{[x_C + (x_C - 2x_D)] \cdot \frac{y_D}{\cos(16°)}}{2} \tag{2}$$

$$A_D = \frac{x_D \cdot \frac{y_D}{\cos(16°)}}{2} \tag{3}$$

$$A_{TOT} = 2 \cdot (A_A + A_B + A_C + A_D) \tag{4}$$

The total area of a single shed, A_{TOT}, is equal to 1034.4 m^2, while the area of the half-sheds (on the west side, that are indoor separated by the shed of the confining CDC, so it is correct to split), using the same calculations but considering only a contribution of 31% along the x-axis is 328.4 m^2.

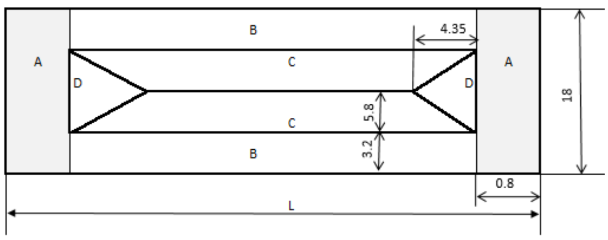


Figure 13 - Areas of shed and corresponding shares

Table 2 - Partial measure of shed's area

Area	Share projected along x axis (m)	Share projected along y axis (m)	Partial area (m^2)
A	0.80	18.00	14.40
B	53.70	3.20	178.77
C	53.70	5.80	297.76
D	4.35	11.60	26.25

The roof contains 7 sheds and 4 half-sheds, as shown in Figure 5, so the plain and titled area are considered to calculate the overall roof's surface of BPS: this value is reported in Table 3 and it is the sum of the residual plain area and area A_{TOT} times the number of sheds calculated with Equation 4.

Table 3 - Assessment of sloped and plain area for roof's surface of BPS

Total projected area of BPS roof	10’722	m^2
Total projected area of sheds	8’238	m^2
Residual flat area	2’484	m^2
Overall roof surface	11’038	m^2

Note that the ratio between “Overall roof surface” and “Total projected area of BPS roof” (that is +3%) can be considered as a corrective factor for any design model implemented afterward. Considering singularly the roof of the three locals, one can calculate with floor surface of Table 1 and shed’s impact in Table 3, that Workshop has a real roof surface of

10’261 m^2, while for Paint Centre and Dressing Room the value corresponds to the one of floor surface, as in Table 1.

1.3 Manufacturing and workflow

1.3.1 Process line in the Workshop

The active technological transformation processes occurring in BPS, happen in Workshop local. The sequence of phases that constitute the core cycle is listed below and illustrated graphically in Figure 14.

1) Bumper load on conformers
2) Wash tunnel
3) Drying tunnel
4) Flame cabin
5) Primer cabin
6) Base cabin
7) Transparent cabin
8) Baking oven
9) Testing by deliberation

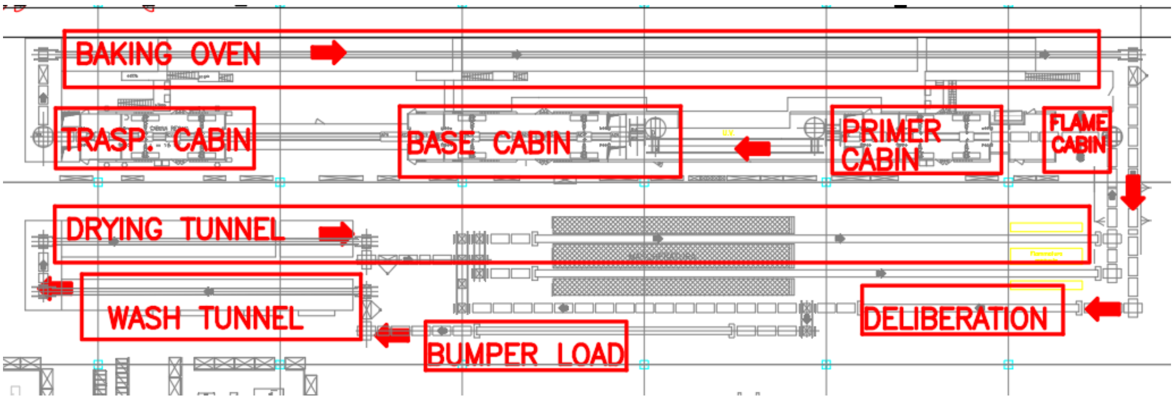


Figure 14 - Core process line in BPS

The process begins when bumpers from external suppliers in special containers (by forklift and later by hand) are loaded onto the conformers called skids (specific slides that reflect the shape of the bumper as in Figure 15), and by means of a roller conveyor are sent to the **washing machine** in Figure 16 (the process takes part in a tunnel): it is constituted by two degreasers, one washer and a spraying pergola of demi-water. The heating is provided with three plate heat exchangers but only one is supplied by external energy, the other two are just as recirculatory.

Figure 15 - Photo of skid with bumper and bumper band

The following step is the drying that is carried out at a temperature of about 80 °C. This phase is fundamental to achieve a great quality of the surfaces of the bumper before the painting, otherwise the application will be low. In all these processes the energy to keep the temperature high is provided by technological heat produced outside the facility.

Figure 16 - Photo of washing machine and drying tunnel

The next step is the effective application of paint in "painting cabins" into **4 steps** manually on the inside surface of the body and automatically on the exterior of the bumper.

For this phase, the reciprocators robot are used (provided of a swinging arms equipped with a spray gun) which, moving along the contour of the body, allow to apply the enamel uniformly.

Like in the manual spraying, the same is done with the use of compressed air guns since, for reasons of bulk, the type of equipment described above cannot be used.

In the first part of the cabin (a photo is offered in Figure 17), the bumper is subjected to heating the surface (**flame section**) before the next primer application: this step is necessary to eliminate residual impurities (usually dust and fat) and to help the adhesion of the varnish.

Figure 17 - Photo of the flame cabin and robots

The process is hazardous since there is an alive flame and in the next stages the utilization of flammable product: a burden factor is the presence of a methane pipeline in the flame cabin. The further part of the cabin is obscured and constituted by several flame detectors whose signals stop the line in case of emergency, turning off the methane in the pipeline via venting channels and extinguish the fire.

Then, on the bumper surface, a primer layer is applied to allow proper anchoring of the paint (**primer section**). For the application of the primer, robots equipped with compressed air spray gun are used. A following drying stage follows the application of the primer to allow correctly the layer already sprayed.

The next step is the application of the **base paint** and finally (last stage in cabins) the **transparent resin**. There are additional drying sections after the base and transparent painting.

The purpose of the drying sections is to allow the paint to rest and the pre-evaporation of the solvents before to enter in the oven. If the solvents evaporated immediately into the furnace, they would create defects on the applied paint layer. The temperature in the drying chambers is between 40 and 50 °C. Everywhere, so, spraying is performed by robot and areas that cannot be reached by automatisms are completed manually after the automatic line.

During the application of the paint, the **conditions in the cabins** are under control, both for technological reasons and for the sake of safeguarding the health of workers.

The parameters under control are (by standard no disclosable documents [29]):

- the temperature, which must be as constant as possible (25 °C);
- pressurized chamber according to precise flow rate;
- relative humidity, which must be between 50% and 70%;
- the number of ambient air recirculation (approximately 500 spare parts per hour in manual application areas).

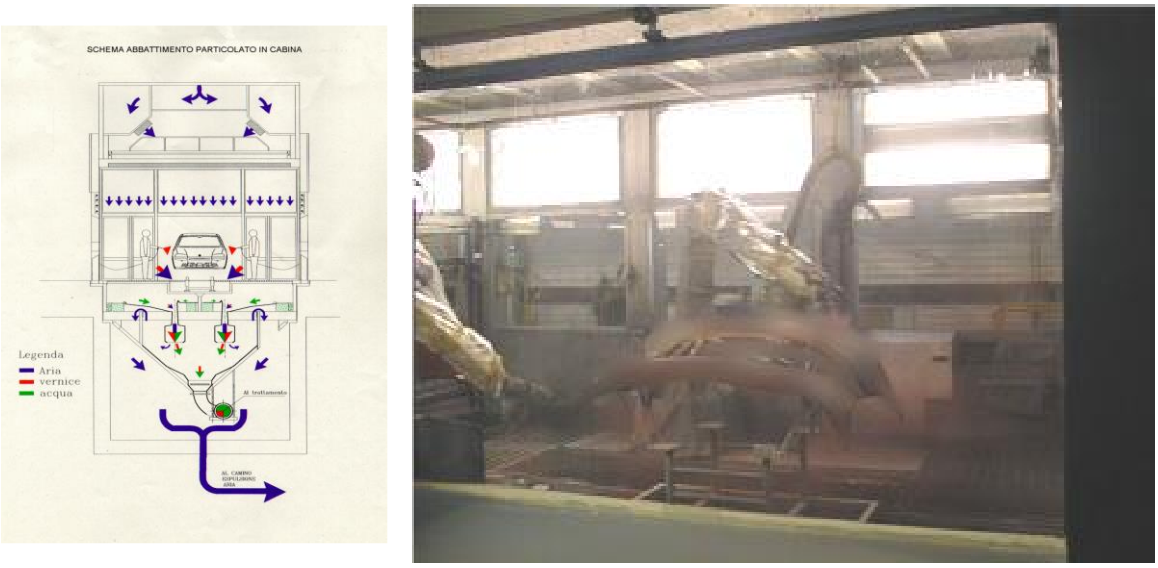


Figure 18 - Illustration of a cabin from [29]on the left and the corresponding picture

To obtain control of all these parameters, the air taken from the external environment is suitably filtered, washed and heated in special heat exchangers. The air thus treated enters the cabin from the top and, proceeding to bottom, removes any spraying residual that has not deposited on the body, dragging it down the cabin where the air is intimately mixed with water, which holds the particulate matter, called VOC[4] (the direction of air flow is represented with arrows in Figure 18).

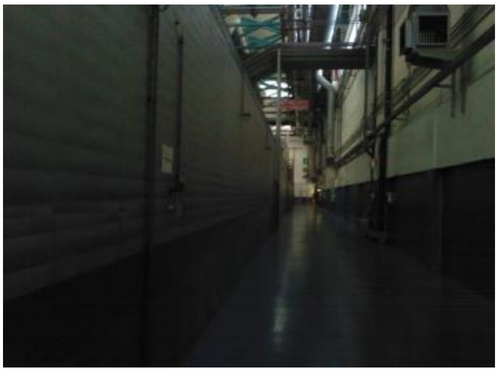


Figure 19 - Photo of the baking oven lateral surface

The bumper is then sent to the **baking oven**, as shown in Figure 19.

By the polymerization, the paint layer compacts and becomes resistant and then the solvents and volatile products from crosslinking reactions are eliminated. This stage takes place at a temperature of about 90 °C; the fumes emitted are conveyed to a specific thermal

[4] Volatile Organic Compounds in Paint Shops are constituted by the molecules of the paint mixed with air, to be removed since dangerous for human health.

post-combustion plant (see paragraph 1.3.3) for the elimination of VOCs, thus being ejected into the atmosphere.

After the painting phase, the bumpers are sent to the testing section for the deliberation (if there is a queue of products, a specific conveyor buffer can potentially stock a limited number of bumpers) and later stored in BPS warehouses, before to be brought at the assembly shop.

One can note that, except for the washing machine, all the thermal setpoints are achieved with Air Treatment Units (CTV or ATU) that, in most of the cases, recirculate the air: since even humidity have to be controlled, there is not only cooling batteries but even humidifiers.

The cab section of the Workshop is underserved by a **Paint Center**, where paint is stored and prepared for the processes above described.

1.3.2 Activities into the Paint Center

These areas are used to stock the paint used in the main department (Workshop), prepare the raw material necessary for the further painting processes and to clean the pipeline (by solvent solution). Paint Center's rooms are conditioned during summer and winter period because of the necessity to keep varnish at the same condition of the cabins (see paragraph 1.3.1): on the roof of Paint Center there is a **cold polo** constituted by two centrifugal pumps and each ATU for space conditioning is made of three batteries (pre-heating, cooling and heating).

1.3.2.1 Solvent preparation

The room for the **preparation of solvent**, used to wash the pipes and to dilute the paints, is a closed room of dimensions of 170 m^3. The solvent used is mainly composed of cyclohexane.

The preparation of the solvent takes place in three cylindrical shaped vases: loading is carried out in a tank located on a special platform with pumping through a pneumatic pump. The pavement of the room has grids at the apertures that are positioned on slopes towards the workshop, in such a way to prevent product spill in case of spreading.

The product possibly spilled would fit into a classified environment considered not hazardous for fire and explosion. The local is well artificially ventilated with an extraction flow rate of 600 m^3/h where the air extraction is from the bottom so that all VOC can be collected, avoiding a rise compromising human exposure.

The fire risk is low but there are some fire-sources like the system used for spilling the solvent inside the tanks. In case of release of the whole tank's content, it is considered that 1 m from the ground will present a hazardous concentration of gases.

1.3.2.2 Paint Preparation

The room for the preparation of the dye is a closed space of 1'400 m^3, where are carried all the components of the dye (i.e. the catalyst). The paints and diluents are placed in closed containers of maximum 300 liters each and are also present the solvent and the soap for the washing of the pipes. The washing becomes necessary in the passage between one stain and the other in order to guarantee its purity: in this way it is possible not only to save raw material (economic benefit), but even reduce the environmental impact and, so, incur in less taxation as emitting class.

The central has 66 containers divided into two roles (see Figure 20): one is the tank where the paint is taken from, the second is a buffer tank, waiting for the first tank to be extinguished.

From these containers, the fluids are transferred via pneumatic pumps, into mixers where diluent is added and the paint is kept in constant motion, by means of pneumatic stirrers (fed by compressed air), to avoid sedimentation phenomena.

The handling of tanks and drums is performed via electrical means suitably equipped, whilst the circulation of paint occurs through a close loop circuit and pushed by pneumatic pumps.

Figure 20 - Photo of buffer tanks, mixers and tanks for paint preparation

A ventilation system ensures a **change of ambient air ranging** from a minimum of 5 to a maximum of 15 spare parts per hour, depending on the use and the handling in the site: ventilation is fundamental because of the fire risk associated to the concentration of paint in the nearby of the tank.

The floor of these area is equipped with adequate **drainage channels** for conveying any eventual paint losses in special siphon, located outside the building and connected to a collection tank to avoid release and evaporation of flammable substances. The whole plant is equipped with an explosion-proof electrical system and a fire sprinkler system.

An additional close local is called “Paint Mini Mixer” that is constituted by two tanks whose function is to mix the dye with the same function and risks of Paint preparation.

1.3.2.3 Paint Warehouse

The room is intended to contain paints, solvents and lubricating oils kept in closed containers, while solvent and exhausted are kept inside a special tank.

Figure 21 – Picture of the room (left) and of the special tank containing exhausted material (right)

As for the stems stored, during handling they must stay closed as a rule; during the activity, there is always an operator that would remove any spilled product immediately.

The spent fuel storage tank is in a slightly sloped area that conveys any releases to a grid, converting them into a built-in reservoir outside. In this area there is even the recovery of solvent for washing of painting machine from the cabins, that is temporally stored in a tank to be later moved off the building by suitable trucks for final disposal.

1.3.3 Post combustion plant

The post combustion plant, sets externally on the east side of the building (as shown in Figure 4), treats smokes from the baking ovens of the paint varnish by combustion in order to destroy the VOC contents of the process: these organic substances are basically made up of paint solvents that are released and evaporated during the cooking phases.

Organic substances are oxidized with methane at a temperature of 720 °C and converted into CO_2 (carbon dioxide) and H_2O (water vapor). The use of the post-combustor for oxidation guarantees abatement efficiency of more than 95%.

Considering the large number of fumes to be oxidized and the high combustion temperature, energy costs would be untenable without the adoption of appropriate recovery systems: in fact, there is a heat recovery for the preheat of water entering in the baking ovens.

Post-combustion abatement abilities are designed considering the maximum capacity of the plant, in order to ensure that the abatement efficiency and its emission are constant over time.

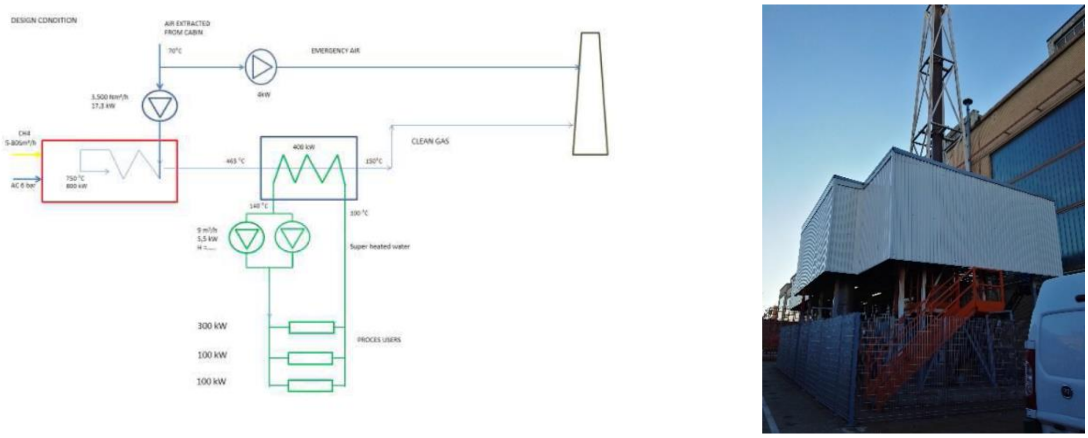


Figure 22 - Scheme and photo of post-combustion plant

1.3.4 Production chain, logistics and internal warehouses

In this paragraph a description of products handling will be offered, to clarify how future interventions will affect and will be affected by the indoor workflow: the complexity of logistics occurs in the Workshop because of the high number of processes and occupants. The kind of production is classified according to [32] as:

- Production per part or manufacturing: it is common practice for automotive companies to produce singularly the components of the final output and each part is treated separately from the others, before the assembly. This is general because, as previously seen, there are three main units (Paint Shop in this case) that work about on the same technology: each unit has its inner divisions, too.
- **Semi-automatic** line: they are usual in assembly shop but even in this special case, where the active contribution of workers is fundamental in some steps (e.g. before the cabins workers have necessity to select the pieces in series and spray over the bottom part of the bumpers; at the end of the line there is a revision section …).
- The layout and the sequence of operations is in **series** and fixed by the product design (sequential machining). This is true only for the "core" process (the passage in the process line) but not for the logistics afterward.

All the information reported on the productive chain are summarized in Figure 23 where, regardless the materials considered, one can note that the processes are mainly on a line series resembling a sort of inner job shop[5] [32].

[5] Because each warehouse has its own dedicated product

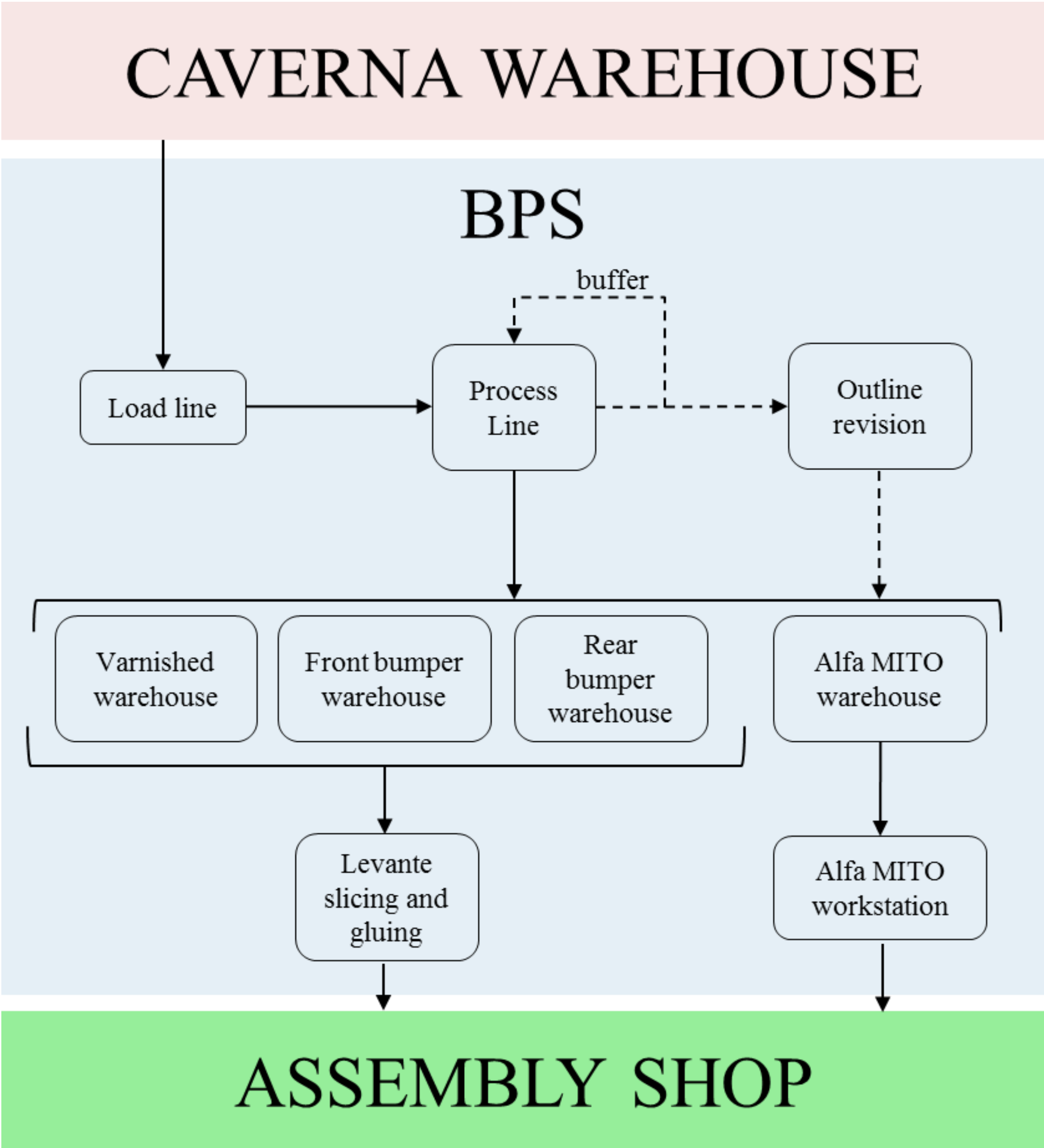


Figure 23 - Scheme of production chain within BPS

The materials treated in this facility are reported on the first column of Table 4 and are all handled by electric means (forklifts and bulls in Figure 25) or by hand. The loading phase, in fact, foresees the transportation of these elements from "La Caverna" to the process line by forklifts on boxes following the path in violet depicted in Figure 24: the south doorway series is, in fact, very used since the forklift traffic is significant and will be analyzed in future chapters.

Table 4 – List of quantities loaded and contents of process's skids

	Loaded in a box	SKID 1	SKID 2	SKID 3	SKID 4	SKID 5
Bumper front LEV[6]	14	1	0	0	0	0
Bumper rear LEV	14	0	1	0	0	0
Band front LEV	12	1	0	0	0	0
Band rear LEV	10	0	1	0	0	0
Mouldings rear LEV	40	0	0	2	0	0
Mouldings front LEV	56	0	0	2	0	0
Arches rear LEV	10	0	0	0	2	0
Arches front LEV	8	0	0	0	2	0
Bumper front MITO	16	0	0	0	0	1
Bumper rear MITO	16	0	0	0	0	1

When boxes are discharged in the center of the building, operators open them and singularly move the pieces on the skids according to the quantities expressed in Table 4.

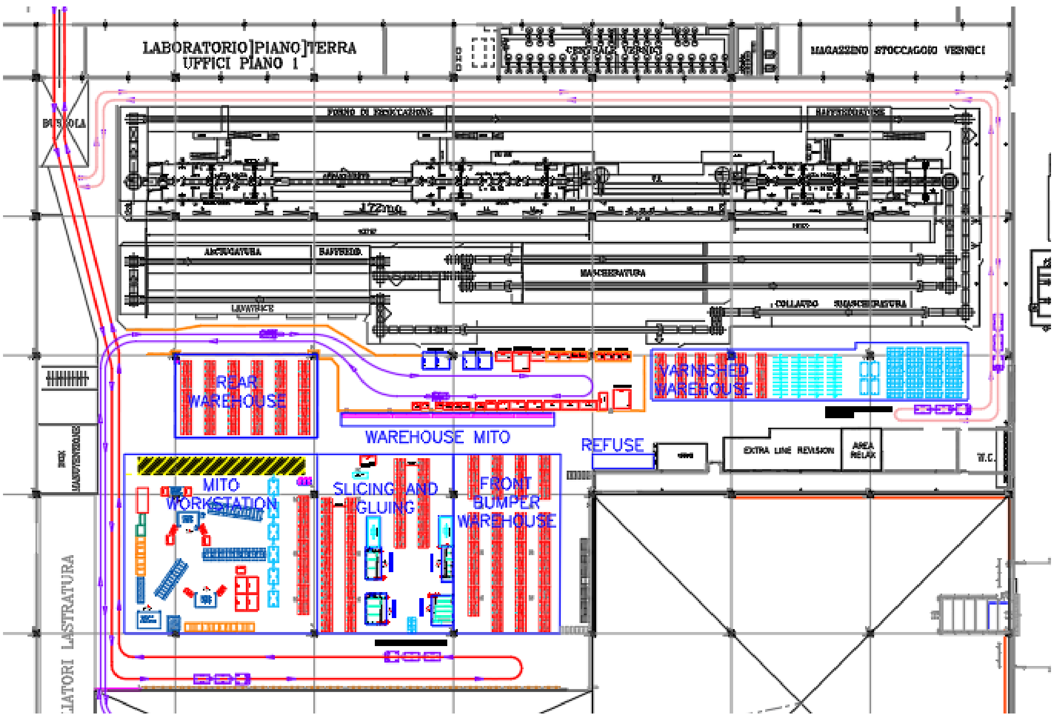


Figure 24 - Current layout of BPS: loading path is in violet (forklift) while the rose and red ones are unload and via bulls. The blue lines represent the indoor warehouses.

Then, when the outputs are ready for the Assembly Shop, they are moved by bulls in containers through the north doorways, according to the quantities reported in Table 5: bumpers and bands move on the red trail, while the remaining pieces on the rose one (see

[6] LEV and MITO will be the abbreviation for Maserati Levante and Alfa Romeo Mito respectively

again Figure 24, where one can note even the crossings among the logistic chains just reported). The rest of the handling within the facility is by hand.

Table 5 - Quantities of final outputs transported by bulls to the Assembly Shop

	CONTAINER 1	CONTAINER 2	CONTAINER 3	CONTAINER 4
Bumper front LEV	1	0	0	0
Bumper rear LEV	1	0	0	0
Band front LEV	1	0	0	0
Band rear LEV	1	0	0	0
Mouldings rear LEV	0	32	0	0
Mouldings front LEV	0	32	0	0
Arches rear LEV	0	0	10	0
Arches front LEV	0	0	10	0
Bumper front MITO	0	0	0	1
Bumper rear MITO	0	0	0	1

All the warehouses and the remaining areas of Workshop are devoted to the storage of products after the deliberation.

Figure 25 - Picture of a loaded bull (on the left) and of a forklift in operation (on the right)

At the end of the process line, the materials are separated and, by hand, sent respectively to:

- Warehouse MITO: it contains the two bumpers MITO from the line before they are sent to the reserved workstation (still by hand).
- Workstation MITO: in this area (close to the south doorway) residual operations are executed. These works consist in adding mini-components to the front bumper, and in the mechanical preparation of the bumper for the installation of lights.
- Varnished Warehouse: where moldings and arches are contained. From here they are moved to the load area where bulls can engage the containers (on the south-east corner).
- Rear warehouse (LEVANTE): it contains even rear bands.

- Front warehouse (LEVANTE): it contains even front bands.
- Slicing and gluing: dedicated to the last steps of transformation for Rear and Front bumpers. After this stage, all the bumpers and bands are loaded into bulls on the south corridor of the facility and transported to the Assembly Shop, following the red line.
- Refuse: a section devoted to all damaged equipment. From here, components are driven to the plant landfill.
- Out-line revision: used in case of materials with damages that can be manually repaired. If the damage is fixed, the component is sent back to the following station.

1.3.5 Shifts, opening time, production scheduling and staff

From the introduction of Maserati Levante in 2016, the adaptation of the productive facility foresaw 2 shifts, but from June 2016 the production rose to 3 shifts a day. The day schedule of working days is organized as in Table 6: the **opening time "t_T"** is 24 h/day whereas on each shift, half hour shall be subtracted because of the lunch break. Then, during the third shift, since the decreased number of workers, there is a **non-collective pause** of 20 minutes that saves working time (and part of the time is devoted to technical cleaning, so there is not a continuative production). Overall, in a working day (5 per weeks) **19.67 h** can be considered as **devoted to the production "t_P"**. Later, one will note that the time of effective production will be even smaller because of eventual equipment failure and slowdowns.

Table 6 - Day schedule and shifts (all values reported are in hours)[7]

	Symbol	Shift 1	Shift 2	Shift 3	Day
Shift time	t_T	8	8	8	24
Lunch break	t_F	0.5	0.5	0.5	1.5
No collective pause	t_F	0	0	0.33	0.33
Technical Cleaning time	t_S	0	0	2.5	2.5
Collective pause		0.33	0.33	0.00	0.67
Production time	t_P	7.50	7.50	4.67	19.67

In Table 7, instead, there are the values of monthly hours of production collected by asking to the supervisor for yearly calendars (note that, except for August, only April 2017, presents a reduced number of working days for Easter Holidays).

[7] See the subscripts: T is for the overall opening time of the plant; F refers to the programmed pauses where with certainty one can say that there is not production; S corresponds to the setup time meaning no production for plant unavailability; P finally is the scheduled time of production and evaluable decreasing the opening time with the pauses and setups programmed.

Table 7 - Productive time during in 2016-2017 (in hours)

Month	Working days	Shifts/day	Production hours/day	Hours/month
Jun. 2016	20	3	19.67	393
Jul. 2016	21	3	19.67	413
Aug. 201	13	3	19.67	256
Sep. 2016	24	3	19.67	472
Oct. 2016	25	3	19.67	492
Nov. 2016	25	3	19.67	492
Dec. 2016	23	3	19.67	452
Jan. 2017	20	3	19.67	393
Feb. 2017	20	3	19.67	393
Mar. 2017	23	3	19.67	452
Apr. 2017	14	3	19.67	275
May 2017	22	3	19.67	433
Jun. 2017	19	3	19.67	374
Jul. 2017	21	3	19.67	413
Aug. 2017	9	3	19.67	177
Sep. 2017	21	3	19.67	413

The staff working on the asset of three shifts is constituted by:

- 30 workers on the 1st shift;
- 30 workers on the 2nd shift;
- 10 workers on the 3rd shift;
- 4 workers on MITO areas alternating throughout the day;

One can note that only 1-2 people per shift work on the Paint Center, and that MITO transformation's processes are lower with respect to LEV ones. The occupancy of the Dressing Rooms is, of course, only at the beginning and at the end of the shifts.

1.4 Energy aspects

Because of Mirafiori Plant extensions and its various energy requirements, the aspects regarding production, distribution, emission and maintenance of energy equipment are split between FCA and Edison Fenice[8]. The maintenance and the regulation (by scheduling) for thermal emitter is ought of EDF, as well as to produce energy with the highest possible efficiency in its power thermal generator at Mirafiori Site.

The yearly energy bill is elaborated on the base of consumptions, distinguishing the fixed (during no-production period) from variable costs of energy and assessing a predictive load

[8] Edison Fenice will be referred as EDF

for the year ahead: the final output is a **fixed cost per unit energy**. Point of interest is the detection of consumptions that occur in local grid connected counters, constantly monitored.

The energy vectors of BPS are:

- Methane for technology at 4 bars[9];
- Superheated water[10] for space heating (at 140 °C and 7.5 bars);
- Technological heat (it is still ASH, but running on different lines[11]);
- Compressed air at 6 bars;
- Electrical energy for technology (called FEM);
- Electrical energy for lighting.

For the further analysis, will be of interest the localization of the counter for space heating and of the two main lines feeding the factory for space heating and technological heat (respectively line 21 and 24, see Figure 26).

It is strongly interesting to clarify that the cost of paid energy for BPS will be easy calculated monthly with the variation of number on the counters: this means that the effectiveness in the energy reduction to the building will be better because risen with the **efficiency** of emission, regulation and distribution (from the counter up to the thermal emitter).

The **energy tariffs** and the corresponding emissions of CO_2 are reported in Table 8: these values are correct for the heating season 2016-2017, but they are assumed constant in the further analysis (they do not vary too much, as reported by energy supervisors).

Table 8 - Unit energy cost and corresponding CO_2 emission

	Symbol	**Heat**		**Electricity**	
Tariff	c_E	0.01178	€/MJ	0.1183	€/kWh
CO_2 emission (f_{CO2})	f_{CO2}	0.088	tonCO_2/GJ	0.3	tonCO_2/MWh

In Table 9 there is a summary of how energy is used, connecting the vector to the final user. Electricity for FEM and Lighting has not separate counters for the two uses, so the consumption is complex to differentiate because they are summed. Thermal energy is consumed at building level to produce Sanitary Hot Water (ACS) and space heating, whereas at process level, to keep the correct temperature in the process line as described in paragraph

[9] Methane adduction is achieved by the grid line at 4 bars, then a pressure reducer, installed on the roof, decreases the pressure to 250 mbar. Then to obtain the flaming process a second pressure reducer is needed up to 40 mbar.

[10] ASH will be used as abbreviation of Superheated water at 140 °C and 7.5 bars.

[11] Space Heating and Technological Heat use the same energy vector (ASH) but with a parallel pipeline: this enables the switch off of space heating line during the summer period without compromise technological processes.

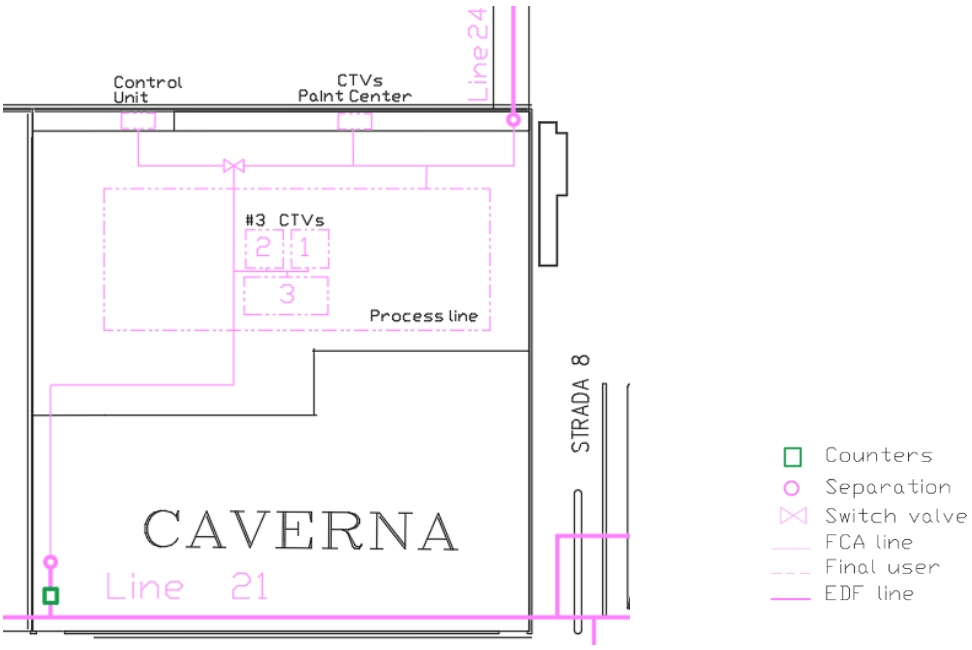
1.3.1: the same function is attained during summer by refrigeration energy (cold water produced by chillers on the roof).

Table 9 - Energy use by vector

	Electrical energy	Thermal energy	Refrigeration energy	Compressed air
Building	Building and process lighting (see 1.4.3)	Space heating for Workshop, Paint Center and Dressing Rooms. ACS. (see 1.4.1)	Summer conditioning for Paint Center. (see Figure 29)	
Process	Process line (see 1.3.1)	Via technological heat (see 1.3.1)		Robots of cabins (see 1.3.1)
Auxiliary plant	Pumping			

1.4.1 HVAC[12] equipment

More attention will be devoted to the thermal energy and HVAC, whose more detailed schemes are offered in Figure 26 and Figure 29. In Figure 26, one can note the two EDF lines feeding the plant: line 24, from the top, offers technological heat to the process, CTVs of Paint Center and Dressing Rooms. Whereas line 21, from “La Caverna”, spears a pipeline to feed the 3 ATU of the Workshop, in the sub roof. There is a Switch Valve (see photo in Figure 28) in order to choose if provide energy to the Dressing Rooms with line 24 or 21, but since technological heat is always running throughout the year, the valve always lets ASH pass from line 24.



[12] Heating Ventilation and Air Conditioning

Figure 26 – Scheme of space and technological heat pipeline map from grid to final user

The three CTVs in the sub roof, fed only by line 21, serve the **Workshop**, they are on during the heating season and their ASH flow rate is controlled by an electric valve (set at the height of the counter) according to the heating requirements. The control of energy output is offered with a bypass system, shown in Figure 27, that keeps the outlet air temperature at 40°C: the inlet air is a mix between the recirculated air (from the internal of the Workshop) and the air intake from the external environment (the corresponding damper is on the roof). These ATUs are made of a single layer of batteries (only heating) with no humidification, while during the summer they provide ventilation.

Figure 27 - Photos of CTV number 3: on the left the bypass system and electrical panel with carry comands, on the right the pipeline to fed the battery. The last photo is the last part of the emission system called "testa di moro".

Table 10 - Technical specs of the three CTVs for space heating in the Workshop

		CTV1	**CTV2**	**CTV3**	**U.M.**
Volumetric flow rate	$\dot{V}$	165'000	150'000	150'000	m^3/h
Number of batteries		4	4	4	
Single battery output		740'000	672'500	672'500	kcal/h
		860.5	782	782	kW
Total pressure - delivery		1'250	1'000	1'000	Pa
Engine delivery		75	75	75	kW
Number of poles		4	4	4	
Velocity		900	800	800	rpm
Total pressure - resumption		800	800	800	Pa
Engine resumption		75	55	55	kW
Number of poles		4	4	4	
Velocity		900	850	850	rpm

The emission systems are the so called “teste di moro”, equally spaced within the local Workshop. The scheduling and control of the ATUs (whose technical specs are offered in Table 10) is committed to the maintainers of EDF, that according to the external and internal temperatures (the second just monitored but not functional for HVAC) turn on and off the equipment choosing which is the best one to keep on. Usually the scheduling foresees CTVs number 3 and 1 on for more time, because they fed the perimetric area (note that ATU number 2 provides thermal energy for the north-west side of the local Workshop, that is “covered” by adjacent local Dressing Rooms and, so, warmer).

Figure 28 – HVAC in Control Unit of Dressing Rooms. Top left: Switch valve; Top right: CTV of Dressing Rooms; Bottom left: Heat Exchanger 140 kW; Botton right: Boiler ACS

The **Dressing Rooms** local is served by one independent substation (called Control Unit, see photos in Figure 28) located on the second floor of the body-building, that adduces ASH from line 24 or, eventually, from line 21 thank to the switch valve in Figure 26 and Figure 28. This substation consists of a **heat exchanger** with a heat output of **140 kW** which serves thermal **fan coils** with a temperature of 60-70 °C. Regarding the production of ACS, this is provided only for the Dressing Rooms and it is made by means of a **boiler of capacity of 1000 l** (kept at a temperature of 60 °C) and a heating power of 58 kW fed by the technological line with an internal coil. In the same substation there is even a small **ATU** whose data have not been found, fed by technological line and shown in Figure 28.

The **Paint Center** is conditioned and climatized since the requirements for an optimal preservation of varnish (as said in paragraph 1.3.2): the temperature must be 25 °C throughout the year. For this purpose, there is an ATU and a chiller of 239 kW.

All the information about HVAC above written are summarized in the Figure 29: in pink boxes the adduction source energy (the thermal generator is far from BPS but one considers only the consumption readable from counter set as in Figure 26 for line 21, whereas it is not possible to differentiate the consumption of Control Unit from the one of process line), in white boxes the HVAC emitters and in green boxes the final user.

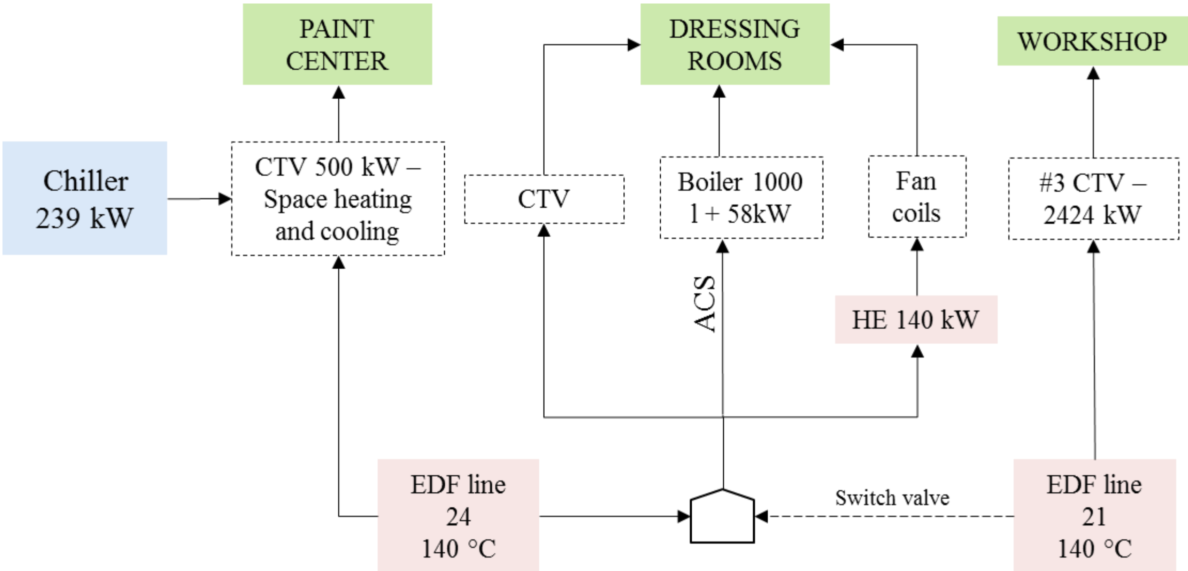


Figure 29 - Scheme of heat utilization and HVAC in BPS from EDF line to final user

1.4.2 Thermal properties of the envelope

As said in paragraph 1.2, historical background of BPS required the extension of the main body (referred previously as Workshop) to two additional bodies. These adaptations were made in different periods of the past where thermal insulation, energy efficiency and thermal comfort were not yet seen as an economical possibility of improvement.

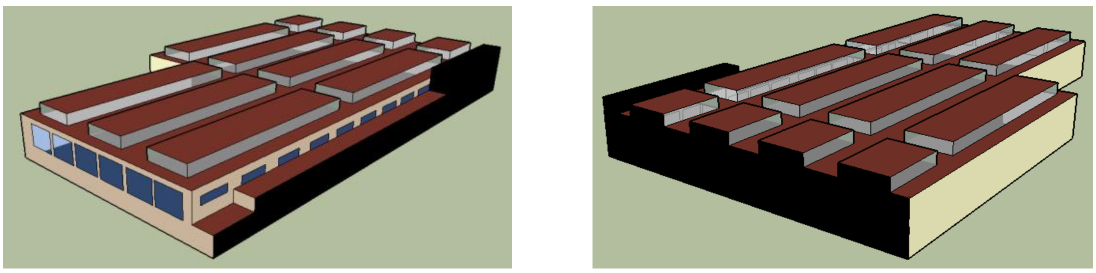


Figure 30 - Illustration of elements with transmittances listed in Attachment A.

The transmittance of opaque and transparent elements of the envelope (see no black surfaces shown in Figure 30) are reported in the tables of Attachment A..

The U-values shown are calculated **without the contribution of air wall resistance** with the Equations 6 and 7 and with the values of thermal conductivity reported in [33] for walls, [34] for fenestration and [35] for the floor:

$$R_i = \frac{l}{\lambda} \tag{5}$$

$$R_{TOT} = \sum_i R_i \tag{6}$$

$$U_{strata} = \frac{1}{R_{TOT}} \tag{7}$$

The values l and λ are, respectively, the thickness of each layer (in m) and the corresponding thermal conductivity (in W/m^2/K), the ratio between the two gives the resistance of the strata (R_i) and, under the assumption of strata in series (exploiting the parallelism with electrical circuit), the resistance of the dispersant element (R_{TOT}) is calculated as the sum of R_i. One can determine later the transmittance of the dispersant element U_{strata} as the inverse of R_{TOT}.

Whereas, regarding the transparent elements, the calculations elaborate a parallel heat flux on the glass and frame area (respectively A_g and A_t). According to [34], the value of window's transmittance U_w is calculated with the transmittance of the glass and the one of the frame (respectively U_g and U_t) as in Equation 8.

$$U_w = \frac{A_g U_g + A_t U_t + l_t \Psi_t}{A_w} \tag{8}$$

For the sheds' skylights the values of quantities in Equation 8 have been calculated considering that there are 3'152 windows on BPS's roof each one with 0.75 m^2 as glass area (A_g), that is about the 87% of total window's area (A_w). The contribution of the spacer "$l_t \Psi_t$" is considered null because these windows are single glass, and simply surrounded by an alluminum frame. There are not darkening closures to consider, but the opening is remoted locally so to guarantee natural ventilation.

Figure 31 - Focus on sheds' windows.

For the floor, the value reported in Attachment A. is the **nominal transmittance of the ground**, without the contribution of perimetric thermal dispersions. In the next chapters, more attention will be devoted to completing these losses, adding more terms to the above-mentioned Equations from [35].

To offer a comparison with the reference building performances, in Table 11 are reported the U-values in the Workshop area and the limiting values to obtain one of the requirements of energy certification for non-residential user according to Italian D.M. 26-01-2010 [36] absorbed in D.Lgs.311/06 (the values shown are for climatic zone E, city with Heating Degree Days up to 3000 °C·day and non-residential user).

Table 11 - Comparison of transmittances for non-residential building (from [36]) and BPS (unit W/m²/K)

Zone E	D.M.	Workshop
Walls	0.34	2.01 (La Caverna) 1.1 (Perimetric)
Roof	0.3	2.488
Floor	0.33	1.989
Fenestration	2.2	3.115 (skylight)
Glass	1.7	2.7 (skylight)

Being the values in excess of the 30% of the reference values, from such analysis it is clear that an energy retrofit is necessary and, when in paragraph 3.1.1 space heating consumption of building will be analyzed, it will result that BPS cannot be classified neither with the lowest energy class according to Italian legislation (class G).

1.4.3 Lighting system

Lighting system in BPS is currently divided into two main branches: process and building lighting. The division occurs because of maintenance reasons and technological development. Process lighting requires specific assessment (in terms of lux on the ground) depending on the process area, while building lighting shall provide sufficient light when manufacturing ends.

Currently on BPS Workshop, the bulbs known and used in next analysis are reported in Table 12 and shown in Figure 32. Building lighting are constituted by old type of traditional incandescence bulbs (type A), with 400 W of consumption and 50 W additional per head for the reactor. They are equally spaced in the local (30 bulbs per shed and 9 bulbs for each half-shed).

Table 12 - Bulbs in BPS Workshop

Type	Power W	Lighting flux Φ Lumen	Number installed	Technology	Frame material
Faeber Sigma 400 IP 23 (A)	450	22’000	246	Mercury vapors	Resin
Beghelli Risparmia 2x58 Rx01 (B)	85	6’885	500	Energy saving	Aluminum

Beghelli Risparmia 2x58 Rx05 (C)	85	7’055	40	Energy saving	Aluminum

Whereas, regarding the process lighting, in 2010 “Beghelli Risparmia” dimmed bulbs were installed with a profitable agreement with the supplier: the cost of installation was zero, but yearly, the earning came from the partially tribute on the saving (because the technology installed before consumed about the double of current consumption).

Figure 32 - Photos of the three bulbs in the Workshop, respectively type A,B and C from the left to the right

In addition, there is, on the **final deliberation section**, a line of bulbs with a very high apparent illuminance but no information is found about. Varnish Warehouse is illuminated by 22 bulbs of type C, whilst on Front bumper and Real bumper warehouses are installed 29 and 12 bulbs of type B respectively (see Figure 24).

1.5 Services and utilities

The areas in purple of Figure 33, represent the services for workers. There are two dressing rooms (in Dressing Rooms body building): on the first floor the male one and the female one on the second floor (in the adjacent local to the Control Unit areas, shown in Figure 28). Each dressing room is provided of a bathroom and a shower area. On the ground floor of the corresponding area there is an additional bathroom and an office for the shift managers.

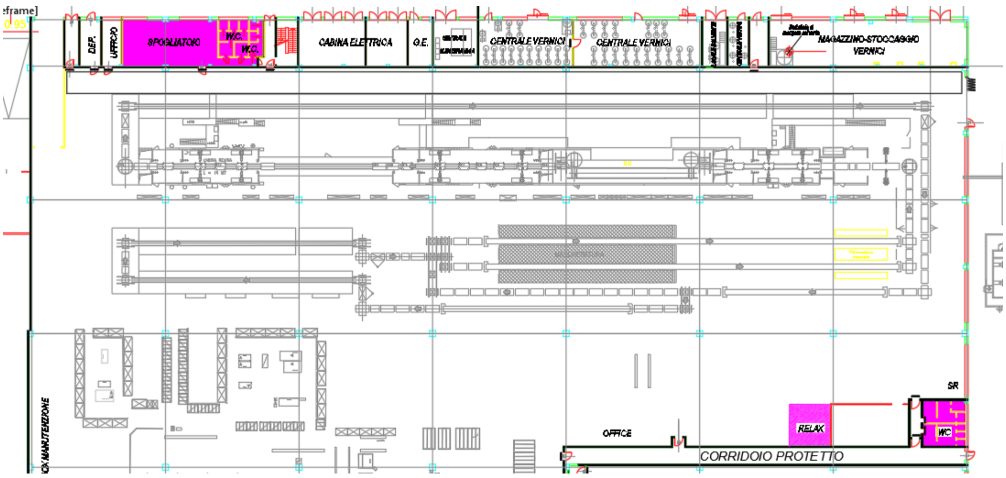


Figure 33 - Services of BPS for workers

On the south-east side there is a "relax area" with coffee machine and an additional bathroom (used very often because closer to the process line). More data about these utilities are reported in Table 13: the first column refers to the bathroom in the nearness of the process, while in the second information refers to a single dressing room (the two dressing rooms are equal).

Table 13 - Infomation about services in BPS

	Bathroom	**Dressing room**	
Floor	41	216	m^2
Wall tiles	121	232	m^2
Sinks	6	20	
Showers		6	
WC	6	4	
Boiler	1		

Note that the bathroom does not have the supply of technological heat as for the dressing room, this makes necessary the use of an electric boiler.

2 Facility diagnosis

In this chapter there is the description of the first interactive phase of this thesis where, through interviews and investigations on the facility described in Chapter 1, one went back at the **issues** and **improvable areas** to detect to the requalification and retrofit scenarios to be assessed in a hypothetical investment plan.

The first part of the chapter is devoted to describe which ways have been used to collect the problems and the suggested solutions, whilst the second lists and motivates the areas of intervention selected and the corresponding measures adopted (i.e. projects or actions as framework of a renovation scenario). The chosen **projects** belong to four different improvable areas of facility's maintenance and they are described singularly in chapter 4 as preparation for the decisional procedure.

2.1 Problems detection and collection

The scenario of a renovation proposal for a functional industrial building requires many data and investigations to be programmed. During the period of internship of the author in the FCA Mirafiori Plant, **one-month full time** was spent to collect as much as possible data on BPS and its possible areas of improvement. All the problems were picked in three ways:

- By interviewing the higher number possible of people of the manufacturing hierarchy working for or involved in BPS;
- By reading and analyzing reports and not disclosable documents obtained by such people;
- By literature research according to determined keywords on Polytechnic Library through PICO website.

The moment of interviews was even an opportunity to know better the plant and collect data that will be used in the next chapters.

2.1.1 Interviews on field

Being FCA a big rated company and constituted by more than 5'000 people working in Mirafiori's plant, achieving information on determined systems or (in this case) building, requires a suitable knowledge hence selection of people to ask for. With the term "manufacturing" one refers to the set of process but even people strongly involved in the transformation phase of the inputs into products. People working in the manufacturing area are the most informed on the state of the art of technologies and services in a determined process unit, though such information are **fragmented** among technicians and managers.

The schematic hierarchy of manufacturing workers, interviewed in this step, is reported in Figure 34, where two main branches are indicated. In addition, this phase involved even interviews to EDF experts.

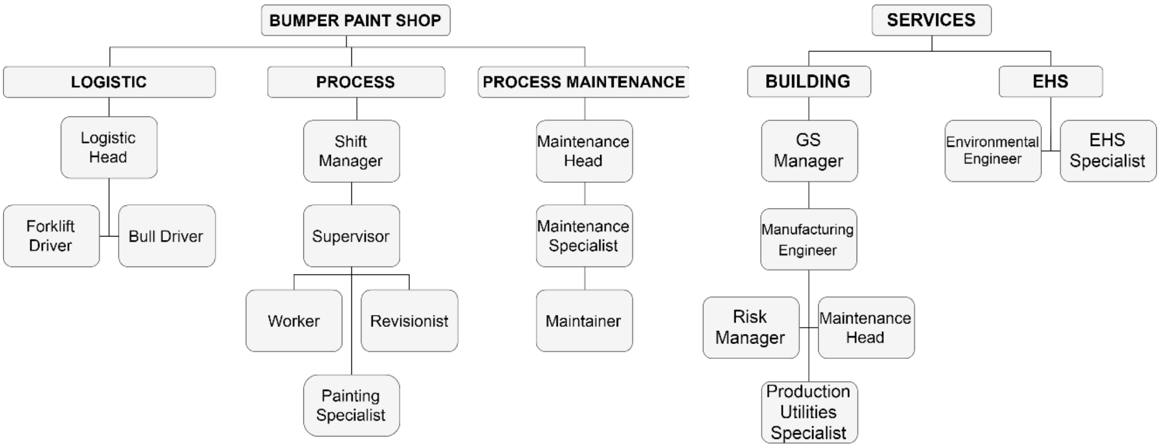


Figure 34 - Manufacturing FCA hierarchy for BPS facility and transverse bodies

The first branch, "Bumper Paint Shop", refers to people belonging to the Paint Shop unit and occupying only this facility at different level of responsibility. They are divided in three groups each one with specific functions to attain. "Services" instead refers to all the transverse bodies in Mirafiori plant dealing with no-process issues: among these "General Services" (GS) and "Environment Health and Safety" (EHS) occupying, respectively, of utilities and environment aspects.

The interviews were executed in a physical meeting (personal conversation) with 25 people asking via mail for a date and obtaining as final output, at the end of each interview, the survey questionnaire reported in Attachment B filled. The questionnaire contained 4 questions to answer freely, obtaining as result, data of about 10 minutes each. The questions are very general and they are reported below:

- References (name and position), so to remember and easily refer the talk;
- Main issue of BPS and area of improvement;
- Which measures are suggested for the improvement;
- Who is the Decision Maker (DM) in case of decisions on potential investments.

The choice of this generality is because the people involved in this step belong to different level of the hierarchy and, with their technical sensibility they can catch a multitude of different aspects characterizing the plant and its level of service.

The outputs of the interviews are reported in the table of the Attachment C: each line is matched with a problem, the corresponding interviewed and its optional solution offered. The last column, instead, refers to the **class of area**:

- Process: if the beneficiary of the intervention is just the company in economic/product terms;
- Lighting: if the solution attacks the lighting system of BPS;
- Thermal: where energy and comfort aspects are mixed and associated to the building utilities;
- Logistic: if the improvement can change the scheduling and activities of forklift drivers;

- Liveability: if the unique beneficiary are the occupants of BPS and hence indirectly the production.

It is worth to add here that at the question "Who is the DM?" most respondents didn't answer because the fragmentation of responsibility does not make easy to detect a decision maker. Improvement actions within industrial environment occur by WCM policy from the comparison with other plants or generally without a clear reasoning on the alternatives, but only on the priority or if necessary.

The rest of discussion, grouping and elaboration of reported interviews will be made later, on the base of all issue collected.

2.1.2 Documents and reports

The occasion of the interviews was also taken to gather further documents and data on BPS. These have been analyzed and therefore used to introduce additional **general** problems (if any) listed in the Table 14.

Thermal problems reported come from the energy advice of the building, where several solutions were already reported as improvement opportunity for the energy performances. The voices are in a general form because in the table they are just summarized, while in paragraph 2.2 there will be an overall explanation grouping all similar issues.

The first process issue comes from win-win[13] projects in collaboration with the energy provider EDF and regard interventions on post-combustion plant described in paragraph 1.3.3. The second process problem considers the optimization in thermal heat flux for control unit of ACS in Dressing Rooms. The last voice, instead taken by safety reports, claims conservatively a problem regarding the diffusion of CH_4 gas after the pressure reducers indoor.

2.1.3 Literature review

To get more ideas and resolutive suggestions on retrofit opportunities in a manufacturing plant, a bibliographic research was done. The purpose of this kind of investigation is mainly to discover "innovative" solutions that can be applied in a retrofit horizon but that are already available on market and sufficiently widespread to be reproduced in FCA environment. The **combinations** of keywords researched on PICO website (i.e. Polytechnic Library) are reported in Table 15 where on the first column there is the matter, on the second the subject and on the third the area of intervention.

The papers and reports containing these keywords are filtered and the most relevant suggestions, matching the model area in terms of possible improvements, are collected and briefly summarized in the table of Attachment D. This bibliographic work is useful to discover remaining hidden voices not dictated by the internal experience (i.e. during the interviews), allowing a sort of "facility diagnosis" on the base of innovative standards.

[13] Win-win activities are initiatives of energy efficiency in FCA's plant made in collaboration with EDF. The design, installation and validation phase are split generally into two parts hence the money saving.

Table 14 - List of issues coming from documentation and not disclosable report

Problems	Solutions	Type
Temperature probes on the perimeter have shown in 2014 lower temperatures and higher humidity in the area far from the processes and close to the boundaries.		Thermal
Thermal bridges in the connection fenestration-walls and sheds' edges.		Thermal
Thermal losses through perimetric walls.	Insulation by means of the injection of polyurethane by spray in the existing gap.	Thermal
Thermal losses through the roof.	Supply and installation of internal insulation in expanded polystyrene panels.	Thermal
Thermal losses through the shed.	Replacement of existing glass panels with double polycarbonate panels.	Thermal
Thermal air stratification with accumulation into the more thermal wasting actor (ceiling).		Thermal
Possibility to increase the energy efficiency on technological heat in the process.	Additional thermal recover in the post-combustor to heat the return of superheated water (line 24).	Process
Optimize the logic flow in the new control unit		Process
Absence of CH_4 detector or gas aspirator for the pressure reducer and manual flaming, because the area is well ventilated and considered not hazardous.	Allow a vertical dispersion of gases through opening of the upper part of boxes or install gas detectors to check gas leakages. Detectors shall present two thresholds of intervention: 10-15% of LEL and 20-30% of LEL (interception of the gas flow).	Process

Table 15 - Keyword's combinations for bibliographic research

Theme	Subject	Object
Retrofit	Industrial	building
Renovation	Factory	facility
Requalification	Industry automotive	services
Refurbishment	Manufacturing	utilities

The sources cited in the reported table can be classified according to the following list:

- Guides [37, 38, 39] to improve industrial environment on energy and process parameter base;
- Researches [11, 40, 41] on innovative methods or materials to improve both comfort and performances with a better energy management;
- Suggestions, based on modern modelling techniques and studies, on the re-design of the building [42, 43] to improve again comfort and energy efficiency;
- Studies [9, 44, 43] on profitability of investments for building's improvement.

Once again, all the voices are classified according to the five defined clusters and will be analysed in the next paragraph.

2.2 Grouping issues and scenarios creation

The purpose of this chapter is to describe and organize the problems collected in paragraph 2.1 in a clear way so to have the current image of the state of the facility. The problems, belonging the same class, will be filtered avoiding the repetition where present. Finally, according to the evidences resulting from the classification and the preferences of the DMs, several projects will be considered as retrofit measures and, in next chapters, analyzed.

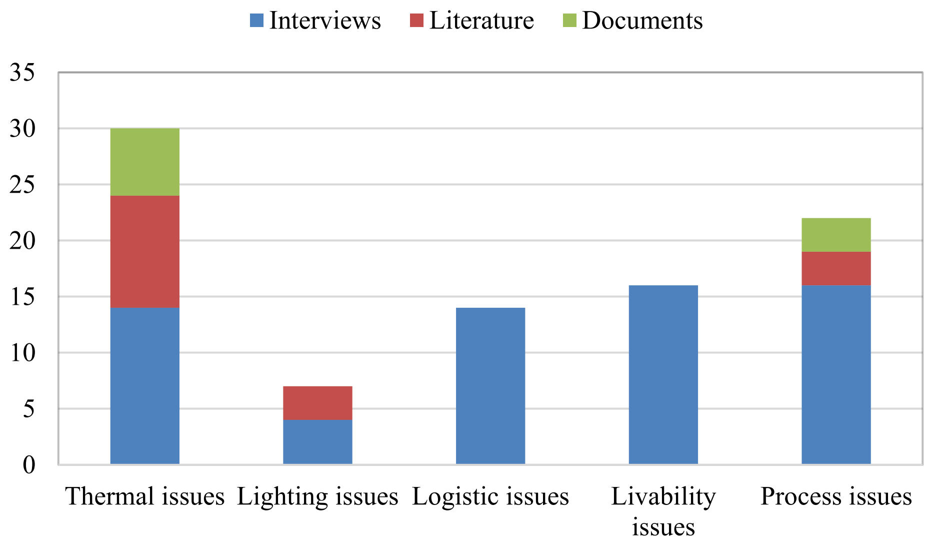


Figure 35 – Problems and suggestions grouped by class and by source with repetitions

The bar chart reported in Figure 35 classifies all the voices reported in the tables of the previous paragraph according to the membership classes and the three "sources" used. Below, for each class, there will be a summary of the most relevant features.

The class of problem "**Thermal issues**" can be summarized as:

- Building envelope with no-insulants allowing high transmission losses, hence no energy classification (for more see 3.1.1);
- Horizontal temperature gradient towards the area far from the process brings thermal discomfort on the perimetric workstation during heating season;

- Thermal stratification leads energy losses because temperature vertical gradient increases dispersions on the most dispersant element of the building, the roof. This phenomenon occurs because of building's height and endogenous heat deriving by Paint Shop process;
- During summer season workers complain about the hot;
- South side of the building (in the nearby of the doorway) is object of complains about the cold due to the air currents (via doorway);
- Fenestration on sheds have technical problems (i.e. sealings, engine, linkages …) and so they contribute negatively to the energy balance for ex-filtration and transmission losses.

"**Lighting issues**" instead can be filtered with the following statements:

- Building lighting somewhere is unavailable and of old technology;
- Process lighting is not sufficient where workers store the bumpers pointing out that the illuminance is poor with respect to other areas;
- High consumption for lighting in the facility;

Regarding "**Logistics issues**" instead:

- South doorways broken (and potholes), stop forklifts, allow dust income and are not well designed in terms of length because forklifts always hit on them. The doorways in BPS, in general, are repaired with costly interventions;
- Poor space for internal handling that leads to human errors, hence product refuse;
- Constructions to be removed in the building because dust accumulation negatively impacts on product transformation and handling.

Whereas for "**Livability issues**", the research brings to define:

- Bathrooms and dressing rooms in bad conditions or not working;
- Rain infiltrations from roof frequently bother workers and the production in general;
- Workers complain for the poor attention devoted to them in terms of services with respect to other units of Fabbricato Principale (e.g. no road to the canteen, no smoking room …);
- No sufficient ventilation rate (and stale air) from workers interviews;

The "**Process issues**" are split in two fractions, the first voices that are specific referring to the technology processes, the last bullet that summarizes the guidelines offered during the bibliographic research:

- With reference to the cabins, there are significant losses for paint overspray and in the tub for paint collection;
- Emission of VOC and CO_2 not negligible from chimneys;
- Heat exchanger for heat recovery of post-combustion plant is not well saturated;
- Optimize physical and process parameters for energy vectors (i.e. compressed air pressure).

After the screening, filtering and grouping of problems deriving from the three ways of investigation reported in the paragraph 2.1, the final output of this chapter is to detect the possible interventions (i.e. projects) to be evaluate as retrofit alternatives. But before this, one decides to exclude from the areas of renovation the "process issues" for the following reasons:

- Each improvement on process technologies is expensed on a devoted **investment plan**, whereas projects attaining building's maintenance, workers, comfort and liveability are matter of manufacturing budget;
- The purpose of this work is to offer a **methodology** that is no-case sensitive and not depending on the specific equipment of the model area (in this case proper of paint shop units);
- Specific improvements for the manufacturing activities cannot be "seen" by the occupants and cannot be matched into a satisfaction level according to defined **criteria** comparable with the remaining projects.

The list of problems expressed above is followed by the corresponding technical solutions reported in the Table 16, again divided by classes[14]. The projects in the table are chosen according to **managers choices** after the **reporting** and analysis of the problems previously classified, bringing the analysis to a real plan of application. The options to be analyzed come from managers' experience or, again, from the comparison with the effectiveness in other FCA's realities.

Table 16 – Projects considered as retrofit measures in response to the class of issues

Thermal projects	Lighting projects	Logistic projects	Liveability projects
Reduce thermal losses through building envelope	Increase lux along the process line	New internal logistic layout	Refurbishment dressing rooms and bathrooms
Installation of air delayers	Upgrade technologically buildings bulbs	Substitution of south doorway	Reapplication of waterproofing layer on roof
Installation of summer and winter microclimate systems	Upgrade process lighting to LED	Decommissioning of old hanging conveyors	Increase ACR in workshop via HVAC and introduce thermal control
Use cool roof to increase summer thermal comfort			Install a smoking room

From now on, each project will be treated separately from the others, even though some intercept apparently (e.g. waterproofing and roof insulation or new layout and new doorways): these interventions just listed will be described accurately in the devoted chapter, studying singularly the effect on the system to leave the impact of superposition (or intersection) at the multi-criterial methodology.

[14] Note that some projects actually act on more classes (e.g. doorways) meaning that the solution will be later automatically helpful under more criteria: this matching, however, does not affect the methodology because the classes considered are not part of the optimization algorithm i.e. each project will be treated separately.

The projects discarded among the possible improvements are reparation of fenestrations and sealings, because they were introduced only in the 90s, and the construction of a road to the canteen, because the closer one is beyond a very busy road by supplier trucks.

2.3 Relevance of the projects and criteria selection

In order to allow a multi-criterial approach to the case study, before the development of the projects, one must know which aspects to analyze to compare the alternatives. For this reason, a series of criteria (grouped in clusters) are chosen according to the most relevant pondering aspects in an industrial environment and with the suggestions of the DMs during the auditing phase. They are listed in Table 17 with a brief description and, if any, the match to papers of MCDA about retrofit where they were already used, considering the conspicuous contribution of [2]. The last column, indeed, refers to the scale used to vote each project (qualitative or quantitative) expressing the satisfaction mark that can assume.

The difference between the scale of “Degree” and “Scores” is that the first assume only an increasing relevance, whereas the second can be either positive either negative.

Below, for each criterion a more detailed explanation is given in order to justify the scores and degree as output of further pair-wise comparisons among projects:

- Variation of maintenance operation: if a project adds in the building an additional system and another improves an existing one, the second will be preferred because new maintenance operations are not needed;
- Impact of the installation phase: a project is considered more impacting according to the installation magnitude, for example if its installation lasts more or is closer to the production cycle and then the probability to slow it are higher;
- Visual comfort: express how much the project acts directly on the visual benefit of the workers in terms of effective increased illuminance or visual satisfaction. This criterion has a negative valuation only when additional hanging equipment are added, while the smoking room is considered more satisfying for the workers’ eyes than shadowing;
- People's satisfaction: it is seen as the direct perception of workers for the improvement and it is not related to the comfort but to the necessity. This voice can be expressed as “the first impression on the project’s benefits”, for example refurbishment of an area is more appreciated than insulation of walls even though the second will indirectly enhance the thermal comfort and energy efficiency;
- “Layout flexibility”: how the intervention is close to the process line because, in case, future projects will be necessary (i.e. negative aspects on many points of view) to adapt the production asset to the new product manufacturing. So, the time horizon for this criterion is of course large but undefined.

Table 17 – Criteria to be considered during the projects valorization

Cluster	Criteria	Reference	Description	Scale
ECONOMY	Investment cost	[10, 13, 15, 45]	Investment costs related to refurbishment of building (efficiency investment) and/or new technological systems (infrastructure investment) assumed as best obtained by supplier.	€
	Variation of operational costs	[10, 15, 45]	Expressed as saving/waste of yearly cost with respect to the previous system available (maintenance costs excluded).	€
	Pay Back Time	[13, 15, 45, 46]	Return of the investment thanks to the improvement if any savings can be estimated.	Years
	Variation of maintenance operation		How well or how bad the project acts on maintenance operations (costs and magnitude).	Scores
	Impact of the installation phase		How much the intervention impacts on the manufacturing processes during the construction phase.	Degree
COMFORT	Visual comfort	[14]	Visual comfort and increased visibility for the workers in the building or anyway improved visual perception of workers.	Scores
	Thermal comfort (heating season)	[10, 14]	Thermal comfort improvement of the workers in the building during winter.	Scores
	Thermal comfort (cooling season)	[10, 14]	Thermal comfort improvement of the workers in the building during summer.	Scores
	Indoor air quality	[14]	Improved air condition in terms of breathability for workers in the building (e.g. increased ACR, reduced concentration of VOC, dust, CO_2 …).	Scores
SOCIAL & SUSTAINABILITY	People's satisfaction	[46, 47]	People's satisfaction is evaluated for building employees and visitors for the general improvement offered.	Scores
	Visual impact	[15]	The visual and the architectural impact of refurbishments in existing built environment.	Scores
	Emission CO_2	[14, 15, 45]	Emission of equivalent CO_2 avoided yearly with the intervention.	tonCO_2
TECHNICAL	Reliability	[10]	Efficiency of the technology or of the requalification result.	Degree
	Technical Life	[14, 47]	Durability of the proposed solution.	Years
	Duration of the work (Lead Time)	[10, 15, 45, 46]	The period between the placing of the order and the end of installation/refurbishment.	Weeks
	Layout flexibility	[10, 45]	How the manufacturing plant could preserve its flexibility with the change proposed.	Scores

3 Modelling and design methodologies

The purpose of this chapter is to offer a clear view of the methodologies implemented to support the design phase in the future analysis. The problems incurring belong to different areas of engineering because the necessity of improvement spaces on several drivers: energy is of course an interesting aspect because it affects not only the economic scale of the facility, but even the comfort of workers and the impact of maintenance.

Energy problems will be divided into two parts: **thermal** and **lighting** issues. For the first, thermal aspects will be analysed with a simple 1D model (implemented on Excel©) and the support of EnergyPlus[15] and MatLab©. The use of E+ will require the necessity of a software for the creation of the geometry and for this purpose SketchUp© (and its free plug-in OpenStudio©) comes in help. Regarding the lighting, the reference normative will be considered for the sizing by Excel©.

Logistic workflow will be studied by a static modelling, that is implemented on Excel©, with the graphical aid of AutoCAD 2017©, where the data recording and space measuring are summarized in, offering a great aid for the design phase.

The inputs for such modelling methodologies come from an in deep data collection on field, considered as a very time-expensive experience of this work: absence of data in the design phase will be covered with a look at the scientific assumption in literature.

Many other information about the design will be explained at the devoted chapter, where the chronological flow will help the reader to understand better what concerns.

3.1 Mono-dimensional model of thermal dispersion

As already said in paragraph 1.4.2, the 1D model implemented reproduces the referenced Italian normative for the assessment on climatic data, U-values, the contribution of no-climatized environment (and thermal bridges) and floor dispersion for **transmission losses**. But, in order to estimate with more accuracy the real impact of space heating on industrial building balance, specific attention will be devoted to the timing and scheduling, analysing thermal energy consumption: the hours-per-month in which this heating system is on proportionally contribute to the saving/consumption of a project for envelope's retrofit.

In next paragraphs, after the setting of the 1D model, there will be a validation using the consumption data of the heating season of 2016-2017, suitably scaled with Heating Degree Days (HDD) to the model-year of Italian normative.

The base Equation, used to estimate the yearly thermal dispersion through an element of the envelope, is the following:

[15] From now EnergyPlus will be referred as E+

$$Q = UA \cdot \sum_{i}^{months} (T_{in} - T_{out})_i \cdot \Theta_i \qquad (9)$$

The Equation 9 is monthly-based and is constituted by:

- The thermal transmittance U (W/m^2/K) of the element (reported in Attachment A.) plus the contribution of air wall resistance, reported in Table 18, summed as in Equation 10;
- The area A (in m^2) of the element, reported in Attachment A.;
- The average monthly temperature difference between inside (T_{in}, set at 18°C throughout the heating season) and outside environment (T_{out}) that is reported in Table 19;
- The hour of running of the heating system (Θ_i). These values are calculated in the paragraph 3.1.1.1 adopting a scaling technique and reported still in Table 19.

Equation 9 is the general form used for all the terms of dispersion (windows and walls). The fundamental contribution is the value of transmittance that now accounts for the dispersant layers of stratigraphy and resistance of internal and external air (supposed in series), listed in Table 18 with Equation 10: according to the direction of the heat flux, the value of internal (R_{si}) an external (R_{se}) resistance are used.

$$U = \frac{1}{R_{si} + \frac{1}{U_{strata}} + R_{se}} \qquad (10)$$

Internal temperature setpoint is considered 18°C for the Workshop and 24 °C for the Paint Center, outer temperature is evaluated by means of [48] on month-base: the temperature difference, so, constitutes monthly a term that proportionally scales the energy needed.

Table 18 - Values of thermal resistance of air wall according to [34]: the figures to be used depend on the direction of the heat flux towards the dispersant element.

Resistance (m^2·K/W)	Ascending	Horizontal	Descending
R_{si}	0.10	0.13	0.17
R_{se}	0.04	0.04	0.04

The quantity “Q” of Equation 9 represents the energy needed to be supplied to the building in order to cover the transmission losses, that can be expressed as product between the heat flux $\dot{Q}_i$ and the time Θ_i. This value will be connected to the energy needed to the grid “Q_{grid}” (see the green counter of Figure 26) thank to the series of efficiencies described in paragraph 3.1.2:

$$Q_{grid} = \frac{Q}{\eta_{tot}} \tag{11}$$

The use of reference's normative is used for the estimation of such efficiencies because the uncertainty of data and calculations cannot guarantee anyway an accurate solution.

From Q_{grid}, one can determine the yearly cost of energy for space heating with Equation 12 and CO_2 emission with Equation 13: the quantity c_E represents the unit cost of energy, whereas the factor "ef_{CO2}" is the emission factor of CO_2 per unit energy (both reported in Table 8 for Mirafiori Plant).

$$C = c_E \cdot Q_{grid} \tag{12}$$

$$F = ef_{CO_2} \cdot Q_{grid} \tag{13}$$

Table 19 - Heating weekdays, data for trasmission heat losses and climatic data for Turin by [48]

Months	**Heating days**	**Outside temperature (T_{out})**	**Inside temperature (T_{in})**	**Temperature difference**	**Daily horizontal direct irradiation**	**Daily horizontal diffuse irradiation**	**Hours of operation**
	day	**°C**	**°C**	**°C**	**MJ/m²**	**MJ/m²**	**h/month**
Oct.	10	12.6	18	5.4	4	5.3	77.7
Nov.	21	6.8	18	11.2	2.7	2.8	457.0
Dec.	21	2	18	16	2.1	2.6	428.7
Jan.	21	0.4	18	17.6	2.5	2.5	672.8
Feb.	20	3.2	18	14.8	3.5	4.3	554.2
Mar.	23	8.2	18	9.8	5	7.2	139.2
Apr.	10	12.7	18	5.3	6.6	10.4	27.2

The heat flux (and the corresponding energy to building Q, and so cost C, will scale proportionally with a burden factor introduced for opaque vertical elements in Table 20 (note that the reference is the general normative UNI/TS 11300 [49] instead of the more specific UNI EN ISO 14683).

In case of confining no-climatized locals (i.e. La Caverna Warehouse for the adjacent wall on the south side) and so the presence of an air mass not subjected neither to the external temperature neither wind speed, the use of Equation 9 is still maintained but the U-value is corrected with and additional resistance in series [33] (between outside air resistance R_{se} and last layer of stratigraphy), evaluated with the following equation:

$$R_{add} = 0.09 + 0.4 \cdot A_i / A_u \tag{14}$$

Table 20 - Value of burden factors to account for thermal bridges for opaque vertical elements [49]

Structure description[16]	Percentage increase (%)
Insulated wall without external agents	5
Homogeneous wall of bricks without insulation	5
Wall with perforated bricks (no insulant)	10
Wall-to-wall with insulant in the interspace	10

Where R_{add} is the resistance of the air mass seen as interface and additional resistance, A_i is the surface of the wall La Caverna, A_u the area of La Caverna Warehouse confining with the external environment. The Italian normative [49] foresees instead a different method for existing building, resulting as a percentage decrease of current values of wall transmittance of 40-50% or using additional information over La Caverna envelope: since in the first case the approximation is too conservative[17], and in the second data are not available, the two methods are discarded.

Regarding the floor dispersion, the contribution of heat flux $\dot{Q}$ is achieved with two terms according to the Italian normative [35]:

$$\dot{Q} = \dot{Q}_p + \dot{Q}_b = U_p \cdot A \cdot \left(T_{in} - T_{falda}\right) + U_b \cdot (2p) \cdot (T_{in} - T_{out}) = \frac{1}{\frac{1}{U} + \frac{1}{\lambda_C}} \cdot A \cdot \left(T_{in} - T_{falda}\right) + \frac{1}{\frac{1}{U} + \frac{2}{\lambda}} \cdot (2p) \cdot (T_{in} - T_{out}) \tag{15}$$

In the equations written above, the two parallel terms express the two ways of heat flux towards the external environment: the first term expresses the impact of stationary ground temperature below the building, the second the effect of basement dispersant area. λ_C is the conductance of the ground (assumed constant at 1.744 W/m^2/K) whereas T_{falda} is considered constant at 15°C throughout the heating season, because the use of a more in deep analysis wouldn't cover the other approximations made with this approach. λ instead is the value of the wet ground thermal conductivity (2.9 W/m/K) over the 2-meter large perimetric boundary surface (for this motivation the dispersant area is two times the outer rim edge of the building).

3.1.1 Analysis of Workshop's consumptions of heating season 2016-2017

In this paragraph, a quantification of consumptions of previous heating season will be offered: the value of the energy Key Performance Indicator (KPI) suitably scaled according to HDD will be compared with the reference value for non-residential user showing that an

[16] Note that are reported only the increase for the kind of structure presents in BPS, before and after the renovation

[17] This because the ventilation rate of La Caverna Warehouse is high, and its temperature can be considered as the outdoor: workers of this area complain that comfort condition is worse than outside due to the lack of any thermal energy gain.

energy renovation is a good opportunity. In addition, a "threshold analysis" is executed to highlight the monthly hours in which the heating system is turned on.

As previously said in section 1.4.1, only the consumption of the Workshop can be detected on the counter of Figure 26 for the Space heating line in BPS (that supply the ATU on the sub-roof of Figure 27): Paint Center and Dressing Rooms are supplied by the technological heat throughout the year and consumption for ACS or space heating cannot be distinguished from the consumption of technological line.

The consumptions, with a time step of 15 mins are shown in Figure 36, the model year used is 2016-2017 because, the **stability of the production** asset in Mirafiori Plant according to the introduction of Maserati Levante, assured no period of integration case and the regular productive scheduling reported in Table 7.

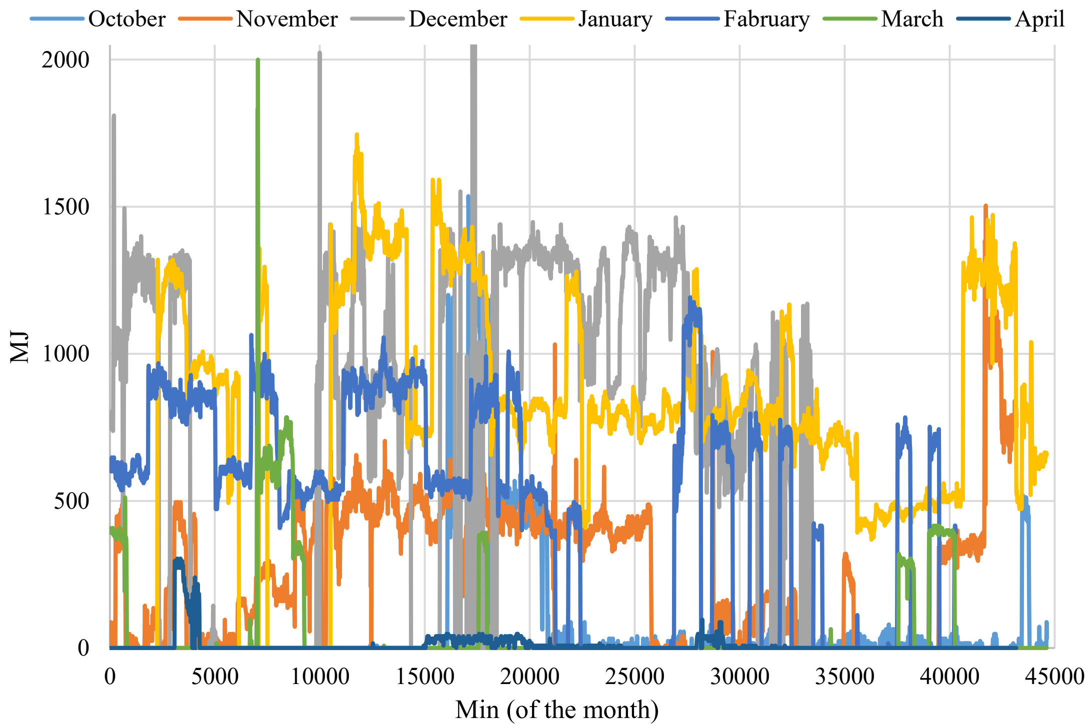


Figure 36 - Consumption in Workshop for space heating in heating season 2016-2017

These consumptions are scaled according to the HDD of the considered year so to obtain a "comparable" value with the normative model heating season. Using the outside temperature monitored by climatic weather station of Mirafiori Plant [29] (T_{ij}, where 'i' is the subscript for the month and 'j' for the day), the $HDD_{2016\text{-}2017}$ and $HDD_{normative}$ are calculated according to Equations 16 and 17:

$$HDD_{2016-2017} = \sum_i \sum_j (18 - T_{i,j}) \quad (16)$$

$$HDD_{normative} = \sum_i (18 - T_i) \cdot n_i \quad (17)$$

Where 18 is the inside temperature assumed constant, T_i is the constant-monthly temperature as in [48] and n_i the number of days in the month i of heating (from 15-Oct to 15-Apr). The scaling equation actually is monthly-based and use the HDD calculated month by month:

$$Q_{grid,scaled} = \frac{HDD_{normative}}{HDD_{2016-2017}} \cdot Q_{grid,2016-2017} \qquad \forall\, month\ "i" \tag{18}$$

Meaning that if in the month-i the consumption monitored in season 2016-2017 was higher because of outdoor climate was colder than usual, the consumption referred to an ideal year should be lower: this assumption will be demonstrated later. The results of Equation 18 and the integral of consumption in Figure 36 are reported in Figure 37.

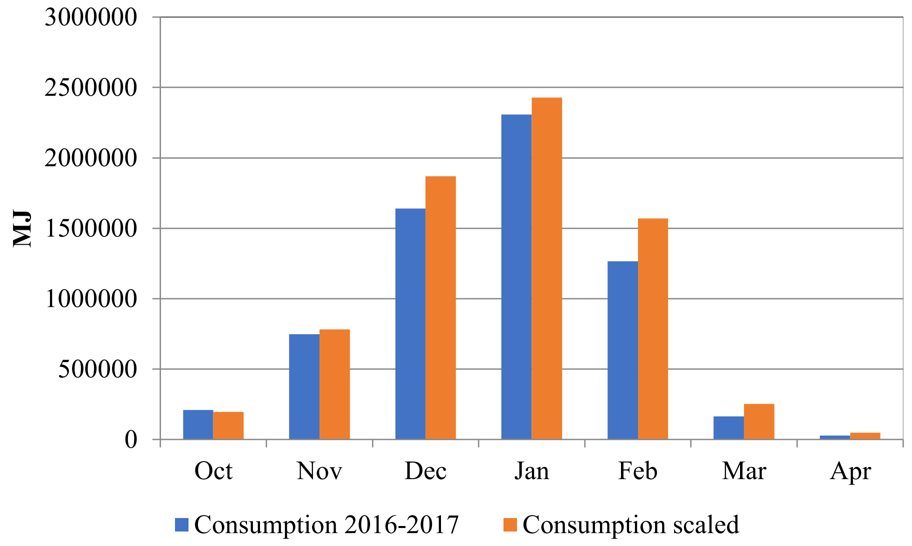


Figure 37 - Consumption in Workshop on month base

As shown above, the heating season 2016-2017 was colder than the ideal year (in fact it represents a conservative condition for the design of heating equipment): HDD estimated were 1965 °C·day for 2016-2017 and 2281 °C·day for the climatic data [48].

The consumptions obtained are 7’145 GJ (or even 1’984 MWh) for the climatic data that will be used in next analysis, and 6’366 GJ (or even 1’768 MWh) as real consumption monitored on 15-mins timestep base that correspond to a cost of 84’000 €/year and emission of 600 tonCO_2 yearly.

With these results, using the volume of the Workshop in Table 1, the **KPI** is evaluated according to the following equation:

$$KPI = \frac{Q_{grid,scaled}}{V_{Workshop}} = 16.6\ \frac{kWh}{m^3} \tag{19}$$

The value of the KPI is compared with the reference value for non-residential user in [36] for building with a ratio Surface/Volume below 0.2 m^{-1} in zones with HDD up to 3000 °C·day (the value reported in 12.7 kWh/m^3): as shown in Table 11 one again the performance of the building is **not sufficient** and an energy retrofit could be profitable because currently the building is consuming roughly 30% more that recommended. This value can be considered a sort of potential saving yearly if a complete (as in DM 26-01-2010 [36]) requalification is executed. Another useful KPI is 199 kWh/m^2, showing that the building is neither in energy class G according to the Italian reference legislation (APE[18]).

3.1.1.1 Threshold analysis of consumption

Using the data of consumption shown in Figure 36, it will be offered a small analysis to detect the monthly-hours of operation of the heating system. As just said in paragraph 1.4.1, the scheduling of Workshop's ATUs is committed to EDF maintenance and the regulation occurs as a mix between experience and by reading of temperature on three sensors installed in the building. Usually the huger ATU (number 3 of Figure 26) is always on (during heating hours). The interest of this analysis is to determine a credible number of hours of operation per month and later scale them according to the HDD, as done in paragraph 3.1.1.

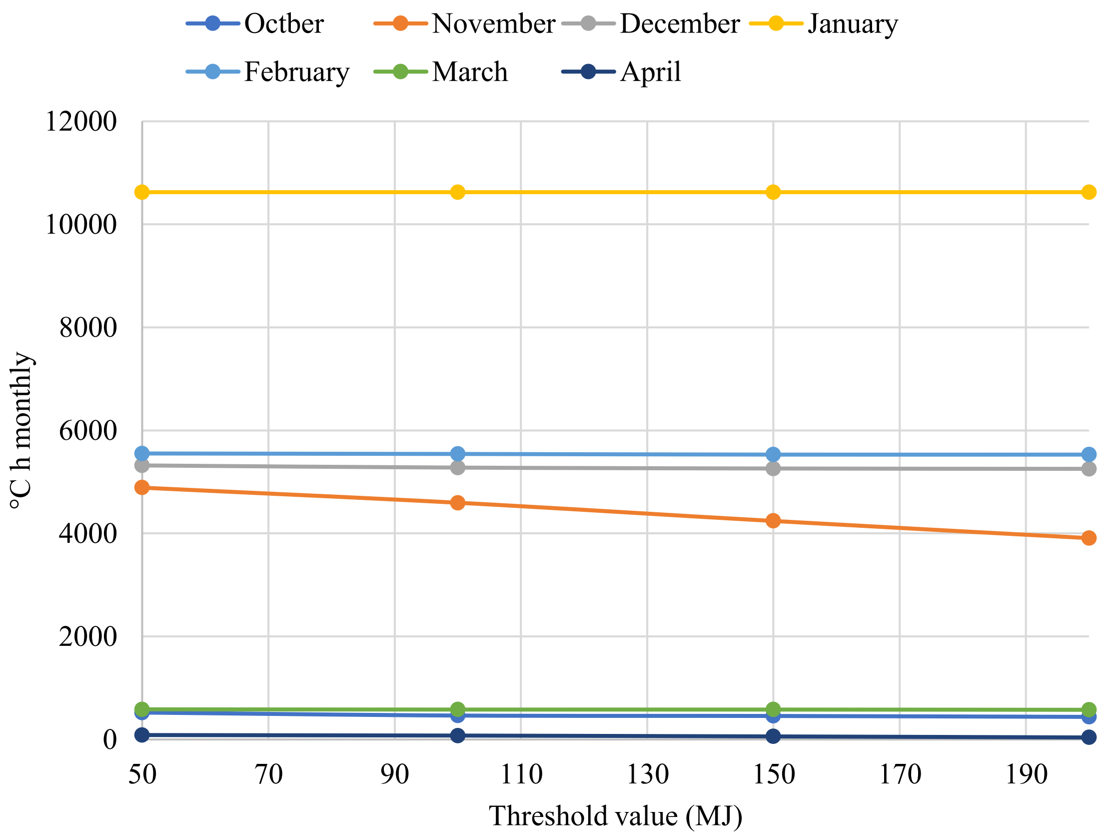


Figure 38 - Summary of threshold analysis: the number of hours is multiplied to the temperature difference

In Figure 36, one can see that every month (except in November) is clearly detectable when the space heating system is on or not: at low energy there are or dumb values or zeros. In November, indeed, the presence of dumb values is more hostile.

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[18] Attestato di Prestazione Energetica

Every month is sifted with an increasing threshold value so to determine if the energy to the ATUs is used for the building (providing hours of operation) or just as antifreeze. For example, setting a threshold value of 50 MJ, one discovers that in November there are 484 h above that power, while with a threshold of 100 MJ the figure is 455 h. Since the impact on building seasonal balance is proportional to the product of temperature difference and the hours of operation in a month, the information over threshold analysis are collected in Figure 38, where operation hours, resulting with a fixed threshold values, are multiplied to DT.

The result shows that to use 125 MJ as threshold value (in the middle of the field tested) is correct, but not in November as for the other months.

The output hours are scaled with the HDD of year 2016-2017 and the climatic data used from [48] as in Equation 18, where instead of energy to the grid (Q_{grid}), hours Θ_i are used: the scaled hours are reported in Table 19, previously shown.

Finally, the energetic sign of the Workshop, obtained with such hours of operation and external temperature of season 2016-2017, are collected in Figure 39 where on the x-axis there is the external temperature, whereas on y-axis the ratio between consumptions (in MJ) and hours of operation (in h) or monthly working days.

The slight linear dependence between power output of HVAC and outdoor temperature strengthens the consideration made in Equations 16, 17 and 18 on proportionality.

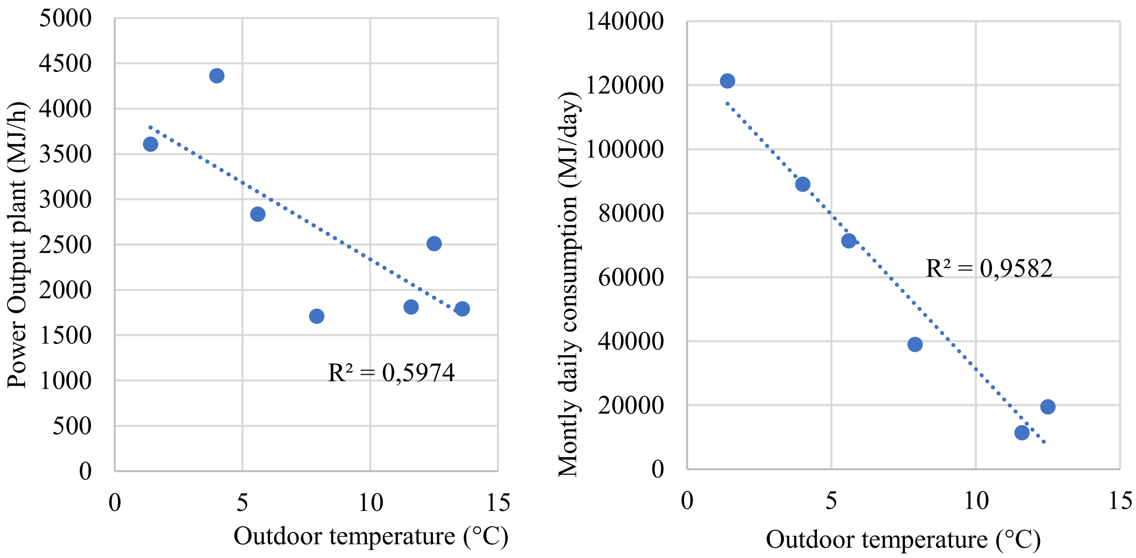


Figure 39 - Energetic sign of the Workshop for heating season 2016-2017

3.1.2 Efficiencies of the series: distribution, regulation, emission

To connect the real consumption of thermal energy needed to supply, the transmission losses and the impact of heat losses from the distribution to the space are considered.

In order to collect a unique value constant throughout the period of heating season, the Italian normative [50] comes in help: this assumption is done in absence of additional data on the system performances. The efficiency to be determined is η_{tot}, that contains the sum of the contributions associated to the three kinds of losses considered: losses for heat transfer in the distribution system η_{distr}, losses due to bad regulation of the system η_{reg} and finally the effect of poor emission of "teste di moro" η_{emi}.

$$\eta_{tot} = \eta_{distr} \cdot \eta_{reg} \cdot \eta_{emi} = 85.3\% \tag{20}$$

The three efficiencies above reported are obtained separately: the first is estimated with calculation whereas the others are pre-calculated and very contributing (93% each).

The distribution losses are associated to the performance of the distribution system, that is the pipeline going to south in the scheme in Figure 26. The evaluations of the efficiency consists into the calculation of the yearly energy losses (Q_{distr}) with basic of heat transfer.

$$\Psi = \frac{\pi}{\frac{1}{2 \cdot \pi \cdot \lambda} \cdot \ln\left(\frac{D}{d}\right) + \frac{1}{h \cdot \pi \cdot D}} = 0.92 \frac{W}{m \cdot K} \tag{21}$$

$$Q_{distr} = \Psi \cdot \mathrm{L} \cdot (\mathrm{T_{water}} - T_{ouside}) \cdot \frac{t}{1000} = 26'404 \quad kWh \tag{22}$$

The first equation allows the calculation of the linear transmittance of the pipeline: the data used are the conductivity of the insulant (λ = 0.045 W/m/K, wool insulation), the diameter of the inner pipe d and the external one D (including insulant layer). The variable "h" instead is the value of external convective coefficient equal to 4 W/m^2/K because the counter is not outdoor and covered by wind (using the recommendation of the same norm [50]).

The linear transmittance Ψ is later used to calculate the lost energy Q_{distr}, where the length L considered is 100 m, the water temperature 140 °C as with EDF contract, and $T_{outside}$ assumed 18 °C (the value is not great influencing, see the temperature difference). The time of the integration is instead "t" and assumed as the total hours of operation as calculated in paragraph 3.1.1.

$$\eta_{distr} = \frac{Q_{consumption} - Q_{distr}}{Q_{consumtions}} = 98.7\% \tag{23}$$

The value of the efficiency η_{distr} is so calculated comparing the distribution losses with the overall consumption scaled in the same paragraph.

The values used for regulation losses η_{reg} is constant and equal to 93% since the regulation is not-automatic and based on "on-off" control. The emission efficiency considered is general for hot air based heating systems for areas with height higher than 4 m.

3.1.3 Validation of 1D Excel© model

In order to justify the **order of magnitude** of the amount of energy loss for transmission evaluated with 1D model above depicted, with the relevant effectiveness of physical reality, this section, using the consumption scaled in paragraph 3.1.1, offers a sort of validation through a yearly energy balance in heating mode to the Workshop (the perimeter of such system is represented in Figure 40).

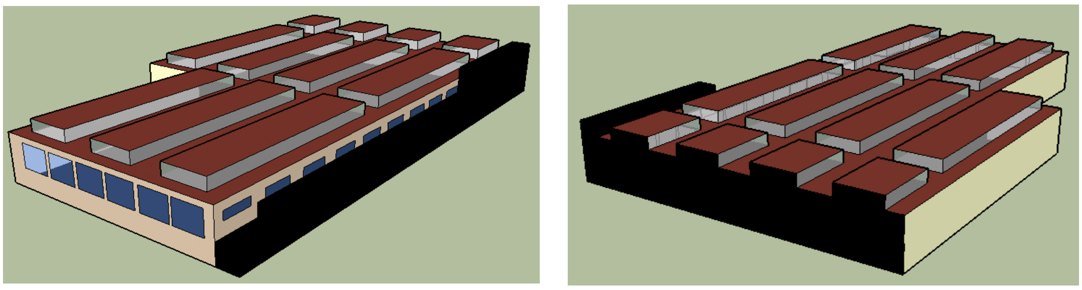


Figure 40 - Bounday of Workshop seen as Thermal Zone for the yearly energy balance: black surfaces represents adiabatic layers

The terms to be used in the balance are listed below and each one is analyzed in the devoted sub-paragraph:

- Transmission losses, calculated with the mono-dimensional method of section 3.1;
- Endogenous heat, coming from technological processes of paragraph 1.3.1, analyzed at 3.1.3.2;
- Free intake from adjacent Paint center calculated again with 1D model in paragraph 3.1.3.3;
- Lighting system, described in chapter 1.4.3 and analyzed with linear approximation in 3.1.3.4;
- Natural ventilation losses via doorways (see 3.1.3.5 and logistic reference);
- Mechanical ventilation offered by the three CTVs on the sub-roof treated with the methodology of 3.1.3.6 to provide fresh air to the Workshop;
- Consumption of the Workshop scaled and corrected with the total efficiency of paragraph 3.1.2.

All the terms are evaluated only during the hours of operations of the heating system (estimated in 3.1.1.1) because it is intention of this analysis to exclude inertial terms (i.e. the variability of building energy) and terms where contemporaneity with space heating system is compromised (i.e. solar gain during the hours of non-operation).

The “integral energy balance” to be considered is summarized in the following equation:

$$E_{transmission} + E_{ventilation} \approx E_{HVAC} + E_{process\ gain} + E_{lighting} + E_{adiacent\ locals} + E_{free\ gains} \quad (24)$$

Where the term $E_{ventilation}$ includes either natural ventilation of doorways either mechanical change rate of the building and E_{HVAC} values 1’693 MWh (i.e. the consumption at the counter times the overall efficiency of chapter 3.1.2). The value $E_{free\ gains}$ contains instead the additional free contribution not calculated for absence of clear data (i.e. solar gain, heat gain from occupants and latent heat …).

The left term of the equation accounts about **2.7 GWh** whereas the second **2.2 GWh** but the difference is accepted because:

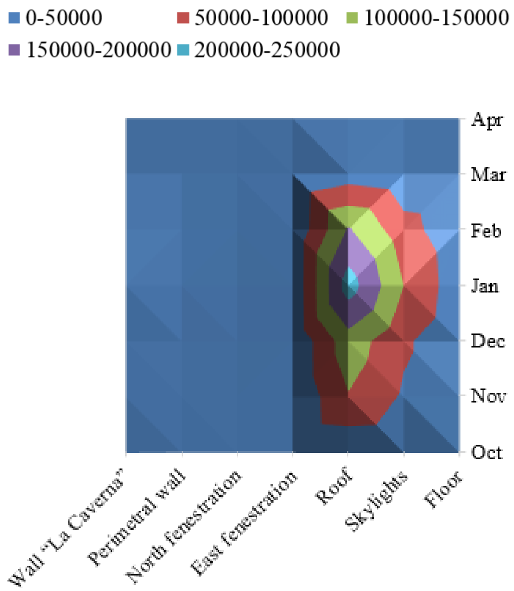
- The value of process gain is underestimated since it accounts only the process heat coming from flat surfaces not considering the contribution of engine and other equipment on the roof of the cabins;
- The necessary error on the real performances of ATUs, since data from technical sheets are used without an accurate investigation (costly and not possible for the necessity of operation during the three shifts asset);
- The contributions of additional free gain (collected in the voice $\mathbf{E_{free\ gains}}$) are not considered and among these there is the solar gain. It is worth to remember that according to [48], the total solar irradiation on the roof is more than 900 MWh only during the period Dec-Feb where contemporaneity is assured by the continuity of space heating operation.

3.1.3.1 Transmission losses of the building envelope

The first negative term of balance is represented by the transmission losses. With the 1D model described, the contributions are always outward the building, and so to be supplied by the HVAC. The dispersant elements of Workshop area are: the floor, the perimetric wall, the confining wall with La Caverna, the roof, the north and east windows and the skylights.

Table 21 - Distribution of transmission losses within the Workshop (kWh)

	Q (kWh)	%
Wall "La Caverna"	83'500	7.3%
Perimetric wall	27'615	2.4%
North fenestration	7'749	0.7%
East fenestration	23'059	2.0%
Roof	642'829	56.4%
Skylights	287'407	25.2%
Floor	67'554	5.9%



The results of the analysis are shown in Table 21: the main actors in the transmission losses are the roof and the skylights, contributing at about the 80% of transmission losses (in a heating season the consumption is estimated to be 1'139 MWh roughly).

3.1.3.2 Endogenous heat

It is purpose of this paragraph to quantify roughly the contribution of technological heat on heat balance during the time horizon considered monthly (i.e. the hours of operation discussed above). The first step of the approximation is to determine the most impacting machine hence the most dispersant surfaces to account for. Considering the scheme in Figure 14, all the processes involving technological heat are considered and so the heat flux leaving the surfaces calculated with the methodology proposed in [51]: washing tunnel, drying tunnel, cabins, dryer ante-oven, baking oven.

Table 22 - Results of endogenous heat investigation in BPS

	Wash tunnel	**Drying tunnel**	**Cabins**	**Dryer ante-oven**	**Baking oven**
Model	HC	2VS+1OS	1OS	2VS+1OS	2V+1OS
Surface Temperature (°C)	23	25.9	24.6	23.1	26.6
Overall Area (m^2)	268.4	251.4	385	150	918.4
Heat flux $\dot{Q}$ (kW)	3.9	6.8	10.1	2.3	27.2

The model evaluates the heat flux with basics of heat transfer, modelling the machineries as simple geometries and using the average surfaces temperature, obtained via an **infrared camera investigation** resulting in the collection of photos in Figure 41. In this phase, several photos of the different surfaces are taken and, averaging the resulting temperatures, one can summarize the information in a single value (also with the support of a laser thermometer for the vertical surfaces).

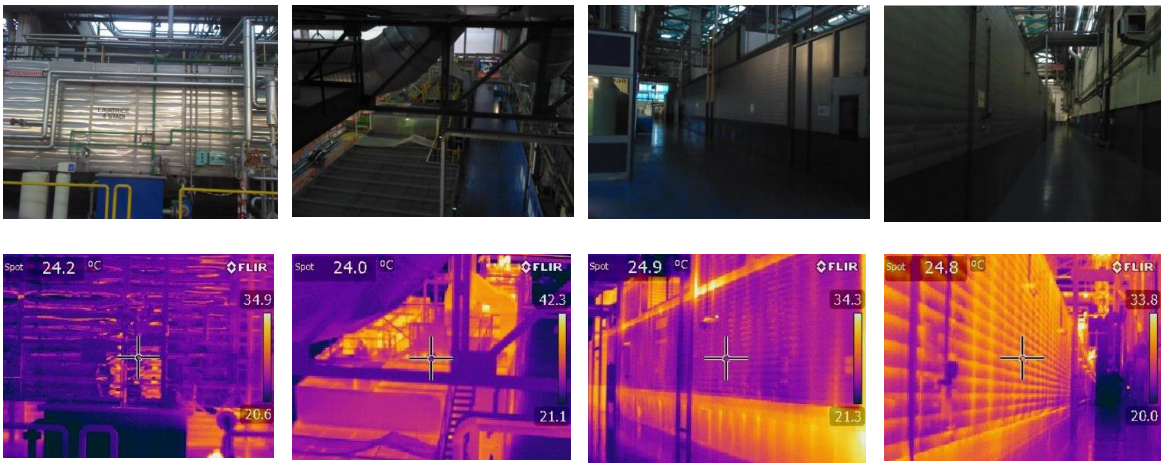


Figure 41 - Results of infrared camera investigation. In order from left to right: Washing tunnel, cabins' roof and two pictures of the baking oven

From the effectiveness of machinery geometry, it is chosen to model as a horizontal cylinder (HC) the washing machine because it is raised from the ground and the bottom surface can exchange with surrounding air. Whereas the long cabins' tunnel, since it is constituted by an inner corridor that shields well the heat flux from the outside, is considered as thermal emitter only from the roof hence modelled as an horizontal surface (1OS). The remaining machineries instead are assumed as thermal emitters from three sides: horizontal roof (1OS) and two vertical surfaces (2VS).

For each surface the heat flux is obtained with the following equation:

$$\dot{Q} = h_{tot} \cdot A \cdot \left(T_{surface} - T_{outside}\right) \tag{25}$$

Where h is the sum of convective and radiative coefficient (W/m^2/K), A the corresponding area of the surface (in m^2) and T the temperatures of the surface and outside environment (18 °C) respectively.

The value of h is evaluated with the properties of air film in the neighborhood of the surface and its geometrical features, summarizing all the information with the Nusselt number. According to the assumption made on the surface, one can obtain the value of the characteristic length L that corresponds to the diameter in case of horizontal cylinder, height for vertical slab and ratio between area and perimeter for horizontal surface.

$$T_{film} = \frac{T_{surface} + T_{outside}}{2} \tag{26}$$

With T_{film} and basics of heat transfer, the corresponding quantities for air are evaluated:

- ρ density (kg/m3)
- λ thermal conductivity (W/m/K)
- β coefficient of thermal volumetric dilatation (1/K)
- μ dynamic viscosity ($\mu Pa * s$)
- Pr Prandtl number (-)

Hence the dimensionless Grashof and Nusselt numbers, with the following equations:

$$Gr = \frac{g \cdot \beta \cdot \left(T_{surface} - T_{outside}\right) \cdot L^3}{\mu/\rho} \tag{27}$$

$$Nu = C(Gr \cdot Pr)^a \tag{28}$$

The value of coefficients “C” and “a”, in the definition of the Nusselt number, depends on the geometry used and the corresponding value of Rayleigh number (Ra=Gr·Pr).

Finally, the output value for h_{tot} is calculated with the sum of convective coefficient (from Nusselt) and radiative one:

$$h_{tot} = h_{conv} + h_{rad} = \frac{Nu \cdot \lambda}{L} + \varepsilon \cdot \sigma \cdot \left({T_{surface}}^2 + {T_{outside}}^2\right) \cdot \left(T_{surface} + T_{outside}\right) \tag{29}$$

Where the quantity ε is the emissivity of aluminum (fixed at 0.1) and σ the Stefan-Boltzman constant (5.67·10^{-8} W/m^2/K^4).

The results of the analysis are reported in Table 22, where the value of the voice “Overall area” corresponds to the sum of the modelled surfaces. The heat flux output from the estimated surfaces accounts at roughly 50 kW, that multiplied to the total number of hours of heating season reaches to an amount of 118 MWh of thermal energy generation.

3.1.3.3 Contribution of adjacent locals

According to the operative temperature of Paint Center (24 °C), the free heat gain coming from transmission is considered as a positive effect on the thermal balance of the Workshop.

The area of the heat flux is assumed as the north lateral edge of such building (extending for 100 m with 8 m in height) with a U-value of 2.589 W/m^2/K (including air resistance). Considering the heat flux calculated as in Equation 9, but where the temperature difference is constant throughout the year, the overall contribution accounts at 29.2 MWh.

3.1.3.4 Lighting contribution to heat balance

The linear contribution of heat output from the bulbs listed in Table 12 is calculated during the hours of operation of HVAC with the product of power per time per each month.

$$Q_{generated} = \sum_i n_{bulb,i} \cdot P_{bulbs,i} \cdot \Theta_i = 370\ MWh \tag{30}$$

3.1.3.5 Natural ventilation through doorways

The energy loss associated to the opening of doorways is evaluated using information about the logistic workflow (i.e. the corresponding opening time per doorway with a fixed scheduling) and assumption on the air mass flow always on month base.

Firstly, the equation used assumes the general form of energy ventilation loss:

$$Q_{v1} = ACR \cdot V \cdot \rho \cdot c_p \cdot \sum_i (T_{inside} - T_{outside.i}) \cdot (f_i \cdot t) \cdot \Theta_i \tag{31}$$

In which:

- “ACR” corresponds to the Air Change Rate (ACR) associated to the opening of the door (the value used is common practice in ventilation engineering i.e. 0.5 vol/h);
- “V” is the volume of the Workshop as reported in Table 1;
- ρ and c_p are the density and specific heat of air (assumed 1.2 kg/m^3 and 1005 J/kg/K respectively);
- The temperature difference is considered as for transmission losses because the opening of doorways will correspond to the ex-filtration of outdoor air that globally decreases the energy content of the thermal zone;
- “f_i” is the frequency of opening of the two active doorways (on the north and south side). It is expressed in times/hour and is the result of analysis conducted in paragraph 3.4.2 where the number of openings for the two apertures per hours monthly are summed up. The final output is the last column of Table 23.
- “t” is the time at each door opening (11 s). This value is obtained with linear assumption because the velocity of the door is 2 m/s during the rising of the cloth

and 0.8 m/s during the closing and considering that the photocell is 1 m far from the curtain (the speed of the forklift/bull is 2 m/s).

- Θ_i are the hours of operation of the heating system reported in Table 19: the product between the frequency, t and Θ_i represent finally the time in which the doorway is up and let air pass into the facility.

Table 23 - Setup and result for energy losses via ventilation in doorways

	f$_i$	ΔT	**E**
	times/h	°C	kWh
Oct	46.6	5.4	1’198
Nov	54.26	11.2	17’015
Dec	50.7	16	21’300
Jan	52.0	17.6	37’709
Feb	55.0	14.8	2’7645
Mar	52.0	9.8	4’347
Apr	58.1	5.3	514

As reported in Table 23, the logistic information are hidden into the definition of f_i, but globally one can say that the impact of the north doorway is more important because the LEV bumpers are moved in couple on the bull as reported in Table 5 (i.e. there are more missions for each box entering the Workshop).

The final contribution of natural ventilation via doorway accounts at 109 MWh yearly.

3.1.3.6 Mechanical ventilation of HVAC for air balance

The dampers of the three ATUs in the sub roof cannot partialize the air flow: this means that when the machine is off the dampers are completely closed, whereas when the fan of the engine sucks air they rotate to a fixed position: this means that the fraction of outdoor air that can be taken from the outside is constant[19].

For this purpose, the contribution of fresh air entering inward is associated to the air fraction flow rate and the temperature difference only, because there is no control over the air humidity: the difficulties are in determine such a fraction. Three methods are considered to obtain this information:

- Ask to the supplier of the ATU, but no answers have been obtained;
- Measure the air flow rate with an anemometer. This method requires the average velocity in the two dampers (inward and return) and the dimension of the section. The fraction is determined with the rate of the volumetric flow rate (product of both quantities) of air from outside and the total flux. This method has not been

[19] This assumption is done because the engine is not provided of inverter and cannot modulate the overall mass flow rate processed by the batteries.

used because of technical impossibility to reach the external damper and bulky of components inside the machine, compromising the accuracy of the measurements.

- Asking to the maintainers of the plant. They don't have such specific information but referred the value of 50% by experience.
- With an enthalpy balance to the ATU in summer condition, as suggested by [52].

The last method [52] is considered, it requires simply the evaluation of the three temperatures in a summer configuration (where there is not the battery gain) and the use of the following equation:

$$x_o = \frac{T_{inside} - T_{mixed}}{T_{inside} - T_{outdoor}} \quad (32)$$

The terms ordered in this way (coming from the adiabatic mixing of air flows to the ATUs) offer directly the fraction of outdoor air researched (x_o). According to the physical measurements with portable "air probe" in the three ATUs, the temperatures recorded (in August 20th) show that when $T_{outside}$ is 36 °C and T_{inside} 30°C (that roughly corresponds to the inside temperature), the mixed temperature is 32°C for CTV1 and 33°C for CTV2 and CTV3.

The resulting fractions are 33% for the CTV1 and 50% for the last two, hence according to technical specs of ATUs reported in Table 10, the overall ACR corresponds to 1.718 as reported in Table 24.

Table 24 – Result of the calculations to determine outdoor air fraction on the three CTVs

		CTV1	**CTV2**	**CTV3**	**U.M.**
Total volumetric flow rate	$\dot{V}$	165'000	150'000	150'000	m³/h
Return temperature	T_{inside}	303	303	303	K
Outdoor temperature	$T_{outside}$	309	309	309	K
Mixing temperature	T_{mixed}	305	306	306	K
% Outdoor air	x_o	33%	50%	50%	44%
% Indoor air	x_i	67%	50%	50%	56%
Renewal flow rate		55'000	75'000	75'000	m³/h
Air Change Rate	ACR	0,461	0,628	0,628	h^{-1}

The equation used to evaluate the contribution is the following:

$$Q_{v2} = ACR \cdot V \cdot \rho \cdot c_p \cdot \sum_i \left(T_{inside} - T_{outside,i}\right) \cdot \Theta_i \quad (33)$$

Where the ACR used corresponds to the sum of ACRs of CTV1 and CTV3 i.e. 1.08 h^{-1} (guessing CTV2 off all the time because it is used mainly for summer ventilation), and the other quantities as in Equation 31. The resulting energy accounts at 1'465 MWh yearly.

3.2 Optimization of insulant thickness

In many real applications, the thickness of the insulant is assigned basing on experience. The purpose of this paragraph is to offer a methodology to design, on economic-base, the optimal thickness for thermal insulation using the approach of [53].

Starting from current value of thermal resistance R of the element (in $m^2 \cdot K/W$) reported for the building envelope in Attachment A, one can determine the overall resistance with the addition of an insulant of an unknown thickness "l_x" under the assumption of strata in series:

$$R_{new} = R + \frac{l_x}{\lambda_{insulant}} \tag{34}$$

Where the quantity $\lambda_{insulant}$ corresponds to the conductivity of the insulant. With the upgraded R-value obtained, it is possible to calculate with 1D model the energy from the grid needed Q_{grid} to cover thermal losses for transmission through the element considered. Then, four economic parameters are considered and collected from literature:

- Inflation rate "r_g", assumed equal to 1.29% in Italy for 2017 [8];
- Interest rate "r_i", assumed equal to 2%;
- Actual interest rate "r_r"
- Present Worth Factor "PWF", that allows to report to the installation year all lifetime costs for energy expenditure.

The value of actual interest rate and PWF is calculated with the following equations (because $r_i > r_g$):

$$r_r = \frac{r_i - r_g}{1 + r_g} \tag{35}$$

$$PWF = \frac{(1 + r_r)^{n_{life}} - 1}{r_r \cdot (1 + r_r)^{n_{life}}} \tag{36}$$

Where the variable n_{life} corresponds to the life of the insulant assumed constant and conservatively equal to 12 years.

With this data, one determines the objective function that is the unit cost of insulant in the lifetime c_{tot}, defined as follows:

$$\begin{aligned} c_{tot} &= c_{insulant} + c_{inst.} + c_{energy} \\ &= l_x \cdot c_{m^3} + c_{inst.} + PWF \cdot Q_{grid} \cdot c_E \quad \left(\frac{€}{m^2}\right) \end{aligned} \tag{37}$$

Where the contributions reported mean:

- The first accounts for the cost of the insulation material, obtained as product between the cost per cubic meter c_{m^3} times the insulant thickness l_x;
- The installation cost $c_{inst.}$ is provided by the supplier and summarizes the complexity in the installation phase;

- The last term considers the cost to sustain for transmission losses through the dispersant element during insulant's lifetime (n_{life}) calculated with 1D model of paragraph 3.1.

With the defined problem, it is clear that the optimal insulation thickness is achievable with **linear programming** for the defined **single objective optimization scalar function**:

$$\begin{gathered} \min\{c_{tot}\} \\ subject\ to\ \ l_x > 0 \end{gathered} \tag{38}$$

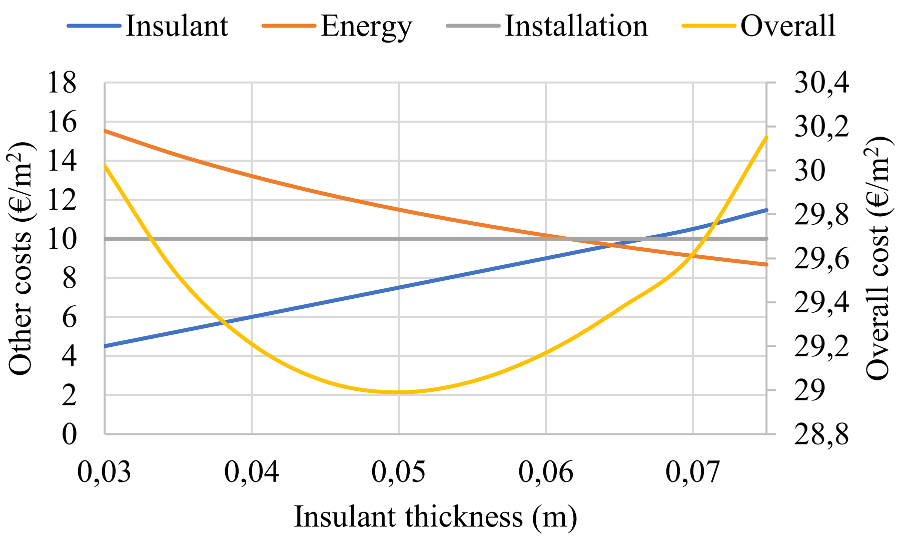


Figure 42 – Cost trends for optimization procedure (roof's example)

A graphical representation of the problem is offered in Figure 42, where all costs are plotted with insulant's thickness (the case reported is the roof insulation): as expected, the energy costs decrease dramatically with the insulation, contrarily the cost of the insulant. Whereas the installation cost, in this analysis, is fixed at a constant volume because there are no technical data about. The searched thickness is the one that minimizes the overall costs c_{tot}, that in this case is equal to 0.049 m.

3.3 Building Energy Information Modelling and comparison with 1D model

In this section, a tridimensional model of the Workshop is offered so that one can analyze the differences between the simple 1D model above described and validated formally with an integral energy balance in heating mode. The model is simplified as to guarantee reduced computational cost and reduced error into the definition of the problem: a more intensive analysis would require too many data not available and lead to an increasing probability of occurring in errors.

The logic workflow of the modelling technique used to perform the energy simulation, remarks the procedure used in [9] to drive an industrial building renovation. This class of approach is defined whole **Building Energy Information Modelling (BEIM)** that is a versatile multipurpose tool used for requalification, green certifications, dynamic building simulation and in general to analyze building energy efficiency. In this case the application will be limited to the energy aspects related to a possible future envelope's retrofit, being in general such scientific field seldom applied for industrial users and for existing building [54, 55].

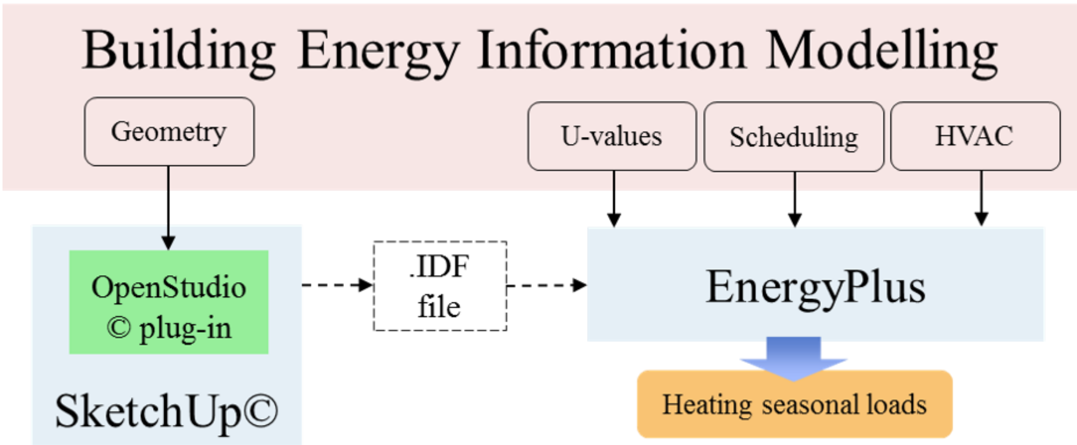


Figure 43 - Flowchart of BEIM procedure

The workflow of the BEIM procedure, described in this section, follows the scheme reported in Figure 43. As shown, the work requires only the study in a retrofit scenario, furthermore main attention is devoted towards an energy summarization of the building behavior skipping architectural, management and life cycle cost aspects requiring different levels of details and making necessary a re-modelling ad-hoc [55]. The aspects of data logging and measurements of real building response are not performed because of lack of resources.

The work is divided into three great branches and performed only by the author: the first step, common to all the remaining parts of the thesis, requires the collection of data about the thermal envelope and geometry of the building. The data are summarized in a 3D model in SketchUp© environment while the free OpenStudio© plug-in helped to define boundary conditions and so set the first assumptions on energy aspects. After, a .IDF file is generated and the remaining setting occurred on E+ environment by an object-oriented interface. The climatic data used, reported on E+ library, are for the city of Turin.

The software used to perform the tridimensional dynamic simulation of the building in analysis (i.e. the area of Workshop) is EnergyPlus because it is commonly used as engine for several energy simulation softwares and considered one of the most accurate, but even very complex to use without a Graphic User Interface (GUI): this makes necessary to approximate the effectiveness of reality to an adequate degree of detail. For this purpose, the BEIM strongly depends on the data available and the assurance on the actors best known in the thermal balance and scheduling.

3.3.1 Geometry creation on SketchUp© and OpenStudio© Plug-in

SketchUp© is defined as “strumento di disegno all’avanguardia” [56] because its simplicity in use helps in the 3D drawings of whatever physical building: it is used especially by engineers, architects and born to enhance their creativity in modelling facilities. With the time and success, it was provided of several Plug-in (extensions) rising this software to a multipurpose level. The extension chosen for energy analysis is the free plug-in OpenStudio©, in turn “a collection of software for whole building energy modelling using EnergyPlus and advanced daylight analysis using Radiance” [57].

The versions of the software used in this work are the lasts and respectively “SketchUp Pro 2017” and “OpenStudio 2.3.0”, whose interface is shown in Figure 44. In order to perform an energy analysis on a building, OpenStudio offers dedicated “functions” in SketchUp (see the blue box) while the modelling geometry functions of SketchUp are in the red box of Figure 44.

The first operation is the creation of a thermal space where the building should be in and later, by importing the technical planimetry of the building in analysis (from a .DWG AutoCAD© 2017 file), starting 3D surfaces are generated by SketchUp tools. The presence of OpenStudio allows, in the Thermal Space, the automatic recognition of surfaces (i.e. floor, walls, roof) and sub-surfaces (i.e. windows, skylights and doors). The skylights and sheds are assumed to be flat, because the OpenStudio identification occurs dynamically with the geometry definition: the formal steps to drawn them sloped would be too long and complex.

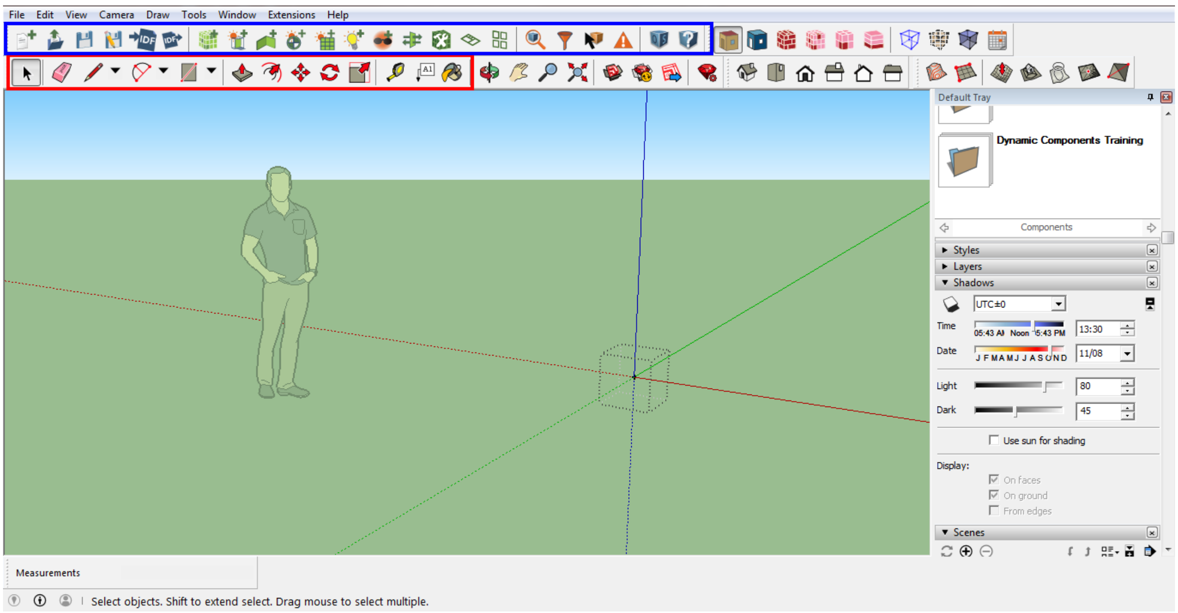


Figure 44 - GUI of SketchUp(c) and OpenStudio(c) plug-in showing the creation of a new thermal space.

After the creation of the geometry, and the automatic assignment of colors according to the type, one can set the boundary conditions to the surfaces introduced with OpenStudio Inspector as shown in Figure 45.

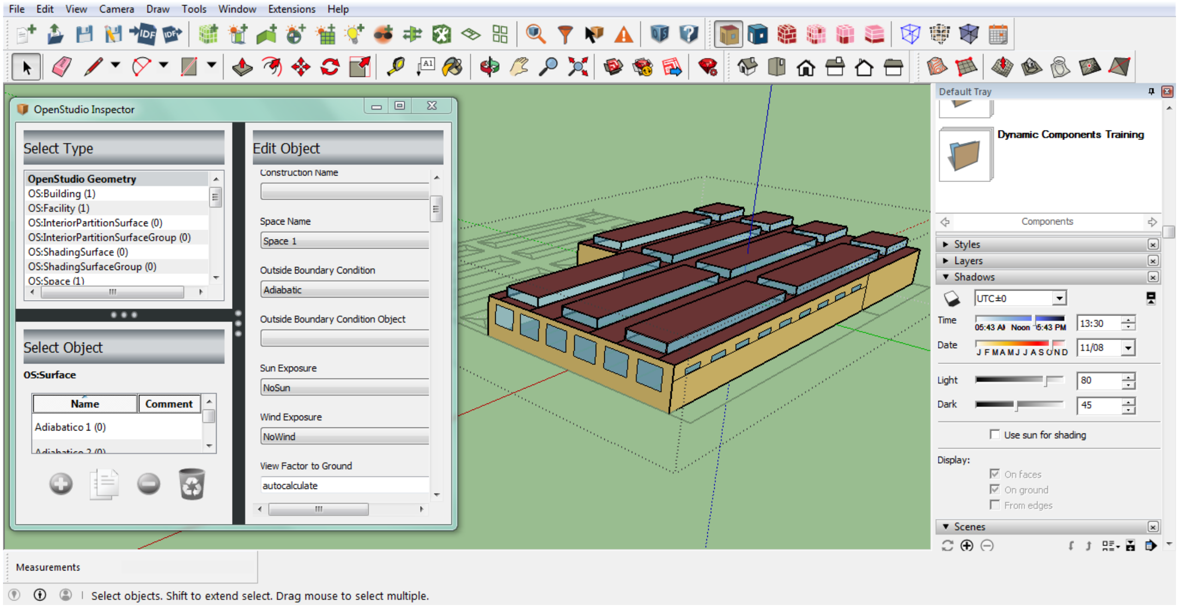


Figure 45 - OpenStudio Inspector for boundary conditions in SketchUp environment

The **thermal boundary conditions** assigned to study only the Workshop are:

- Adiabatic walls with no-sun and no-wind of the confining wall with Paint Center and Dressing Rooms, because from that side there is a positive energy gain not considered;
- Adiabatic wall with no-sun and no-wind for the confining wall with CDC, because the contribution is null do to the operating temperature setpoint of Ex-Imbutiti;
- No-sun and no-wind on confining wall “La Caverna”, assuming conservatively that the outdoor temperature is perceived.

Doors and doorways have not been modelled because of:

- The thermal energy ventilation contribution through them would be more impacting that the transmission losses;
- Transmission losses would be lower with-respect-to losses through the others envelope elements because of dispersant surfaces‘ size;

Overall, for the thermal space considered, in the OpenStudio model there are 77 surfaces and 55 sub-surfaces, and 1 construction set to organize later in E+ as well the properties of the building envelope. After this, the OpenStudio work is concentrated and imported in the .IDF file to be executed on E+ environment.

3.3.2 EnergyPlus settings and final outputs

E+ is a whole building energy simulation program with whom is possible to obtain the heating and cooling loads necessary to keep fixed temperature setpoints throughout the year, modelling at different possible levels of detail the thermal volume considered, the utilities and the HVAC [58]. Nonetheless, it is a garbage-in garbage-out software meaning that the setting, if coherent with E+ coding, will be read and executed achieving outputs without any verification. The simulation, performed on the version 8.8.0 of E+, is dynamic and allows the selection of the climate according to defined locations. The physics of the program is based on heat balance equations of conductive, convective, radiative and condensation fluxes: the area in analysis is divided in thermal zones (conditioned or not) and outer environment whereas the conditioning equipment is modeled as built-in function.

The purpose of this sub-paragraph is to discuss about the **simplified model realized on E+** and explain the assumptions done.

The .IDF file generated with OpenStudio is so reported on the E+ Launcher together with the weather file of Turin imported by E+ official site [59]. E+ Launcher is a small program that is able to execute .IDF file running a series of boundary programs within E+ environment and correctly organize the visualization of the outputs (see "View Results" in the bottom box of Figure 46). When a simulation of E+ is run, the script contained in .IDF file and encoded in software language is launched and is read by many sub-programs. But the setting, for BEIM simulation, occurs in "IDF Editor" a devoted tool to correctly encode the information with an object-oriented GUI in the .IDF. Below a description of the different settings for the simulation.

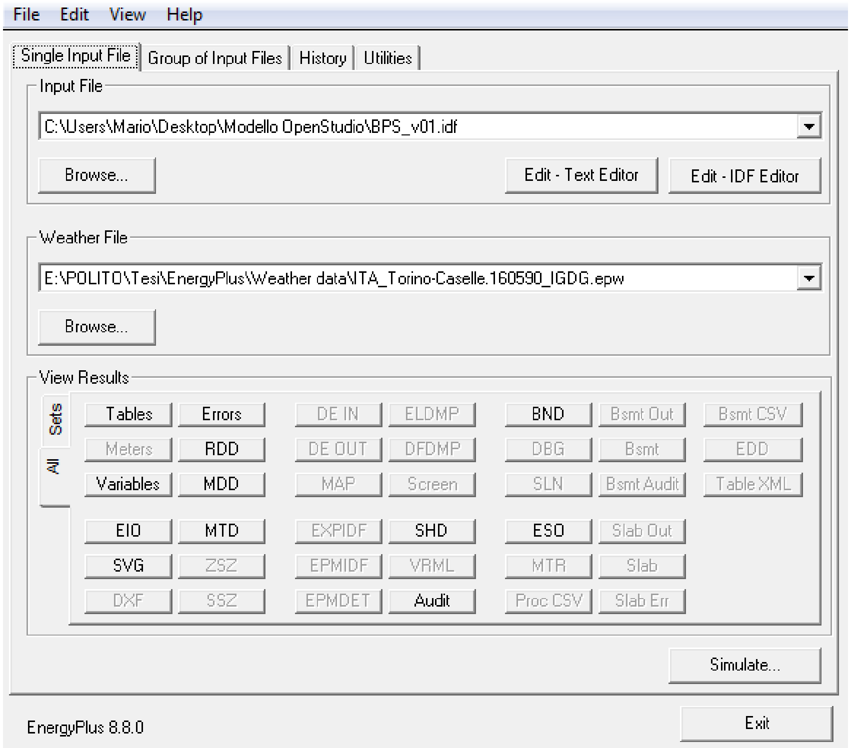


Figure 46 - E+ laucher GUI on the left and .DXF file on the right

The first setting is the convective coefficient to be considered, and "TARP" is chosen. It is a complex algorithm that evaluates the total convective coefficient "h" splitting into two contributions: the forced and natural convection coefficients for external and internal convection, whereas for conduction the scheme used is called "Conduction Transfer Function" that is able to work with the inertial properties of the building envelope through "response factors". Ground dispersions instead are not modeled dynamically, because of lack of data, but with the ground temperature that is set at 15 °C throughout the year. A detailed description of the governing equations used is in the Engineering Reference of the user manual of E+ [58].

The time step is 15 minutes but can be increased up to 1 minute: the robustness of the software solutions is assumed to be sufficient and not tested explicitly but, performing more costly simulations, the difference in terms of heating load was null.

The "Run period" chosen for the simulation is from October 15th to April 15th, according to the Italian definition of heating season: the "Scheduling" foresees temperature setpoint of 18 °C 24h/24h during the weekdays, no-holidays and no-special days whereas for the remaining time the building is left in cool down (heating system off) as in reality.

The core of the work is into the definition of the building envelope: firstly, the properties of materials and the thickness of the strata, according to Attachment A, are inserted as "Material", later the objects "Constructions" are defined for each dispersant element putting in series the materials objects as in Figure 47. The windows are modeled as "Simple Glazing System" with the overall U-value of the opening (see U_W in the second table of Attachment A), assigning as value of "Solar Gain Coefficient" the corresponding value of the glass. After in "BuildingSurface:Detailed" each construction built is linked to the geometrical entity imported from OpenStudio in the .IDF file.

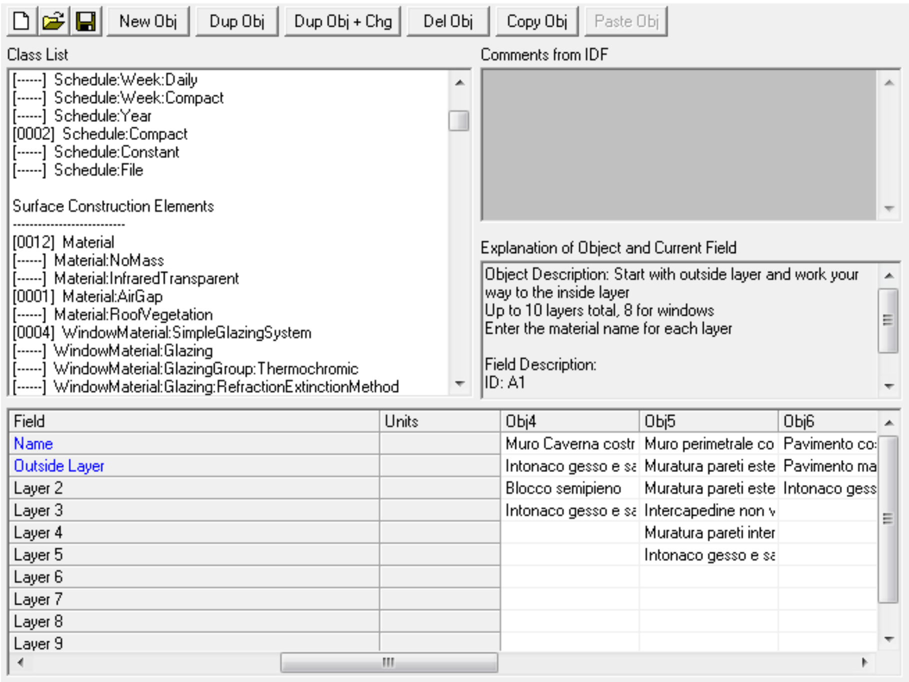


Figure 47 - IDF Editor in E+ environment

The HVAC is modeled with the object called "IdealLoadsAirSystem" that is able to keep the setpoint temperature in each point of the single Thermal zone.

The ventilation and free internal gains are not modeled because:

- The real impact of natural ventilation is the result of internal handling logistics and many other factors regarding the building envelope (e.g. in and ex-filtration through windows), depending on the pressure difference with the outside that is unknown for lack of resources.

- Mechanical ventilation contribution depends on the fraction of fresh air treated in the three ATUs and, according to what said in paragraph 3.1.3.6, the value is not accurate and determined only as order of magnitude.
- The impact of free internal gains is not considered in the model because the analysis of paragraph 3.1.3.2 once again was only indicative but remarks the real complexity beyond the methodologies.

The three contributions, of course, would have improved the level of detail of the model, but meanwhile the possibility of occurring in error (i.e. lack of code control) would have risen: in addition, it is worth to remember that this model would be used only for transmission losses that depend only on temperature difference (the temperature indoor is fixed during the plant hours of operation). To model even ventilation and internal free gains, will bring only to a variation of heating loads, **useless to determine the effect of an energy retrofit** (i.e. the contribution will sum for pre and post scenario).

If one wanted to add the contribution of the ventilation it would be enough to fix an ACR for the period of operation as in [9] in order to determine the overall energy need to the building in a design phase matching the overall consumption.

3.3.3 Heating loads and differences with 1D case

The dynamic simulation of E+ is performed on a Windows 7 64 bit Home Premium PC with Intel Core i5-2450M CPU 2.50 GHz and 6 GB of RAM in less than 10 seconds. The overall **energy to building** necessary to be supplied is 8’454 MWh[20]. In Table 25, instead, the comparison between the transmission losses calculated with the 1D static model and, above described dynamic simulation on E+: the comparison is once again senseless because the two models are based on different assumptions in timing, but you can appreciate that the order of magnitude is the same.

Table 25 - Transmission losses comparison with 1D and E+ model

	1D kWh	E+ kWh	Weight %	Difference %
Perimetric wall	27'615	27'780	2.4%	0.6%
North fenestration	7'749	7'489	0.7%	3.4%
Wall “La Caverna”	83'500	141'024	12.3%	40.8%
East fenestration	23'059	21'396	1.9%	7.2%
Roof	642'829	654'801	57.1%	1.8%
Skylights	287'407	234'486	20.4%	18.4%
Floor	67'554	60'557	5.3%	10.4%
Total	*1'139'713*	*1'147'533*	*1.00*	*0.7%*

[20] Note that this value is lower than transmission losses because of free solar gain. The displacement (about 300 MWh) can be considered as the order of magnitude for solar gain to add into the 1D balance of paragraph 3.1.3 where on the left side of the balance equation there were roughly 400 MWh less.

The last column of Table 25 reports the relative difference between the two methods for each dispersant element, whereas the third how that element **weights** on the total. The model used for La Caverna (outdoor with no wind and no sun) wall results too conservative reaching roughly the double of losses estimated with Excel. A small difference is on the roof: this result is important because the **roof and skylights** have the larger dispersant area and are the most important actors on the overall thermal balance of BPS (roughly the 80% of transmission losses seeing their weights). Overall (see line 'total'), the displacement between the two transmission losses models is negligible.

In general, the explanation to the differences between the two models are summarized below:

- Mono-dimensional model is based on a static approach where hours of operation are based on scaled hours of season 2016-2017 whereas scheduling of the 3D model allow 18°C only during the weekdays. Actually, the turn-on hours of HVAC are chosen according to the experience of the maintainers.
- Dispersion 1D model for La Caverna considers an additional air wall as resistance between outdoor temperature and indoor area. The assumption on E+ (outdoor) is too extreme and in fact it leads to different results but of the same order of magnitude;
- The temperature used for 1D are monthly averaged whereas in the dynamic simulation they change each timestep, taking in account the contemporaneity with solar gain;
- E+ model takes in account thermal bridges between dispersant elements;
- The model in E+ has a dynamic variation even on wind impact and so on convective coefficients (forced and natural).

3.4 Static modelling of internal logistic

The purpose of this paragraph is to describe the model used to analyze and discover the benefits from a new internal layout of BPS. Because of the high complexity of real movimentation and its dynamicity not reproducible, the model chosen can be classified as "static" and "analytic", being based on simplified equations and the detection of a typical day load so to have a versatile multi-purpose approximation throughout the thesis.

It allows to reproduce the internal handling of boxes, pieces and containers so to determine: the number of means needed (i.e. during the design or optimization), the saturation of the drivers and, finally, the handling costs. The inputs for such model come from: data collection on field, approximation of logistic workflow from production data, technical specs of equipment, measurement of timing, spaces and performances, general effectiveness of the actors still performing in the current layout.

3.4.1 Typical day profile: static approach

As said in paragraph 1.3.5, the constancy in the production asset occurred from June 2016 when LEV and MITO established the current layout and activities. But the production in car's manufacturing industries (especially if the product is premium brand as Maserati

Levante), depends strongly on external sales: being Mirafiori a dated industry, and being Maserati a brand that requires many attentions, the speed and accumulation of products is not trivial. This means that in this analysis there will be a strong simplification of reality with a static model for the sake of obtaining a yearly analysis coherent with the overall logistic impact. Anyway, the calculations are done on hour-base, but the results of this approach will be compared with three real weeks, whose data available are used.

The production records in BPS are reported in terms of "kit" that is the base-content of a skid. There are five kits:

a) Front LEV: that contains front bumper and front band;
b) Rear LEV: as for the "Front" but contains the rear;
c) Arches LEV: with the 4 arches;
d) Molding: with the 4 moldings;
e) MITO: with the two bumpers of Alfa Romeo.

The first data used in this analysis are the monthly production kits "$n_{k,j}$" that, according to the month "k" and the kit "j" and the hours of production in the month k "$t_{P,k}$" (see Table 7), one can mutate for each month in the average velocity of the production $v_{k,j}$:

$$v_{k,j} = \frac{n_{k,j}}{t_{P,k}} \qquad \left(\frac{kit}{h}\right) \tag{39}$$

Where the term $n_{k,j}$ corresponds properly to number of kit "j" produced in the month "k": this is the **starting data available** from the collection in the facility and covers a period of 1 year so to determine whether the analysis can roughly summarize seasonal rhythms. The values of $v_{k,j}$ are summarized in the following figure:

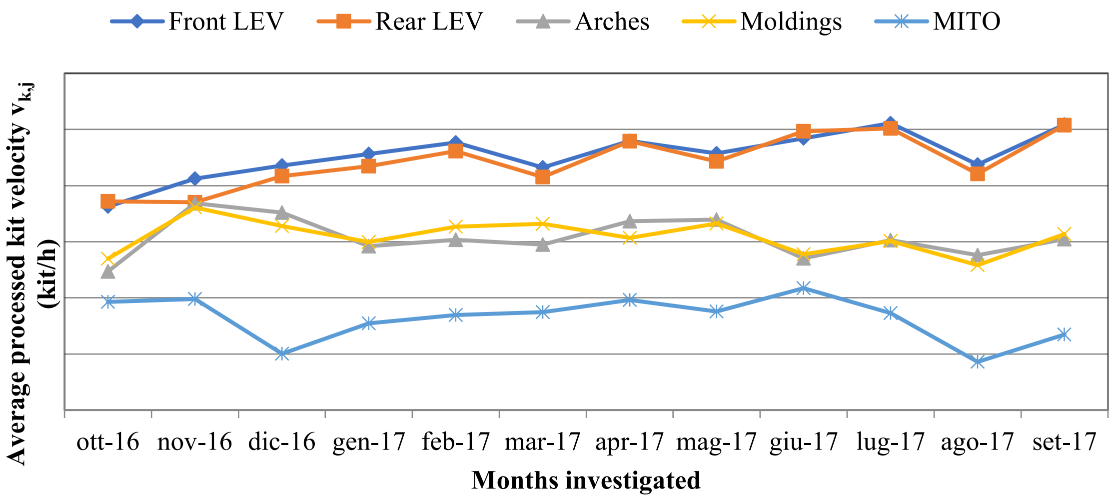


Figure 48 – Average montly velocity of kits ($v_{k,j}$) from the data available on $n_{k,j}$ and scheduled production time.

Saying in advance that the production of kit (number of kits produced monthly) is very variable throughout the year according to the production commissioning and holidays, the production velocity just averaged and illustrated in Figure 48, keeps a variation below the

30% for all kits, except MITO kit, because of its secondarily in the production asset. The month with the fastest production is April 2017, the slowest is October 2016.

According to the reasonings just discussed, the use of $v_{k,j}$ for next analysis is complex and month-dependent: this approach will take too much time to be applied on an Excel© file giving as results a simulation still affected by the variability in the production. To approximate again the reality, a new velocity on yearly base for each kit "j" is introduced:

$$v_j = \frac{\sum_{k=1}^{12} v_{k,j}}{12} \qquad \left(\frac{kit}{h}\right) \tag{40}$$

With such defined velocity v_j, it is possible to determine the number of kits "j" expected to be produced in a shift "s" by multiplying for the production time $t_{P,s}$ assigned to the shift (reported in Table 6):

$$n_{j,s} = v_j \cdot t_{P,s} \tag{41}$$

Where $n_{j,s}$ is the number of kits produced (virtually in the model) in a shift according to the constant kit's velocity calculated previously. This value will be compared with the real data recorded in paragraph 3.4.1.1. Other quantities coming from this analysis are the number of pieces effectively produced in the shifts $n_{h,s}$ and the boxes $n_{b,h,s}$ to be moved in that time horizon.

$$n_{h,s} = n_{j,s} \cdot n_{h,j} \tag{42}$$

The quantity $n_{h,j}$ is the number of pieces "h" contained in the kit "j", so with the product by $n_{j,s}$ the resulting quantities is $n_{h,s}$, that is the number of pieces "h" produced in the shift "s" from the kit "j".

$$n_{b,h,s} = \frac{n_{h,s}}{n_{b,h}} \tag{43}$$

Where since the pieces "h", coming into the facility in a fixed number within a box, already reported in Table 4 and referred as $n_{b,h}$, the corresponding number of boxes $n_{b,h,s}$ to be moved in that shift "s" is simply evaluated. The integral of $n_{b,h,s}$ throughout the day gives the amount n_b of "input missions" necessary to feed the Workstation, by the forklifts.

All the data needed to evaluate such equations are summarized for the 5 kits in Table 26 however the yearly average velocity is not reported for corporate secrecy.

Table 26 - Logistic fragmentation for material handling to be used in the static model

Product **h**	**Number of the kit** **j**	**Pieces in the kit** $n_{h,j}$	**Pieces in a box** $n_{b,h}$
Bumper front LEV	a	1	14
Bumper rear LEV	b	1	14
Band front LEV	a	1	12
Band rear LEV	b	1	10
Mouldings rear LEV	c	2	40
Mouldings front LEV	c	2	56
Arches rear LEV	d	2	10
Arches front LEV	d	2	8
Bumper front MITO	e	1	16
Bumper rear MITO	e	1	16

3.4.1.1 Comparison of static model with real production data

This paragraph offers a comparison of the modeled system with the reality in terms of number of kits produced per shift $n_{j,s}$. The averaging process described in the previous chapter starts from the number of kits produced monthly $n_{k,j}$: this data is available from the beginning but not too specific. It was asked to the shift managers to give more specific data over the production and from August 2017 a new schedule was introduced to collect more data on shift-base. The data of three weeks (each with 5 working days) were collected and suitable averaged on shift-base to be compared with the model.

The first week is the week 31, that is the pre-summer-holiday week; the second week 35 and the last week 37. The choice is not random because it was asked to give a *stable week with an average regular production* (week 37) and two different production situations occurring rarely (week 35 represents the *initializing of production after summer holidays*).

The results, that for the Front Bumper LEV kit are shown in Figure 49 (where real data are averaged and compared with the static model), show that the **static averaging approaches to stable production rhythms**. In particular, blue, red and green bars represent the data of production of weeks 31, 35 and 37 respectively; whereas the violet and spread blue the averaging of real data and modeled. The comparison is offered on shift base, so to show that studying the model on a day-base profile is profitable because one can catch strong variability.

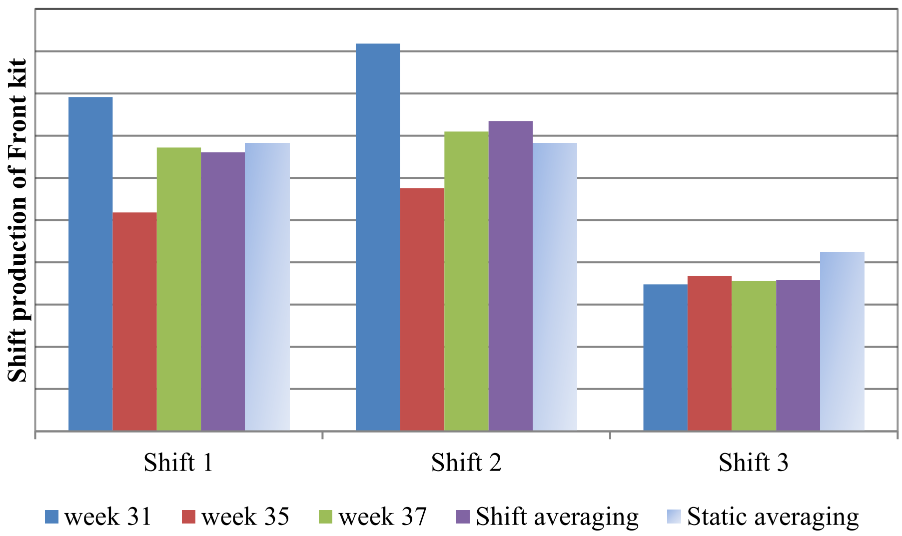


Figure 49 - Comparison of static averaging process with real shift data

From the analysis, it is clear that the week that best-fits the static modelling approach is the more stable one (see green bars and spread blue ones of week 37), but the average of the three weeks through the day is comparable with the static averaging (see violet and spread blue bars, respectively).

The comparison with-respect-to the other kits is reported in Figure 50: each image represents the relative difference between the kits produced in the week (in year 2017) and the kits to be expected by the static model introduced. In the first two images, it is clear that the difference is very high because the weeks in analysis are far from stable production but, fortunately, this occurs rarely.

In particular, for week 31 the MITO production was irregular and not continuous; for this reason the difference is not reported. Whereas the difference of the static model with respect to week 37 is below the 20% for all the kits and, in addition, one can say that the model approaches more to the reality for the second shift for all weeks. Anyway, regarding the productivity of MITO, its velocity can reach different values because the production, actually, **is not continuous** and depends strongly on the Assembly Shop speed.

Definitely, the static model is not able to catch **the variability of the productive asset** different from stable days, but the use of a different approach is unjustified because:

- The real production asset depends on external factors (i.e. sales and accumulation), too difficult to model;
- The impact of internal layout in terms of variable costs is not so important with respect to other projects, so more detail will be useless for the purposes of the thesis;
- The production depends even on plant reliability and so failure timing, variables not easy to treat that require more times and more data collection on field;
- Static approach is simple and allow easily to attain many tasks and approximation for other purposes (see for example 3.1.3.5);

- Static model approaches the reality at least on stable weeks and shifts, allowing the simulation on a credible product workflow, otherwise the use of conservative measures would bring to overestimate the costs;

The use of a model anyway gives a reference behavior of the system that can be usefully used to detect the displacement where internal parameters are changed.

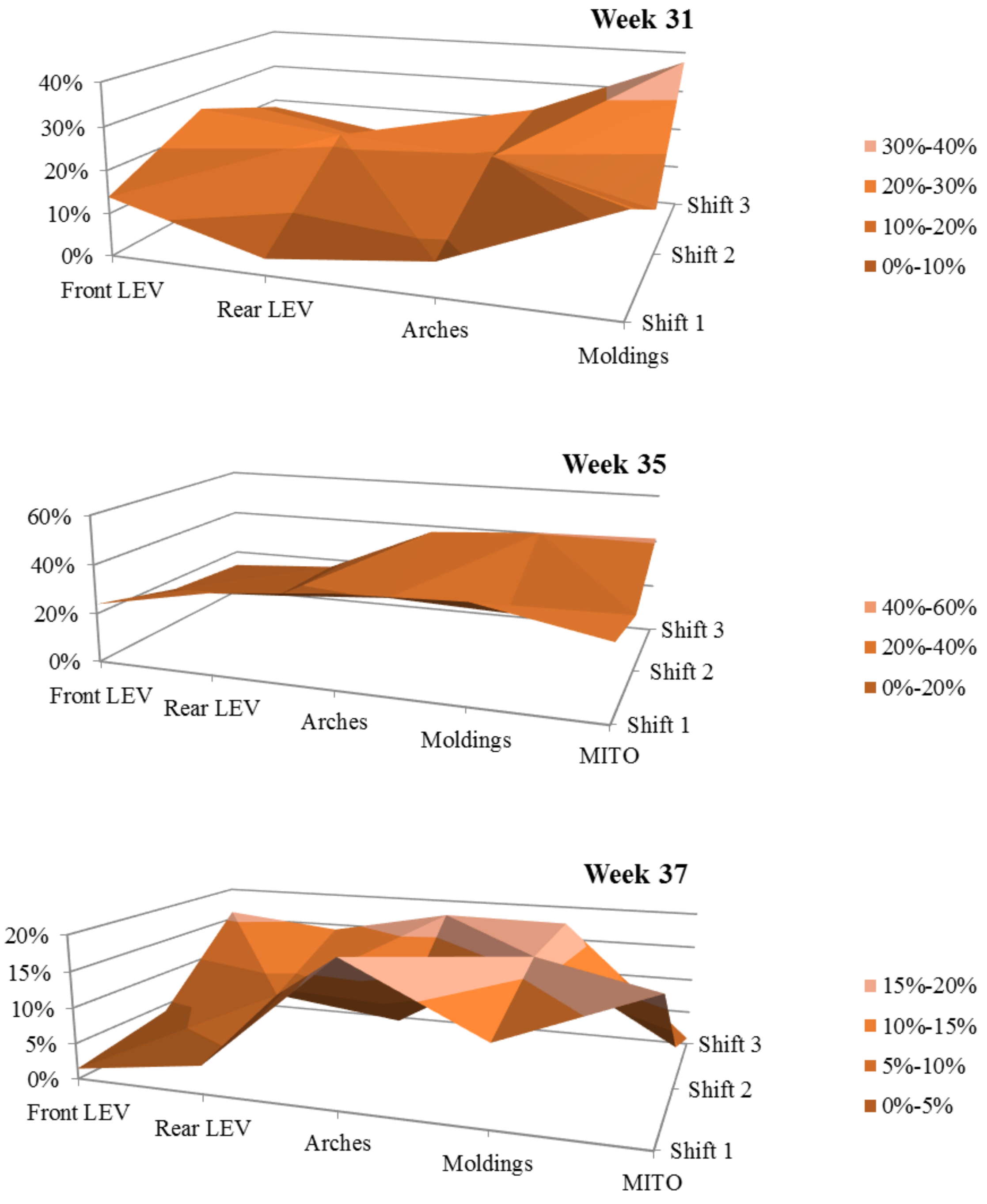


Figure 50 - Comparison of ideal week with real data of week 31, 35 and 37

3.4.2 Gates opening frequency

In this paragraph, using the model and data above mentioned, one wants to calculate the frequency of opening of the two main doorways used in BPS for internal handling (input and output cycle). The starting point is $n_{h,k}$, that is the number of pieces "h" produced in the month "k", estimated with the Equation 42 of the static model from October 2016 up to September 2017. This value is conservative (i.e. higher than real) because it comes out from the data on kits processed in BPS: the refused in fact are moved out of the facility with a different method.

Later, for each month, using the input "$n_{b,h}$" and output "$n_{c,h}$" fragmentation of pieces in boxes and in containers (i.e. reported respectively in Table 4 and Table 5), one can calculate the input and output missions on month base.

The doorways opening frequency is calculated with the following equation, where the number of missions just calculated is divided by the production time in the reference month Θ_k reported in Table 7.

$$f_k = 4 \cdot \frac{\sum_h \left(\frac{n_{h,k}}{n_{b,h}} + \frac{n_{h,k}}{n_{c,h}} \right)}{\Theta_k} \qquad \left(\frac{times}{h} \right) \tag{44}$$

Such value is multiplied by four for two reasons:

- As in the static model, for the no-contemporaneity of available items to be moved, input and output cycle can be divided in two steps hence two openings;
- Conservatively one can include the contribution of the remaining openings for other reason (e.g. entrance and outlet of workers in the shifts, intervention of maintenance crew).

3.4.3 Traveling model for movimentation means

The traveling path and its cost is treated similarly for any kind of mean considered: forklift, bull, workers and AGV (Automated Guided Vehicle). The base difference is into the "**safety coefficient BF**" that summarizes its efficiency and reliability: the error to be considered as burden factor for a mission is larger for workers than for driverless vehicles.

Considering the scheme in Figure 51, a "mission" is the act able to load from one position (A) to another (B) a box (in blue) and later to unload the vacant back. It can be divided into two fractions: "input cycle" and "output cycle" correspondingly. The ideal mission is so characterized by two points distant "d" between the starting position of the box and the requested location, the same distance "d" is so traveled 4 times: two for the input cycle and two on the output cycle. This assumption is done as conservative distance in order to represent the no-contemporaneity into the availability of vacant box soon after a load cycle.

This approximation is coherent with true reality of an internal layout asset, since the forklifts/bulls/AGV tends to alternate the input phase of a product with output phase of another available one: fortunately, for the case in analysis, the distance d is common to all products treated in the manufacturing activities, meaning that the mean is always on the same path and there are not time losses into the redefinition of the destination at each product-change.

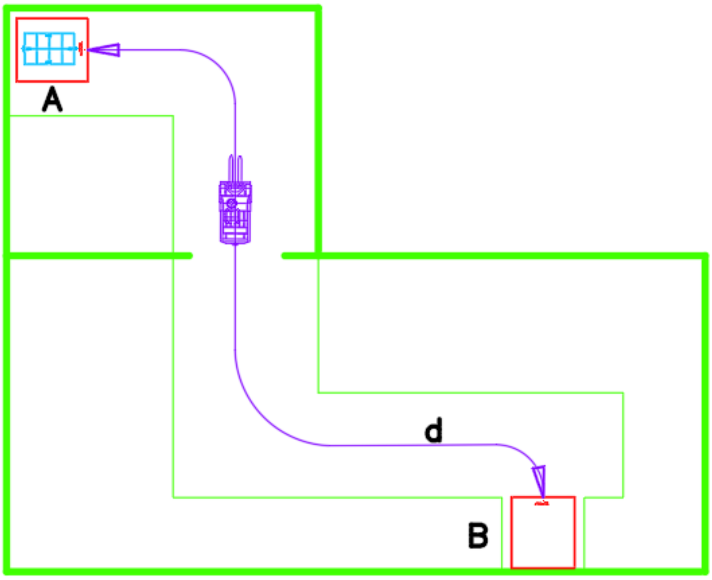


Figure 51 - Scheme of base travel from position A to B of a box along a path of length "d"

In equations, per each general **element to be moved "r"** one can determine the time for the input cycle and output cycle separately and later define the overall time for the mission, using a simplification of the equations in [60]:

$$t_r = \left(t_{fi,r} + \frac{d_i}{v_i} \cdot 2\right) + \left(t_{fo,r} + \frac{d_o}{v_o} \cdot 2\right) \tag{45}$$

Where the subscripts "f" stands for fixed times, necessary for the steady phase (i.e. rise of the fork to the correct height, load and unload step); "i" and "o" refer to the input and output cycle, respectively. The velocity is reported with variable "v" and differentiated for the two cycles because with unload mean one expects a faster motion.

$$t_{mean} = \left(\sum_r n_r t_r\right) \cdot (1 + BF) \tag{46}$$

Then, with the calculation of the mission time, on day base, the overall time needed for that purpose (t_{mean}) is evaluated with Equation 46 with the quantities:

- "n_r" corresponds to the number of daily missions for the element "r" defined in paragraph 3.4.1 for boxes (so called n_b), but similarly one can treat workers moving pieces by hand, or for containers;
- "BF" is the safety coefficient associated to the mean in analysis. As said previously, it is higher for human driven vehicles and used on percentage base.

Later, the number of means needed can be designed or evaluated with the upper approximation of the ratio between the t_{mean} and the time devoted to the production t_P (see note[7]) by:

$$n_{means} = ceiling(\frac{t_{mean}}{t_P}; 1) \quad (47)$$

Whilst an interesting factor is the "Saturation factor" of the single mean, expressed as the effective time devoted to the task assigned[21]:

$$SF = \frac{t_{mean}}{t_P} \cdot \frac{1}{n_{means}} \cdot 100 \qquad (\%) \quad (48)$$

The economic part of the movimentation is simply split in three contributions (all in €/h):

- Salary of the worker;
- Amortization cost of the mean;
- Energy cost (and so CO_2 emission) according to the model of the electric mean reported in 3.4.4.

3.4.4 Electric means consumptions

For forklift, bull and AGV the model used to estimate the electrical consumption starts with the matching of battery data duration and information obtained by technical specs. The output power of discharge of the battery is obtained with the following equation:

$$B_{DPR} = \frac{B_C \cdot B_V}{B_D} \qquad (kW) \quad (49)$$

Where B_{DPR} is the discharge power rate of the battery calculated with: B_C is the battery capacity from technical datasheet (in Ah), B_V is the voltage and B_D the duration in "h" of the mean, collected asking to the workers (for the forklift is 19 h, just one working day).

With the value B_{DPR} it is possible to determine the consumption according to the hours of use t_{mean}, hence yearly, and the estimation of variation in layout costs:

$$C_E = B_{DPR} \cdot t_{mean} \cdot n_{working\ days} \cdot c_E \qquad \left(\frac{€}{year}\right) \quad (50)$$

In the above reported equation, the term C_E corresponds to the yearly cost variation in layout management, $n_{working\ days}$ instead is the number of theoretical working days in a year (as reported in Table 7) and c_E the unit cost of energy for electricity (see the value at Table 8). Because the electricity vector is a strong influencer of the cost of maintenance for the layout, even CO_2 emissions are considered with the same formulation used in Equation 13.

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[21] SF is useful in case of design or optimization of logistics layout since it represents the required efficiency from the workers: a low value might indicate that the means is effectively used for small time and can be used for additional purposes.

3.5 Lighting model

The two methods reported in this section aid for an early-stage design of the number of the bulbs to install in an internal area (with rectangular shape) according to the manufacturing task up to definition of consumptions and so potential energy savings. The first starts from the replacement of current installed bulbs whereas the second comes from UNI 10380:1994, that was integrated in UNI 12464-1:2011 [61], to achieve a certain requested Illuminance "I" (in lux).

3.5.1 Total flux method

Considering the overall input lumen flux of current "j" luminance system Φ_{tot}, and the lumen of new proposed single bulb $\Phi_{bulb,i}$, the number of bulbs to be installed is:

$$N_i = \frac{\Phi_{tot}}{\Phi_{bulb,i}} = \frac{\sum_j \Phi_{bulb,j}}{\Phi_{bulb,i}} \tag{51}$$

The quantity Φ_{tot} is in turn calculated as the sum of all the lumen coming from installed bulbs "j".

3.5.2 Utilization coefficient method

According to [61], the value of illuminance necessary to be achieved in Paint shops is known. This is the target threshold to reach with the correct number of bulbs. Considering an area (for example a rectangular warehouse of dimensions $L_a \cdot L_b$) to be illuminated one can determine the distance between lighting system and the workstation "h". With these geometrical quantities and using the following equation, the parameter χ_K is evaluated:

$$\chi_K = \frac{L_a \cdot L_b}{h \cdot (L_a + L_b)} \tag{52}$$

For the analysis, the reflectivity χ_r of the ceiling and walls are needed and assumed with the suggestion of [61] to 0.8 and 0.65 in the half of the reported scale.

Then the "maintenance coefficient" χ_m is assumed to be equal at 0.8 (on unit scale), assuming average maintenance yearly.

The last coefficient is the "utilization coefficient" χ_u, that is function of all the others and reported in tables commonly used in technical reality:

$$\chi_u = f(\chi_K, \chi_{r,ceiling}, \chi_{r,walls}) \tag{53}$$

With all these coefficients it is possible to determine, in case of direct illuminance, the value of bulbs with the following Equation:

$$n_{bulbs} = \frac{I_{residual} \cdot L_a \cdot L_b}{\phi_{bulb,i} \cdot \chi_u \cdot \chi_m} \tag{54}$$

Where $I_{residual}$ is the value of illuminance (in lux) requested by [61] decreased with the contribution of other devices and $\Phi_{bulb,i}$ the lumen flux coming from the single bulb to be installed.

3.5.3 Energy consumption estimations for lighting systems

In the area of BPS, the electrical consumption for lighting is added to the consumption of other electrical equipment installed: so, from the reference global counter it is impossible to go back to the impact of a series of bulbs.

But fortunately, when "Beghelli" lights were introduced in 2010 with the energy-saving agreement described in 1.4.3, in order to correctly quantify the effective use of dimmed bulbs, all devices were provided of wi-fi antenna to communicate with a local PLC that can count hours of operation and electrical absorption.

However, the data are collected monthly in terms of "total hours" and "total kWh" separately for the bulbs type B and C of Table 12:

- "total hours" is the sum of the hours of operation of bulbs of the same type;
- "total kWh" is the sum of the consumption of bulbs of the same type;

Dividing suitably these two quantities for the number of bulbs one can attain the hours of operation per bulb (reported in Figure 52) and consumption-per-bulb.

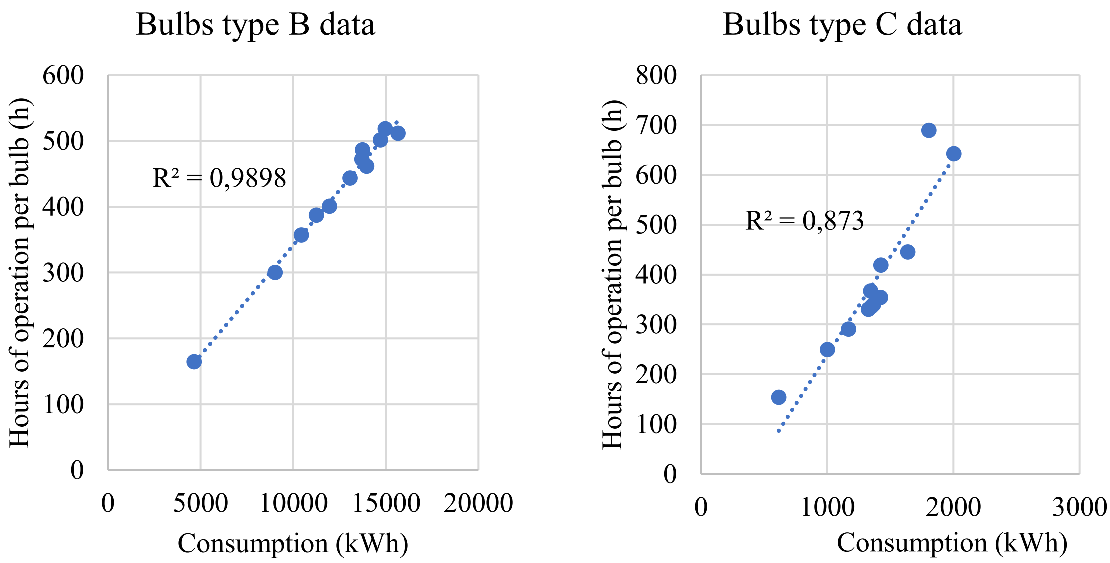

Figure 52 - Data from PLC on dimmed bulbs.

In Figure 52, for the two bulb types, it is reported on the x-axis the overall consumption in kWh (the "total kWh" discussed above, so by dividing this quantity for 500 and 40[22]

[22] The hours and consumptions are distributed equally spaced with the number of bulbs of Table 12 because of no additional data available. Even though, this approximation is accepted, for the sake of simplicity, because

respectively one can obtain the consumption-per bulb in kWh/bulb monthly) and on the y-axis the hours of operation per bulb. The linearity between such quantities allows to consider constant the power output even for dimmed lights.

Actually, by integrating the hours of operation throughout the year, one can note that the value is 5000 h and 4620 h for type B and C respectively: in conservative way it is decided to use 5000 h as reference value for all the next analysis and even for traditional bulbs.

In Figure 53, one can note the trend for yearly hours of operation (corresponding to the hours of bulb type B): this profile will be extended to the building lighting and used to calculate the energy consumption with the multiplication by lighting power.

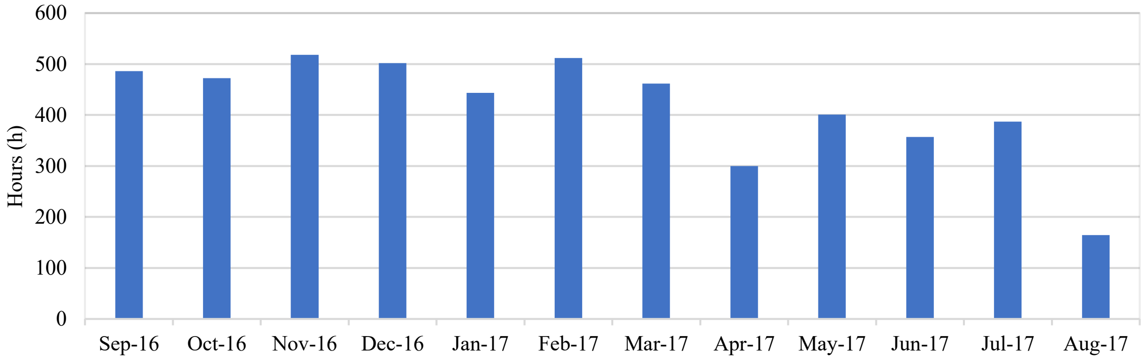

Figure 53 - Yearly trend of turn-on hours for lighting system in BPS

Whereas for dimmed lights, the "total kWh" collected on the PLC and suitably divided for the number of bulbs, brings to the consumptions of 294 kWh/year and 411 kWh/year for each bulb of type B and C respectively.

3.6 Cost scaling methodology

The methodology described below is used to scale the cost of some projects according to a characterizing quantity. For example, in case of re-application of the waterproofing, if the same project is done elsewhere with costs and dimension known, this procedure estimates the updated cost for a different dimension. Assuming a characteristic size S and the corresponding cost C, for a similar project of size S' the cost is:

$$C' = C \cdot \left(\frac{S'}{S}\right)^n \tag{55}$$

This rule is called six-tenth rule because it scales the unit cost according to a specific coefficient "n" equal to 6/10.

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the bulbs are subjected to the same "boundary conditions" in terms of building lighting and guarantee the linear regressions of Figure 52: the scheduling of lighting system in BPS in fact is entrusted to supervisors.

4 Projects design and valorisation

In this chapter all the retrofit measures proposed in Chapter 2 are developed and analysed in the perspective of the considered criteria with the support of design methodologies of Chapter 3. Each project is included in the considered subclass, hence subparagraph, so to split clearly the problems to the area of intervention belonging. The quantitative criteria are evaluated with the modelling techniques or by asking some suppliers in order to reduce the error in assumptions. The list of suppliers is hidden and corresponds, for each kind of activity, to the favourite companies in the local market that usually deal with providing and installing new solutions in FCA Turin plant. For two projects, instead, old bills and reports are adapted to detect the necessary inputs to proceed.

4.1 Thermal projects

4.1.1 Retrofit of building's envelope

In this section are summarized the five projects involved into the reduction of U-values of building's envelope through additional coating and windows' substitution. All the results, related comments of 1D model and provider's information are reported in Table 27 where the last column is devoted to the E+ outputs.

The first column expresses the dispersant element considered (to be improved after the diagnosis of Chapter 2), and in the third the technical solution proposed by the coded Supplier: the alternatives are summarized as footnotes but it is worth to highlight that the considered coating materials are available in the quantity needed and recommended for the specific case. The column "Opt?" expresses whether the optimization tool is used, since for perimetric wall there is no need. The cost of the project strongly depends on the insulation thickness chosen, so the specific and total cost is reported. "Money saving" refers to the economic saving from the intervention as displacement percentage from the current consumptions' costs. The last column reports the comparison with the BEIM technique that is used as in a parametric analysis changing the building's properties and checking the variation in heating requirement.

The first project assumes 5 months as lead time and is considered a technical solution that is economic but not good under the point of view of architectural impact, because internal coating corresponds to a raw finish. The displacement with E+ is negligible because the wall has just three internal edges (see left image of Figure 11) hence thermal bridges have not great impact on the improvement. Differently for the second and the third project listed, where the lack of correction of thermal bridges increases the thermal flow and does not allow the same benefit of a flat model, but overall these differences can be associate to the way E+ treats the addition of a thermal strata.

Table 27 – Technical solutions of projects for envelope's retrofit

Element	Area (m^2)	Technical solution	Opt?	Supp. code	Costs	Money saving	PBT (years)	E+
Wall La Caverna	1'920	Internal coat with mineral wool 88 mm 0.035 $W/m^2/K$[23]	Y	12	66'084 € (34.4 €/m^2)	3.68%	21.3	-3.4%
Perimetric wall	799	Spray polyurethane injection in the 100 mm air gap	N	13	15'980 € (20 €/m^2)	1.24%	15.2	-45%[24]
Workshop roof	10'261	FescoBoard 49 mm 0.05 $W/m^2/K$ and waterproofing layer	Y	2	180'000 € (17.5 €/m^2)	24.4%	8.7	-48%
Paint Shop roof	550	FescoBoard 49 mm 0.05 $W/m^2/K$ and waterproofing layer	Y	2	9'438 € (17.5 €/m^2)	/	6.76	/
Sheds' glass	2'717	Multiwall polycarbonate sheet 25 mm $U_g = 1.3$ $W/m^2/K$[25]	N	14	142'000 € (52.5 €/m^2)	2.8%	51	-7.7%

For the interventions on the roof, the installation time considered is lower, because the surface is flat and a velocity of 500 m^2/day is still conservative including both waterproofing layer and insulation, whereas supply time is guessed as 3 weeks.

Regarding the glass substitution, the frame is not changed because they were installed just in 90s and are made in aluminum sheet: the glass chosen in accordance with the supplier has enhanced thermal properties (low transmittance but high solar transmittance) and already installed in the Plant. The lead time, scaled from a previous installation of the same sheet, is assumed to be 16 weeks because the work can be done only during the weekends.

In each case, the target U-values are not reached because of the inherent thermal properties of the components and for the economic inconvenience.

4.1.2 Improve thermal summer comfort with cool roof

Cool roofs are materials (usually varnishes) that increase the solar reflectance of the surface and its thermal emissivity so to reduce incoming energy and enhance thermal comfort during summer season. This project deals with a possible application of such materials on the workshop (where most of the workers are) analyzing the negative impact in winter mode, where the roof will reflect useful solar radiation acting as a passive cooling

[23] There were overall three technical solutions for this project: Supplier 12 offered even rock wool (optimal thickness 45 mm) but with a PBT higher than 40 years, and Supplier 13 that suggested a Siferite coating (optimal thickness 35 mm and PBT 45 years). The internal coat is a solution that reduce interior finish but brings largely better energy performances.

[24] This great displacement is justifiable in physical terms, but on yealy money saving it accounts to less than 0.5% variation from the 1D model.

[25] Supplier 15 suggested a multicarbonate sheet with a lower energy performance and costs resulting in a higher PBT, so the alternative is not considered.

mean. Being the plant not conditioned during the summer period, the variation in OPEX can be appreciated only in the heating mode that the analysis tries to simulate.

For this purpose, a simple static 1D model on month base, implemented on MatLab©, is compared with the dynamic model of EnergyPlus©. The first approach is taken from [62], where per unit roof surface an energy balance is executed considering all the modes of heat exchange and the material properties. The output of this balance is the winter heat flux per unit surface "q" passing through the roof assumed monthly constant, and according to the sign can be inward or outward (this strongly is influenced by the solar impact).

$$q = \frac{T_{out} + \frac{(1 - \varsigma_{roof}) \cdot G}{(h_{conv} + h_{rad})} - T_{in}}{\frac{1}{h_{conv} + h_{rad}} + R + \frac{1}{h_{in}}} \qquad \left(\frac{W}{m^2}\right) \tag{56}$$

This equation is solved monthly to obtain the heat flux using the following quantities:

- Outdoor T_i and indoor temperature T_{out}, from [48];
- ς_{roof} reflectivity of the roof;
- h_{conv} convective coefficient ($W/m^2/K$) assumed constant as in the static model of section 3.1;
- R thermal resistance of the roof ($m^2 \cdot K/W$), from BPS data reported in Attachment A;
- G Solar irradiance per unit surface (W/m^2) estimated with ratio of total daily solar radiation in [48] and the daylight hours;
- h_{rad} radiative coefficient ($W/m^2/K$) depending on the roof surface temperature and calculated with the following equation.

$$h_{rad} = \varepsilon_{roof} \cdot \sigma_0 \cdot \left(T_{surface}^2 + T_{out}^2\right) \cdot \left(T_{surface} + T_{out}\right) \qquad \left(\frac{W}{m^2 \cdot K}\right) \tag{57}$$

Where:

- ε_{roof} is the roof emissivity;
- σ_0 is the Stefan-Boltzman constant ($5.67 \cdot 10^{-8}$ $W/m^2/K^4$);
- $T_{surface}$ is the temperature of the external surface of the roof, that is unknown but can be found with the following equation iteratively using MatLab©.

$$T_{surface} = T_{in} + \left[1 - \frac{\frac{1}{(h_{conv} + h_{rad})}}{\frac{1}{(h_{conv} + h_{rad})} + R + \frac{1}{h_{in}}}\right] \cdot \left[T_{out} + \frac{(1 - \varsigma_{roof}) \cdot G}{(h_{rad} + h_{conv})}\right] - T_{in} \tag{58}$$

The MatLab© code works on the last two equations up to a convergence with a relative error on temperature below 0.1%: a surface temperature is guessed, the convective coefficient h_{rad} is updated with this value and used again the last equation to determine the new value of $T_{surface}$. Considering the above written equations, the heat flux strongly drops with the increase of roof reflectance ς_{roof} and emissivity ε_{roof}.

The material commonly applied for industrial buildings, and its price quotation, was offered by Supplier 11. So, the code was used on month base assuming a constant heat flux (based on the typical day features) two times: with the current optical properties of black waterproofing layer (i.e. ς_{roof} and emissivity ε_{roof} equal to 0.05 and 0.91 respectively) and the new values from varnish datasheet (i.e. 0.83 and 0.90). The surface considered into the calculation is the overall workshop's roof (i.e. 11'038 m^2).

The resulting heating penalty (suitably increase with HVAC's efficiency of paragraph 3.1.2) accounts roughly at the 11% of heating seasonal consumption corresponding to 8'983 €/year more in OPEX. This value is compared with E+ result where the same optical properties are changed in two simulations (as in a parametric analysis) obtaining the same variation in heating loads: actually E+ estimate just the 3% more as heating load increase. The two penalties resulting from the two approaches are comparable with the one estimated in [40] for industrial user.

The supplier helped into the definition of cost and related technical aspects:

- The installation and supply cost are 7 €/m^2;
- The installation is very rapid, even 1'000 m^2/day, allowing a lead time below 4 weeks;
- For the environmental framework of Mirafiori plant (i.e. a production plant close to a metropolis like Turin) the technical life is below 3 years because dust and pollution rapidly get dirty the white varnish.

4.1.3 Installation of air-delayers

This project acts on the thermal stratification within the building, common phenomenon in facilities with high height. The value of vertical thermal gradient is checked with thermo-inspection in December the 5th 2017 (see photos of Figure 54) on the perimeter of the building resulting in 0.40 °C/m. The temperatures used to obtain such value, shown in the scheme of Figure 55, are taken in four different points of the perimetric envelope, in the order: south-east corner, south wall (far from the doorway), north-west and finally east side.

The average outside temperature of the measurement day was 0°C (because of the snowy weather); note that the temperatures in the photos somewhere are below 18°C because of:

- The subject measured is the wall and not the surrounding air;
- Human and instrument measurement errors;
- Emissivity of the infrared thermo-camera is set at 0.97 (for the user manual considered the emissivity of the concrete).

With this data, the assumption used in next analysis is that the temperature on the ground is 18°C whereas on the roof the value is 23°C. The **method** used to model energetically the building remarks the procedure of paragraph 3.1.3.1 that, dividing the vertical air value in two parts, studies only the **transmission losses** through the envelope. To simplify the study, the external temperature is set constant at 5.6°C throughout the year (because the temperature gradient is available only for a model day), estimated averaging the outdoor temperatures with the heating days of the month.

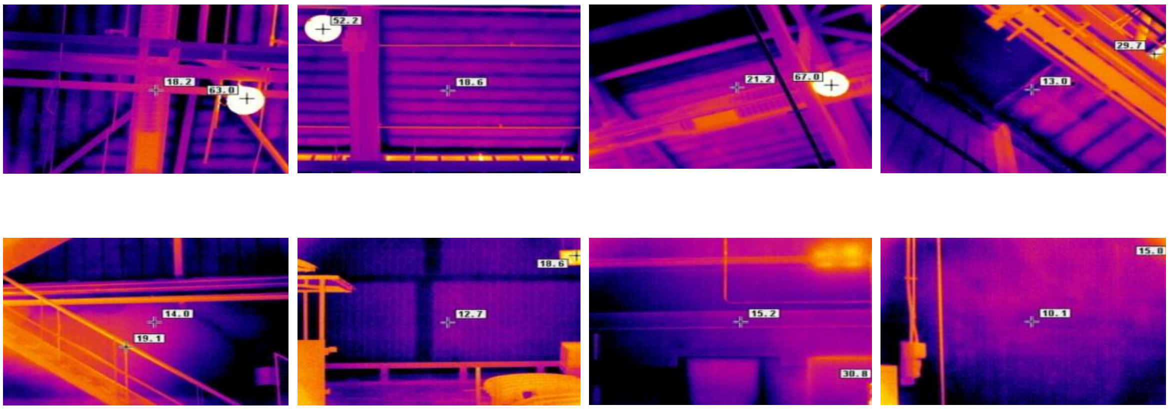

Figure 54 – Thermo-photos of BPS's walls in corrispondence of the four probe measurements. Above the photo of the roof and below of the perimetral envelope.

The thermal flux is calculated element-by-element with Equation 9, but using as reference time the overall length of the month: the money saving dynamically applies even when heating system is off because the thermal dispersion in the upper part of the building contributes more than in a de-layered air volume.

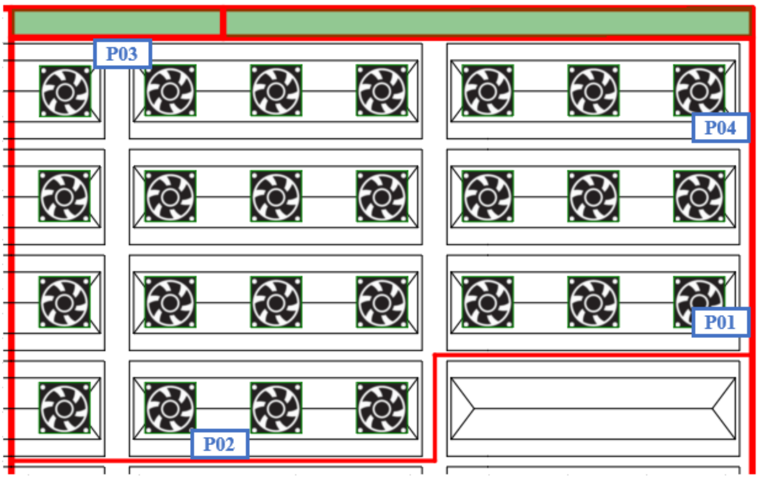

Figure 55 - Schematic views of installation points for air-delayers and measurement probes.

The energy saving is estimated using the difference between the thermal dispersion in the scenario with stratification and without and accounts at 2'332 GJ/year. From this value, one can estimate the money saving conservatively because the real saving is actually **higher** since:

- Ventilation ex-filtration is not considered, and the air flow is even upward for the buoyancy forces from the temperature gradient;
- Burden factors are not considered for dispersant elements.

The price quotation and technical specs of air delayers are offered by Supplier 10, that recommends a device each 400 m^2 (see position in Figure 55) that is a vertical fan of 690 W. So the overall yearly money variation is estimated with both the contribution of thermal benefit and electrical energy cost during the time of operation of the system. The design, cost and installation of the system is set at 6’600 €/fan obtaining 165’000 € as CAPEX for 18’500 €/year as OPEX saving (PBT about 9 years).

The lead time is assumed to be 10 weeks (at least) because there is no Italian producer of such technology. An additional benefit is summer ventilation that can be increased keeping on the fans.

4.1.4 Installation of adiabatic refrigerators

In order to improve thermal comfort during cooling season, it is decided to use adiabatic coolers that have already been installed in Mirafiori Plant in the past. These systems are based on an alveolar membrane that, being invested by a flow of nebulized water and by ambient air, allows a stream giving a different temperature perception in the surroundings. The machine is constituted by a fan and a water tank, therefore it is needed only electrical energy from the grid and the device can be used everywhere.

Being this system already tested in Mirafiori Plant, the number chosen is 3 (see positioning in Figure 56) corresponding to the three-main areas suffering for the warm technological processes, in response to the diagnosis. The price quotation was asked to Supplier 6, that recommended a device with an air flow of 24’635 m^3/h and 1’500 W covering a ground area of 325 m^2. The capital cost is 4’560 €/cooler including the supply and installation. The electrical consumption (and related variation in maintenance costs) is assumed to be estimated for 10 h/days for 55 days/year corresponding to the hottest days of the summer season.

Lead time is guessed to be 40 days and technical life 10 years, according to information from Italian supplier.

4.1.5 Installation of radiant heaters

The purpose of this project is to add an additional system for winter heating in the workstations where many workers complain about the cold from doorways. As for the project shown above, the technical solution is cheap and practical: electrical radiant heaters connected only to electrical grid so to avoid costly hydronic design.

The position and the number of heaters, shown in Figure 56, was chosen according to the suggestions of the diagnosis and of supervisors to support both perimetric and busy workstations. The reference supplier, Supplier 7, recommended a radiator to be installed at a height of 4 m, with a range of 19 m^2 and a consumption of 5 kW with a cost of 560 €/radiator: being just and additional heating system, the positioning is not performed according to the technical datasheet but according to the workstation with a high rate of occupancy. The electrical consumption is estimated guessing 50% of use during the heating hours reported monthly in Table 19.

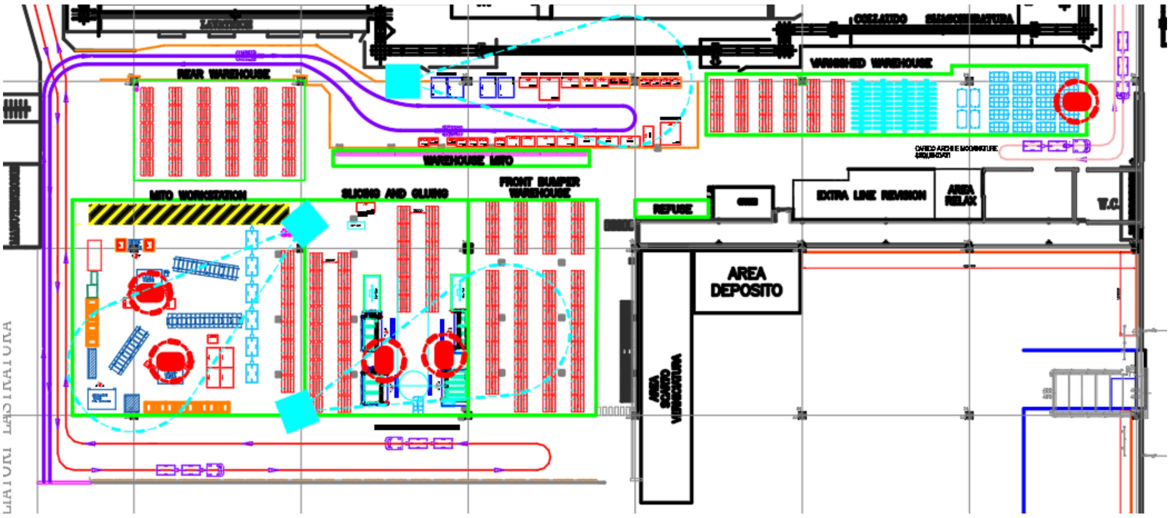

Figure 56 – Possible positioning of adiabatic coolers (in blue) and radiant heaters (in red)

Supplier 7 indicated a lead time of 10 days from the placing of the order, and a technical life of 10'000 hours, meaning more than 8 years.

4.2 Lighting projects

4.2.1 Upgrade technologically building bulbs

The final purpose of this project is the energy saving associated to the substitution of building bulbs (type A in Table 12) with new LED lights of 234 W and 25'000 lumen each[26]. The design methodology used, preserving the overall lumen flux (reported in paragraph 3.5.1), decreases the number of bulbs from 246 to 217 achieving an energy saving of 59 kW. Note that the advantages of this projects are not only economic but even on the maintenance aspects because type A bulbs are old.

The illuminance provided at the ground is 371 lux, calculated with the methodology of 3.5.2 for diffuse lighting: this value is common for the situation ante and post opera.

Regarding the costs, Supplier 8 offered as price quotation the value of 547 €/bulbs and for the installation additional 125 €/bulbs since they are at a height of 11 m: the overall cost (145'000 €) corresponds to a yearly money saving of 35'481 €.

The lead time is divided into 20 days for the supply and 4 days for the installation (1 h per bulb with two installers). Technical life for LED technology is assumed to be 10 years.

4.2.2 Increase illuminance in process area

In this project, one wants to increase the number of bulbs (picking the remaining from the FCA indirect material warehouse) in stations where interviews reported a poor illuminance with respect to to process area. Being in a Paint shop, the effect of a good illumination is

[26] These bulbs (GentleSpace Philips) are chosen because either available for industrial order either still used in Mirafiori Plant for the same application. On economic base, they are the best offer from the Supplier in terms of luminous efficiency. These bulbs from now on are referred as type D.

strongly impacting on visual comfort of workers and product quality: for this reason, in [61] there is the minimum recommended value of 1'000 lux for painting activities.

During the interviews, many workers and BPS manager referred this issue as a wrong design because the workers sometime wrong the pieces to be moved (leading economic losses) and suffer for the difference of illuminance when they move from a station to another. In particular, the area to improve are the three main warehouses, confirmed by a test with luxometer made in October the 12th at 12 AM in a cloudy day with building and process lighting both turned at the maximum power. The measurements, summarized in Table 28, that are done using the luxometer in many points and averaging the results for each station, show that where a technological process occurs the lux increases confirming the interviews. Whilst in the remaining warehouses the value is below the normative threshold (because effectively there is no paint application) but high occupancy.

Table 28 – Average of lux measured in the area during a cloudy day

Product area	**Process station**	**Illuminance measured lux**
MITO	Drilling	1400
	Headlight insertion	1300
LEV	*Rear Bumper Warehouse*	*560*
	Front bumper Warehouse	*490*
	Manual load area	960
	Varnished Warehouse	*450*
	Outline revision	1700

So the purpose of this intervention is to increase the lumen flux (hence lux) in the three warehouses (see Figure 24 for the relative position) whose lighting data are collected and summarized in Table 29. The measure used to improve the lighting is by introducing additional bulbs of the same type from the FCA stock but considering the cost still as a CAPEX.

Table 29 - Current state of poor illuminated warehouses with high occupancy

Warehouse name	**Type B**	**Type C**	**Surface**	**Illuminance measured**	**Illuminance average**[27]	**Total flux**	**Power installed**
			m²	**lux**	**lux**	**lumen**	**W**
Varnished Warehouse	0	22	350	450	443	155'210	1870
Rear bumper Warehouse	12	0	244	560	339	82'620	1020
Front bumper Warehouse	29	0	396	490	504	199'665	2465

[27] This column is obtained dividing the total lumen flux to the surface of the area showing that the utilization coefficient method is simple but useful with regular illumination as in industrial environment.

The utilization coefficient method, illustrated at paragraph 3.5.2, sets as residual illuminance to provide 668 lux (i.e. 337 lux are the base level introduced with building lighting as calculated in 4.2.1 whereas 1'000 lux is the target) and, using the measured geometrical data, obtains as output a displacement in the number of bulbs of 31, 29 and 31 respectively for Varnished, Rear and Front bumper Warehouses.

Using the consumption data of paragraph 3.5.3, the yearly energy extra cost is assumed to be 30'424 kWh (i.e. 3'599 € and 9.13 ton_{CO2} more). Regarding the investment costs, the economic value of this bulbs is decreased with respect to the real purchase in FCA to 72 € and 111 € for type B and C respectively (an extra-cost of 30 €/bulb, considered for the installation because the height is 3 m from the floor, brings the CAPEX to 10'506 €).

The supply time is conservatively guessed to be 2 working days, whereas if 20 man·mins/bulbs are considered, the overall lead time is just less than 3 days (installation provided by two men on three shifts). Bulbs lifetime, i.e. 55'000 h from datasheet, is assumed to be 11 years because of roughly 5'000 h of use yearly (still from analysis of lighting consumption in 3.5.3).

4.2.3 Upgrade technologically process lighting

As for the project 4.2.1, here one wants to substitute all the existing process bulbs in BPS with LED ones in order to obtain a great economic earning. Supplier 8 suggested LED bulbs (type E) with the same lumen flux of bulbs B and C but with almost the half of the power consumption (47 W versus 85 W). This solution, using the method of the total lumen flux, is applied to all the 544 bulbs referred in Table 12 obtaining 547 new LED bulbs. The power difference (-44%) is scaled to the consumption estimated giving a yearly energy saving of 71'859 kWh (corresponding to -8'500 € and -21 ton_{CO2}). Being the cost of each bulb 80 €, and considering additional 30 €/bulb, the CAPEX accounts at 60'252 € and the PBT to 7 years.

Regarding the impact of the installation, under the same assumption of the previous projects, the lead time value is 23 working days and technical life of the bulbs 11 years again.

4.3 Logistic projects

4.3.1 Decommissioning of old hanging conveyors

The hanging corridors to be decommissioned are shown in Figure 57: they were conveyors that moved to the assembly shop products no more treated in BPS. The beneficiary of this project is the internal logistic of the facility because more space will be available for the carryings-on.

Figure 57 - Photos of the hanging conveyors to be removed

These constructions are not cleaned and represent a point of accumulation for dust that of course decreases the product quality. Simultaneously they represent a danger for the occupants because no maintenance is performed. When Maserati Levante was introduced as main product within Mirafiori plant, a pilot area was partially decommissioned (see the rectangle at the cursor position in Figure 58).

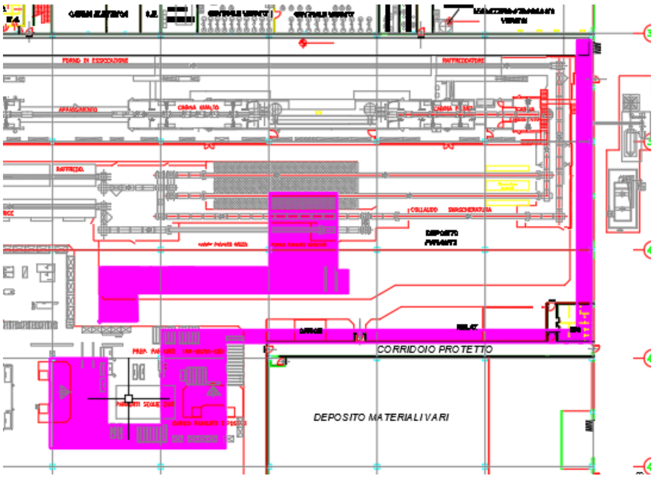

Figure 58 - Projected surface of hanging conveyors to dismantle

From the information of decommissioning's order of the removed part and with an interview with Supplier 5, one determines the cost of the whole decommissioning intervention.

This kind of activity is divided into two parts:

- Decommissioning of the construction;
- Sale of decommissioned pieces and further recovery of investment costs.

The first cost is paid to the supplier, while the second is achieved by the recovery policies. The estimation of the overall cost of the intervention is obtained scaling the cost of the pilot decommissioning. Indeed, the previous construction was 244 m^2 large, the decommissioning cost was 106'000 € and the earning was calculated with the voices reported in Table 30.

Table 30 – Earning after the pilot area decomissioning

CER[28]	Description	Mass ton	Specific earning €/ton	Earning €
17.04.05	Iron and steel	231.5	200	46’300
16.02.14	Expired equipment	3.18	300	954
17.04.11	Cables	2.86	1’384	3’957
17.04.02	Aluminium	1.92	808	1’550

Subtracting the earning from the decommissioning cost one can determine an overall cost of 53’238 €, net of the earning. Note that, thank to the earning, the cost has almost halved.

Under the assumption of uniform construction composition, using the overall cost, the size of the pilot and the size of the new area to be dismantled (1’298 m^2), one can calculate the cost with the cost scaling methodology introduced in paragraph 3.6, obtaining 145’000 € as final cost. The cost calculated for the decommissioning accounts at 560’000 € and it is a realistic value because it was compared with the price quotation of the Supplier 5, which was asked the remaining information necessary for the analysis. The costs are very high because most of the work shall be done by hand without lifting means for problems of internal encumbrance.

The lead time for the project is 5 months, with a full occupancy of the area, meaning that the work is very impacting on the manufacturing cycle.

4.3.2 Substitution of south doorway

The south opening of BPS is defined “bussola” because it is constituted by the series of two rapid doorways (see Figure 11). Each door is constituted by:

- Two proximity sensors to check if the vehicle is in the nearby;
- One electric engine that allows velocity of 2 m/s and 0.8 m/s for the opening and closing, respectively;
- Self-supporting upper beam;
- Mantle in polyester fabric of dimension;
- Electric cabinet and related manual buttons for opening and closing.

In addition, between the two doorways, there is the structure in sheet and plexiglass to enhance visibility and protect from cold air flows.

In a second interview with the maintainers, it was asked which are the specific problems of south doorways (indicated as the most negatively impacting on the thermal comfort because closer to the Mito Workstation) and the response was:

- The path of forklift drivers sometimes intercepts the doorway causing blocks and interventions to substitute the damaged parts;

[28] CER is the reference code for the material of the asset to dismantle.

- Presence of potholes that are un-comfortable for the drivers and increase the refuses;
- The oldness of the structure does not stop anymore the air flows and the dust.

The first bullet leads to think for a new design of the doorway (larger so to reduce shocks frequency) but actually, the doorways frequently have failures for the oldness, as reported on the register on maintenance for year 2016 summarized in Table 31.

Table 31 – Register of maintenance executed on south bussola in 2016

Maintenance in 2016	€/pz	#	€
"Sostituzione cinghie"	40	2	80
"Raddrizzatura lamiera"	100	10	1'000
"Ricablaggio fotocellule"	20	1	20
"Riparazione fotocellula"	100	8	800
"Barre guida piegate"	50	10	500

The overall cost of substitution (2'400 €/year) is widely justified by maintainer and by the other sources interviewed in 2.1.1 but, before the price quotation, a dynamic analysis is offered to choose the right size and avoid accidents with forklifts.

A schematic view of the critical path is shown in Figure 59 where one can detect the operating range needed "r", the distance between forklift's wheels "s" and height of center of gravity "H", data obtained by technical datasheet. The purpose of this investigation is to discover the minimum distance of the doorway's side from the wall so that the forklift does not need to have additional curve within the bussola and can drive a single curve. The distance shall be higher than the minimum radius "r".

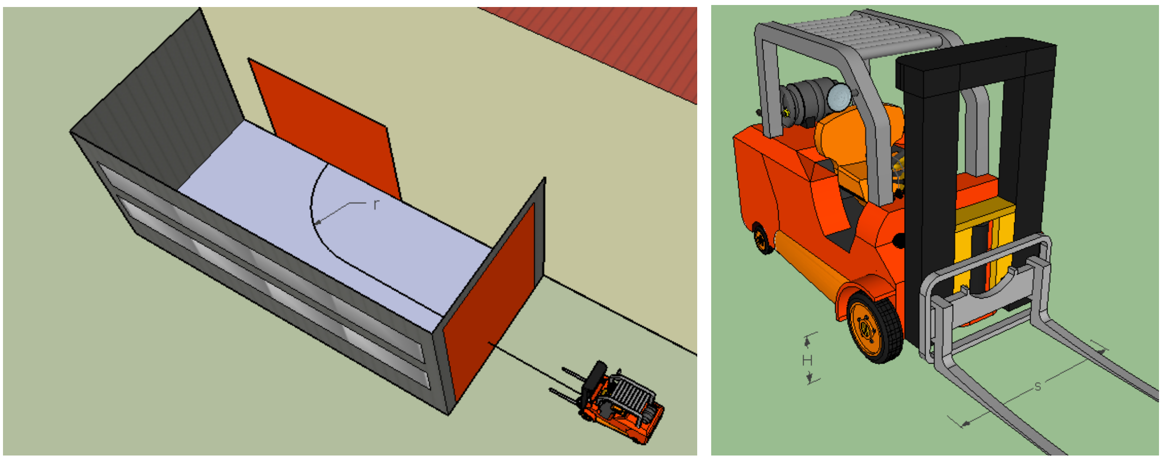

Figure 59 - Schematic view of forklift's path and geometrical lengths used in the analysis

One can express the two mechanical balances of the vehicle. The first is the equilibrium to the forces (equilibrium to the skidding), where the friction forces acting on the wheels shall keep the vehicle stable.

$$f_{fric} \cdot m \cdot g = m \cdot \frac{v^2}{r_1} \tag{59}$$

In this equation, the term f_{fric} is the friction factor assumed to be equal to 0.5 (chosen because the two materials in contact are gum and concrete), whereas "v" is the standard velocity of the load mean (from datasheet) and g the gravity acceleration. The second balance used expresses the equilibrium to the mechanical momentums of the vehicle with respect to the wheels, the rotating point.

$$H \cdot m \cdot \frac{v^2}{r_2} = m \cdot g \cdot \frac{s}{2} \tag{60}$$

Where "m" is the vehicle mass and "s" the distance between the wheels shown in Figure 59. The two equations reported above are solved for the radius "r" with the data collected in Table 32: the results show that the skidding momentum is more influencing because, to be satisfied, requires a higher radius.

Table 32 - Physical quantities used in dynamic analysis of forklifts

Average velocity of load forklift	v	4.4	m/s
Gravity acceleration	g	9.81	m/s^2
Friction factor gum-concrete	f_{fric}	0.5	-
Height of centre of gravity	H	0.49	m
Wheels' spacing	s	0.98	m
Radius from 1st balance	r_1	3.95	m
Radius from 2nd balance	r_2	1.97	m

Considering the largest box's width (2 m), the radius r_1 and a safety additional space of 1 m from the forklift, the required distance of the left side of the first door from the wall is 6 m.

This result justifies that the current dimension of the door is sufficient and does not need any re-design, but the occurrences of accidents have to be decreased with additional training session for the forklift's drivers.

The price quotation of Supplier 4, for the new installation is 29'000 € divided as follows: 500 €/door for the decommissioning, 7'000 €/door for supply and installation whereas 14'000 € for the structure. The technical life is assumed to be 8 years, because the datasheet life is 1'000'000 cycles, whereas daily there are at least 500 openings (from layout analysis in paragraph 3.4.2).

4.3.3 Redesign of internal layout

This project tries to solve several problems listed in the interview phase, according to the internal handling of pieces feeding the process line. In particular, the current layout (see the first scheme in Figure 60) brings:

- High number of crossings for the high frequency of load forklift (violet path) with the unload bull (red path);
- Poor space to stock the additional pieces produced or refused;
- High saturation of forklifts and corresponding possible slowdown of the process;
- The load forklift is forced to pass frequently through the south doorway by a passage in poor condition, causing the reduction of product quality.

The change of the internal layout is already under analysis to catch a good compromise considering cost, safety and flexibility of the operational asset. A possible solution is analyzed in this chapter in economic terms as a renovation measure to solve simultaneously more issues emerged on the production plant. The new proposal, schematized in the second picture of Figure 60, is basically characterized by:

- New load forklift's path, there is no more the passage through the bussola but a new door in the middle of La Caverna wall is opened. The position of the door is strategic because there is less path to do. The box is discharged along the blue vertical line;
- An AGV system is introduced as middle-means connecting the blue station to the process line. There is so the need of workers on the blue line to move pieces from boxes over carts that can be transported by AGV;
- To solve the problem of poor space and create the path of AGV, the Mito Workstation is moved to the Assembly shop. The remaining warehouses are just moved keeping the dimension unvaried.

The economic benefit of the intervention corresponds to the reducing in cost of internal handling that is calculated considering the two layouts and the methodology proposed in paragraph 3.4. Firstly, in Table 33 are listed the assumptions done on each transportation mean and for the additional workers working on the blue station to use in the static model. Fixed times and velocity are estimated measuring and studying the productive processes.

Table 33 - Data and results on means to be used in static model

		Forklift pre	**Forklift post**	**AGV[29]**	**Worker at blue station**	**U.M.**
Fixed times	t_f	100	100	30	10	s
Distance	d	215	35	124	6	m
Velocity	v	2	2	0.833	1.5	m/s
Means		*2*	*1*	*1*	-	#
Safety coefficient	BF	15%	15%	5%	-	%
Saturation		50%	43%	63%	-	%

[29] These data are taken from AGV's datasheet and compared with the relevance of Supply 9 that provided Mirafiori Plant in the past with many installations in Assembly Shop.

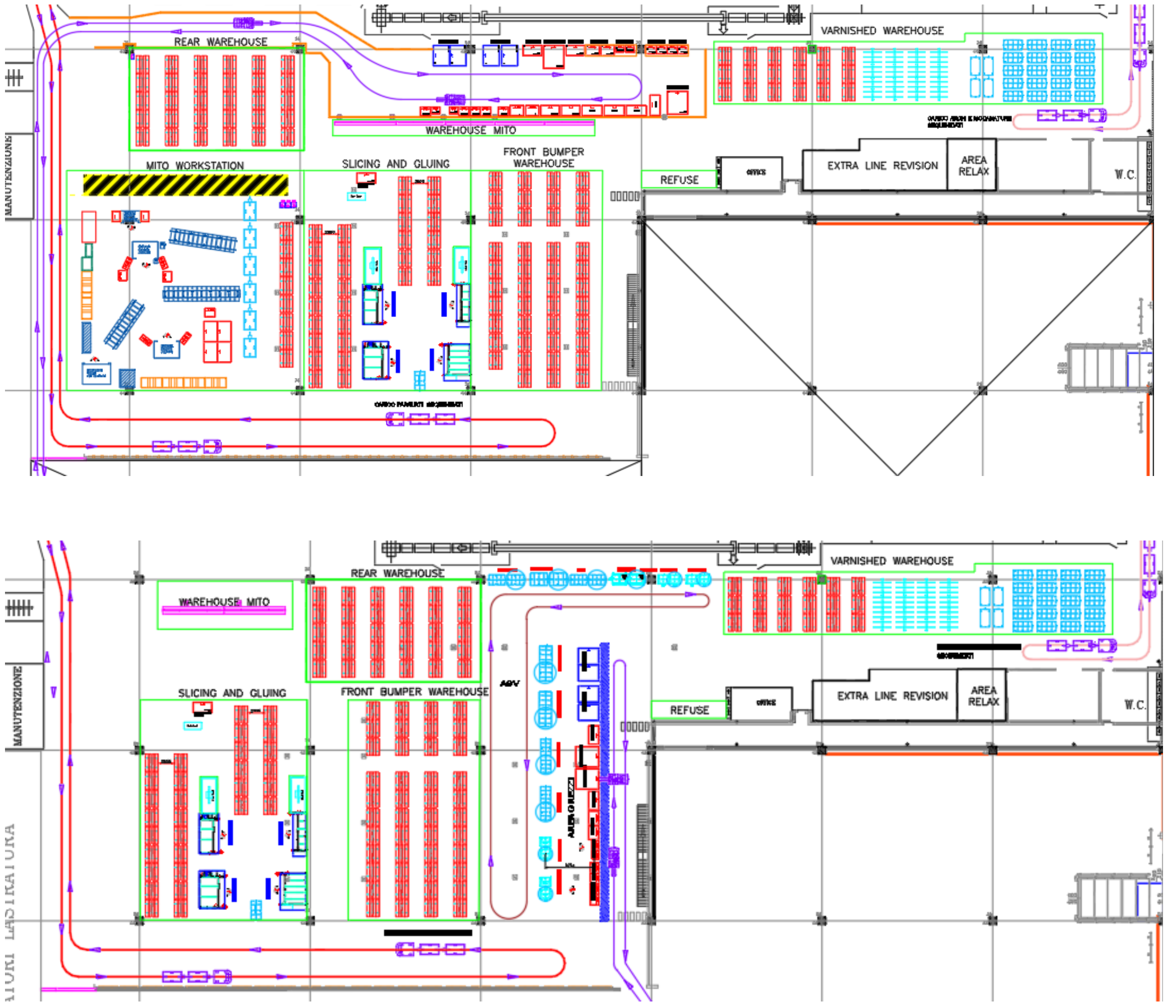

Figure 60 - Current internal layout (above) and proposed solution (below)

The path of the load forklift in the current state is very long because the pieces in La Caverna are disordered, so the middle of the warehouse is considered conservatively. In the post-opera scenario instead, a new doorway is introduced in the middle wall so to reduce this distance up to 35 m on average.

Regarding the load cycle, with the new layout, on 98 boxes/daily corresponding to 392 missions/daily (see calculation of $n_{b,h}$ in paragraph 3.4.1) one can calculate that, reducing the forklift path of 180 m hence the variable time, the daily saving is 9.8 hours. In addition, note that the number of forklift drivers decreases from 2 to 1 with a saturation of 43%.

The next step is to evaluate the extra cost of workers that have to unload the pieces from boxes and put them on the AGV's carts. Once again, they are modelled with a static approach using as parameters the results of measurements on field, the number of pieces in a box and that they can move 1 piece/mission[30] (except moldings and arches) resulting in 8.4 h/day of additional work.

[30] Except for molding and arches because, being light, they can be moved one per hand.

Later, the AGV sizing (i.e. selection of the number of the robot needed) is calculated with a simplified approach of [63] that remarks basically the static model above considered where the fixed times (reported in Table 33) are the load and unload times, again assumed as suggested by the supplier. The AGV's route is a close loop and it is constituted by 20 magnetic tags to stop the robot at the corresponding station. Therefore, assuming a burden factor of 5% and the cart capacity as for the manual transportation carts within BPS, the number of daily missions is 203 that with 1 vehicle are executed with a saturation of 63%.

Table 34 - Economic displacement assumed with the new internal layout for CAPEX estimation

	Hours variation[31] h/day	**Hourly cost** €/h	**Daily saving** €/day	**Yearly saving** €/year
Forklift salary	-9.80	18.75	183.80	44'478
Forklift energy	-9.80	0.17	1.63	394
Forklift amortization	-9.80	1.25	12.24	4'466
AGV energy	12.40	0.02	-0.25	-60
Worker salary	8.38	18.75	-157.17	-38'036

For the economic valorization of the new internal layout, the voices considered are reported in Table 34, and one can note that the energy terms are negligible, even though the AGV is more efficient. Firstly, all the costs are referred to 1 hour, and later scaled to the time horizon of 1 year. The second column of Table 34 reports the daily time saving obtained with the new layout proposed, therefore where the variation corresponds to an extra-cost the saving will be negative.

The worker's salary (the same for forklift's driver) is guessed as 30'000 €/year, value that has to be spread over 240 days/year and 8 hours/day to obtain 18.75 €/h. The energy consumption and related costs of the electric means are estimated with the simple model of 3.4.4, whose results and data are summarized in Table 35. For the AGV the data are asked to the supplier whereas the battery duration of forklift is assumed to be 1 working day as reported by the worker of the charge station of Mirafiori Plant and forklifts of BPS. The amortization of the forklift is estimated with [60] assuming a cost of 55'000 € spread over 5 years and 8760 hours/year. The overall saving achieved is 11'242 €/year considering 240 days/year for the cost elements.

Table 35 – Energy data on electric means used for the economic valorization of the new internal layout

		Forklift	**AGV**	
Battery nominal voltage	B_V	48	24	V
Battery Capacity	B_C	575	70	Ah

[31] These values are obtained from the analysis considering the net timing (i.e. the operation time needed times the safety coefficient) assuming all the modeled elements as in a static workflow.

Battery energy		27’600	1680	Wh
		27.6	1.68	kWh
Battery duration	B_D	19.67	10	h
Average power output	B_{DPR}	1.403	0.17	kW
Hourly cost		0.166	0.02	€/h
Hourly CO_2 emissions		0.421	0.05	kg/h

The investment costs of the proposal, reported in Table 36, value 35’518 € and are estimated taking in account:

- The cost of AGV and its equipment according to information of Supplier 9;
- The cost of the new doorway to open (from Supplier 4);
- The movimentation of the different workstations to be moved. This cost is estimated with logistic engineers assuming 7 men working for 8 hour/days.

The lead time is assumed to be 6 weeks (but clearly the production will stop only during the effective moving phase).

Table 36 - Investment costs for new internal layout

	Specific costs	**U.M.**	**Quantities**	**Total cost €**
AGV	17’500	€/AGV	1	17’500
Magnetic stipes AGV	12	€/m	124	1’488
Magnetic tags AGV	9	€/tag	20	180
Installation AGV	750	€/g	2	1’500
New south doorway	7’500	€/doorway	1	7’500
Warehouses handling	7’350	€	1	7’350

An additional benefit, that is hidden in the analysis, is the increase of free pedestrian area so to enhance the accumulation feature of the plant and even reduce the risk of accidents.

4.4 Liveability projects

4.4.1 New waterproofing layer on the roof

The technical type of sheath, chosen from FCA standard, is made up of bitumen (a mix of plastics) and in between a polyester sheet interposed. On the top of the sandwich, there is a slate strip that has the task of reflecting the UV rays and in this way the bitumen has a slower degradation.

Even this project is evaluated using reports from similar works in Mirafiori Plant because the cost and the relevance depend on the surface type and building height. According to the data collected, the considered cost is roughly 10 €/m^2 and the velocity is 100 m^2/day/worker (by Supplier 2), leading to 104’000 € and 6 weeks for Workshop roof in case of a team of 6 workers.

This solution will decrease the maintenance that intervenes when rain infiltration occurs, whereas the technical life is assumed to be 10 years (still by Supplier 2).

4.4.2 Intervention on HVAC to raise up ACR and thermal control

The scope of this project is to increase the air change rate of the area where most of the people in BPS are, that is the Workshop. Considering the HVAC equipment described in paragraph 1.4.1 and analyzed in 3.1.3.6, one can calculate that in case of no-recirculation (the fraction of outdoor air x_o is equal to 1) the overall air change rate is 3.8 h^{-1}, whereas currently it is 1.718 h^{-1} when the three ATUs are on. The design value, and even more the current one estimated, is low compared to the values to be considered in other kinds of user but note that old industrial buildings with a high volume such as BPS cannot justify relevant cost for mechanical ventilation only to guarantee a volume change.

In this project one evaluates the variation of costs occurring raising up the ACR from 1.718 to 3 h^{-1} considered in FCA as the recommended value for paint shop facilities and introducing a logic controller for the three CTVs.

Firstly, the feasibility is analyzed to check if the thermal batteries can provide enough energy or if they are undersized. For this purpose, it is supposed that the three CTVs process only outdoor air (x_i=0%) and, assuming an outdoor temperature of -8 °C (design condition for Turin from [48]), one calculates the output temperature with the equation:

$$T_m = \frac{G_i}{G_m} \cdot T_i + \frac{G_o}{G_m} \cdot T_o + \frac{\dot{P}_{max}}{G_m \cdot c_p} \tag{61}$$

Where the quantities G are the mass flow rates and, respectively, recirculation “i”, outside “o” and overall processed “m” (called mix flow rate) and $\dot{P}_{max}$ the design power output of the batteries. In this case, the quantity G_i is equal to zero and T_o is -8 °C. The result of this investigation leads to a temperature output of 53 °C for each ATU: being this value widely above 40 °C, the feasibility of this project is confirmed.

Knowing the energy consumption “E” in a heating season, from the analysis in 3.1.1, with and ACR known, it is interesting to determine the new energy requirement “E’” under “ACR’”. So, one wants to demonstrate that “E” is directly proportional to the difference between the output temperature (40 °C) and the “withdrawal temperature” T_p with the following equation:

$$\begin{aligned} E &= M \cdot c_p \cdot [x_i(T_m - T_i) + x_o(T_m - T_o)] \\ &\propto T_m \cdot (x_i \cdot M + x_o \cdot M) - x_i \cdot M \cdot T_i - x_o \cdot M \cdot T_o \end{aligned} \tag{62}$$

Where the variable “M” corresponds to overall mass processed by the HVAC in a heating season (sum of air mass from outside and inside) and T_m the output temperature from the system (assumed to be equal to 40 °C). Below the equation to calculate the withdrawal temperature in order to simplify the previous equation:

$$T_p = x_i \cdot T_i + x_o \cdot T_o \tag{63}$$

Considering that x_i and x_o are complementary, one can simplify the definition of E with:

$$E \propto M \cdot T_m - M(x_i \cdot T_i + x_o \cdot T_o) \propto M \cdot \left(T_m - T_p\right) \propto T_m - T_p \tag{64}$$

With the obtained equation, one can calculate the energy variation with respect to to current consumption seasonally with the direct proportion reported below.

$$\frac{E'}{E} = \frac{T_m' - T_p{}'}{T_m - T_p} \tag{65}$$

The displacement between E and E' corresponds to the energy variation after the intervention to be considered as variation in operational costs (+12'486 € for 93 tonCO_2 yearly increase). These two values are affected by high uncertainty because:

- Updated data on ventilation are not available, so nominal value are expected to be different from real flow rate;
- A fluidynamic model of the circuit is not included so the impact of dampers pressure drop is neglected.

The investment cost (5'670 € by Supplier 3) of this project is associated to two actors:

- Labor cost for the mechanical adjustment of the fixed dampers;
- Supply and installation of temperature probes and PLC for the automatic control of HVAC.

In this way, the ATU can optimize the working point (i.e. increased regulation efficiency) and not depend more on the sensibility of EDF maintainers, but anyway for this project the Pay Back Time cannot be evaluated. The impact on thermal comfort is considered negative during the winter because, in case of battery's puncture, the building will cool down more rapidly, and during summer because warmer outdoor air moves inward. The lead time is estimated to be 1 month because of arrival time of PLCs, whereas the technical life is guessed 10 years.

4.4.3 Refurbishment of dressing rooms

It was asked to Supplier 1 to consider even the renovation of dressing rooms described in 1.5, resulting in 260'000 € as investment cost for 24 weeks as lead time. The impact on workers 'routine is considerable because they have to use the change rooms in "Fabbricato principale" that means to cross the road at the north. The opportunity of a renovation can be useful to switch the rooms in order to have the male one at the third floor, as suggested by a female worker.

The remaining qualitative preferences are the same of bathroom's refurbishment but the architectural impact and on people satisfaction is higher because the relevance of the work is higher.

4.4.4 Refurbishment of workshop bathroom

According to the description and dimension of the bathroom (reported in paragraph 1.5) it is asked to Supplier 1 the price quotation (32’500 €) and the estimated lead time expressed in man hours (i.e. 500 h). Assuming two workers working 8 hours per day per 5 days, the lead time values 6 weeks.

The intervention is necessary because of the oldness of the service and the high maintenance costs, as failures and discomfort occur very often. One determines as null the variation in OPEX because the design is left unchanged. The installation blocks perpetually the utilization of the bathroom, so workers have to use the one at the north part of the building, not causing hardship. Of course, the feedback by the occupants will be positive because 2 interviewed asked for this renovation but ”technical” life of the solution is considered as assumption to be 20 years.

4.4.5 Addition of a smoking room

The adoption of a smoking room indoor derives from the others already installed in the main building in Mirafiori Carrozzeria and the shift manager of BPS says that the 80% of workers are smokers. The same construction concept (octagonal shaped) will be re-proposed here for BPS using as costs and lead time the data from reports referring to previous work.

The building is constituted by an aspirator (to keep at 3’000 m^3/h the air change rate of the room) and a conditioning equipment to be used during the hottest month of the year (1000 W). The aspirator is constituted by an air duct leaving the building and an engine of 750 W.

Guessing the same cost of the room already installed in Mirafiori Plant, one can assume as CAPEX 49’000 € and as OPEX (associated to the yearly ventilation and summer conditioning) +693 € yearly, estimated conservatively with the electric energy requirements during the opening hours. Being an additional room to the facility, it is considered as negatively impacting on maintenance and layout flexibility. The impact on the thermal comfort is negative during the winter (it will remove heat to the space nearby) but positive during the summer because the room represents a way to change Workshop air and a free heat sink.

4.5 Projects ‘matrix database

All the information on projects above described or synthetized are reported in a database referred as “Projects‘ matrix” shown in Attachment E in three tables. In this matrix, each line, corresponding to a criterion listed in paragraph 2.3, and each column, corresponding to a specific project of this paragraph[32], is filled with a qualitative or quantitative values estimated with **numerical models, supplier analysis** or **business knowledge**.

One choses a scale A, B, C, D, E for the qualitative criteria “scores”, where the marks A and E are good and bad respectively, whereas C is a neutral impact. For “degree”, instead,

[32] Particularly 16 criteria and 20 projects for an overall dataset of 320 elements.

the scale is again of 5 elements: from Very Low (VL) to Very High (VH) passing on a medium influence (M). The two scales used are the simplest possible, to allow the DM to have a clear control of the decisional system preserving the comparison between two projects if they are both good or both bad: one can see this as compromise between computational costs and uncertainty on true expectations.

In addition, there are some “grey cells”, meaning that there is uncertainty on the data reported, and “red text”, meaning that the cell is filled with a “dumb value” that is the maximum or the minimum assumed. These numbers are reported to complete the filling and permits a future implementation of MCDA approaches.

Below some comments reading the project matrix criterion per criterion:

- “Variation in maintenance” refers as time horizon to the technical life of the new system introduced or refurbished. The impact is good for the projects on the roof because all of them act on the waterproofing layers indirectly. It is positive even for the lighting projects because lamps currently installed are beyond their warranty time. Instead, the impact is negative if a new system is added in BPS.
- “Thermal comfort” is assumed to be achieved even with insulation of perimetric walls since the accumulation of heat during the day allows a heat release during the night, enhancing the local comfort and reducing the night operating hours and dependence on HVAC.
- The criterion “Impact on the installation phase” can be seen as a compromise between the duration and the closeness of the installation to the process line and further influence on the production velocity. The impact is very high if there is necessity of production stop or if doorways, glass and living areas are retrofitted.
- “Visual comfort” is increased if higher illuminance is provided with lighting projects of with glass substitution, but even with the refurbishment of living areas where the current state does not arouse a pleasant visual perception during the occupancy.
- The project “Increase ACR via HVAC” is assumed as negatively impacting on thermal comfort and not neutral because during the winter, in case of battery perforation and stops, the risk of cold air intake is possible, and during the summer the heat gain will be higher.
- “Indoor air quality” summarizes all the possible improvements on internal air. It is assumed positive for interventions on doorways, waterproofing layer, air delayers (they help in summer ventilation) and for adiabatic refrigerators because they allow a local conditioning by mean of water.
- “People satisfaction” resulting by the interventions is only with positive acceptation, so a simple pair-wise comparison allows easily to fill the corresponding criterion line.
- Technical “reliability” is assumed very high for system with an efficiency and lifetime known or/and if the system is simple and well widespread in the market. For this criterion there is high uncertainty because the effective peculiar use will affect the prediction of the lifetime.
- Even the “duration of the work” is assumed in accordance to the information of suppliers but effectively the values depend on many factors, not easily predictable.

5 Decision Analysis and Portfolio method

This bibliographic chapter provides a brief introduction to the aspects characterizing a decisional process and the corresponding adopted measures to study them. A focus on the historical developments of such disciplines shows as huge is the usefulness to solve different problems type in many environments and contexts.

The roadmap is constituted of three paragraphs with a first attention on the general matter of Decision Analysis (DA), the goal of the methods and a focus on Multi-Criterial Decision Analysis (MCDA) that arises as the most used branch to face with human judgment and varied criteria. The second paragraph tells about an important subfield of DA, the Portfolio Decision Analysis (PDA) that solves multiple choice problems where, as for the case in analysis, the prioritization of interventions is not matched with investment's planning because of complexity among intra enterprise hierarchy. The last section shows the innovative PDA approach adopted for the case in analysis, that is developed and implemented by the Department of Economics and Business, University of Catania (Catania, Italy) to be used in next chapter under the owner assistance. This approach will be depicted under the theoretical point of view marking how the mathematical operators are able to describe this preference model and allow a transparent pathway of decisional flow.

5.1 Introduction to DA and problem type

Decisional problems belong to private and professional everyday life of people: a manager that has to choose the best supplier to develop a partnership with, students analysing university rankings or employees being grouped in classes for a job vacancy. All these delicate decisional problems arise frequently and are often complex to solve because involve several criteria.

Enterprises no longer consider only one criterion (the most common is the price): to start long term relationships, respect sustainable and environmental decisions, activate business policy plans, companies consider multiple criteria in their decisional processes.

The discipline that develops tools to support the decisional processes is defined Decision Analysis (DA): these methods support the decision maker providing stepping-stones and techniques to find a compromise solution where an "ideal" does not exist. The decision maker is placed at the hub of the decisional process where, through the help of an analyst, the subjective information gathered, also known as preference information, are used to obtain the compromise solution. The DA is a discipline that encompasses mathematics, management, informatics, psychology, social science and economics [64].

The DA field was born during the Second World War from the connection of two branches of science: decision theory and system analysis; later, in the 60s, DA evolved in two different parts developing new tools to solve conflicts between objectives, dealing with uncertainty about the outcomes, and evaluation of multiple options.

A typical DA workflow is summarized in the scheme of Figure 61, where a suitable model chosen for the case, has to be improved and revisited until a clear and robust conviction about the certainty on the final action is achieved [43].

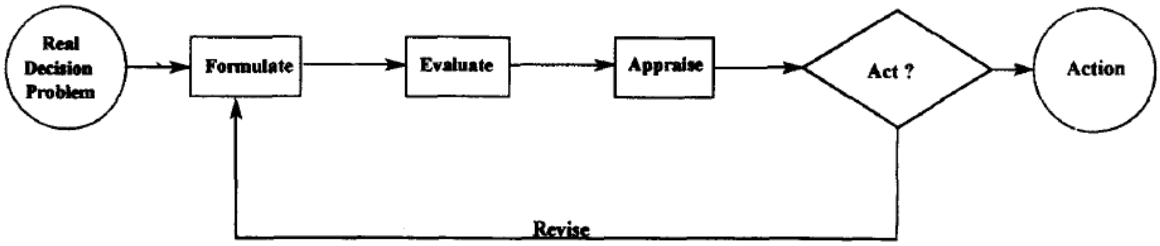

Figure 61 - Logic flow of decision problem from [65]

More in deep, one can consider the flow chart of Figure 62 to understand better the parts of a decisional process: the problem type strongly impacts on the expected outputs that indicate the most flexible approach to model the actual Decision Maker (DM)'s preferences in the so called "Aggregation procedure". The DA algorithm chosen, so, is applied and calibrated by the analyst (i.e. an expert of DA) to the problem in analysis, considering the preference information of the DM who often sees the method as a black box.

In literature, the decisional processes are divided into two cases: "decision making processes" and "decision aiding processes" that actually see two different types of decisional actors. In the first case, there is a Decision Maker (or a few more) that conducts the final decision, whereas in the second case there is no a real person because the one who is asking for help is an organization or an administration that maybe does not want to arrive to a conclusion, but the decision situation is too complex and characterized by multiple stakeholders and decision variables that require an elaborate process of understanding [66].

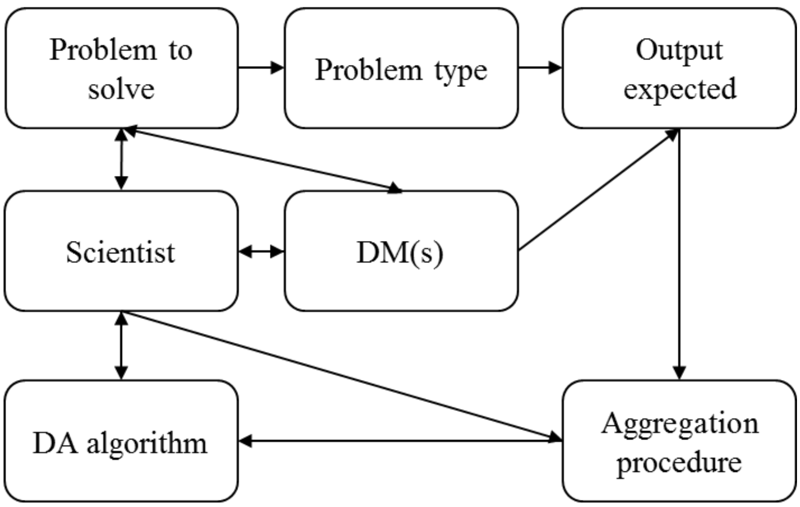

Figure 62 – General framework of decisional process

The first engineering application of DA, carried out in the 60s, regarded the oil and gas utilization, the next extension was in the private industry and lately in the public sector. The field of application in private industry is very widespread and commonly used especially for the energy and environment issues because of the multi objective nature, the complexities, the uncertainties of sources and the risky capital-intensive investments [65].

The kind of problems that scientific studies have engineered, creating suitable resolutive methods, are classified into four types according to [67]:

- The *choice problem,* where the goal is to select the single best option (e.g. an action, a plan or a project) or reduce the group of options from a subset of equivalent or incomparable 'good' options. For example, a manager selecting the right person for a particular project or for a job vacancy.
- The *sorting problem,* where the options have to be sorted into ordered and predefined groups with similar features, called categories, for organizational or predictive reasons. For instance, employees can be evaluated for classification into different categories such as 'outperforming employees', 'average-performing employees' and 'weak-performing employees'.
- The *ranking problem,* where the options have to be ordered from the best to worst by means of scores or pairwise comparisons. A typical example is the ranking of universities according to several criteria, such as teaching quality, research expertise and career opportunities.
- The *description problem,* where the goal is to describe the options and their consequences. This is usually done in the first step to understand the characteristics of the decision problem.

But MCDA community considers even additional three problems, that at the end are a combination of the first four:

- *Elimination problem*, as a particular branch of sorting problem;
- *Design problem*, where the goal is to create a new action meeting the goal of DM;
- *Elicitation problem* that tries to elicit preference parameters for a specific MCDA method [64].

5.1.1 Classification of DA methods

The paper [65] and its upgrade [68] classify the DA's methods used in energy sector according to the scheme shown in Figure 63, where one can note three main families.

The **first branch** is the "Single objective decision making (SODM)" (or "Decision making under uncertainty") that is used where outcomes are uncertain and evaluations of trade-offs are difficult: in other words, where the alternatives are not listed or available and the purpose is to rank them. The mathematical base comes from the Bayesian decision theory. The most common techniques are the Decision Tree, where actions, decisions and events are explicitly emulated in the form of a tree: the limit of this approach is for the inability to treat complex problems because the complexity magnifies the tree. The second approach is via influence diagrams that are characterized by smaller diagram size allowing a simpler modelling of concepts.

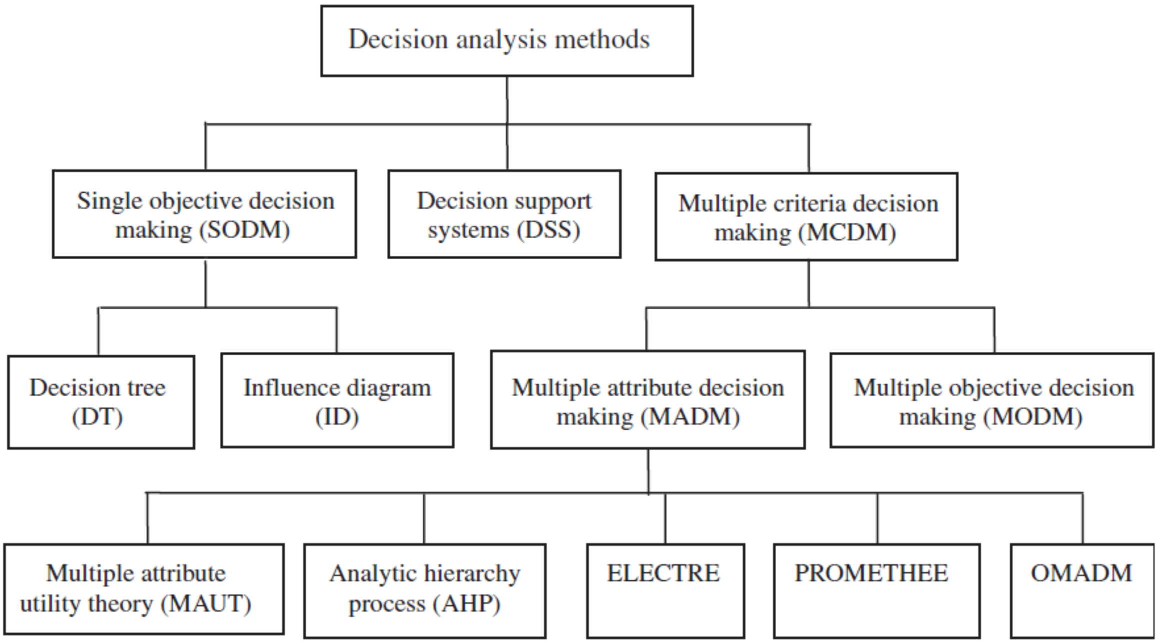

Figure 63 – Tree for DA's classification according to [68]

An additional method that can enter in this class is the "Multiple attribute utility theory (MAUT)" that is the theory to help DMs in assigning utility values to outcomes by evaluating them in terms of multiple attributes and, combining these individual marks, it is possible to obtain the overall utility measures.

The **second branch** is "Decision Support System (DSS)" that refers to decision aiding tools and databases that can be used to support the DM when necessary. This instrument can be profitable in case of unstructured decision problems that are difficult to handle, but sometimes this software is difficult to calibrate: via user graphic interface it is able to explore different strategies, but the user must often depend on personal knowledge and expertise on the problem in order to choose the less wrong parameters in the model.

The **third branch** is "Multi Criteria Decision Making (MCDM)" or "Multi Criteria Decision Analysis (MCDA)", that is the most widespread among the engineering problems and deals with the decision in presence of multiple objectives with conflicting criteria and difficulties in selection of alternatives, incommensurable units and difficulties in design/selection of alternatives, large amounts of information that makes difficult to see heterogeneity into the comparison of criteria. It is useful where social, economic and environmental indicators are compared [68].

MCDA analysis is strongly depending on the interaction with one or more DM **allowing**:

- Aid into the decision process to comprehend better the case;
- Define with higher accuracy the better allocation of sources (e.g. money expenditure);
- Improve the communication among the members of the organization;
- Detect the areas with opportunity to be improved;
- Detect scale of priorities.

Each procedure belonging to MCDM is based on several steps that differentiate according to the method used but are roughly common: definition of problems, objectives and criteria; analysis of the alternatives and criteria's scoring; implementing of the method and final decision. The **advantages** can be summarized in the following bullets:

- Reduction of the uncertainty and risk of the choice;
- Possibility to control the methods selecting different criteria and objectives by the decision makers;
- Transparency of the decisional process flow for internal and external actors.

There are mainly two groups within this class of problems "Multiple attribute decision making (MADM)" and "Multiple objective decision making (MODM)". In MADM usually a small number of alternatives are generated, and these must be evaluated against a set of criteria that sometimes are hard to valorize. Whereas in MODM, the alternatives are not predetermined but a set of objective functions have to be optimized and are subject to a set of constraints.

MADM techniques embrace many methods that have been developed in recent years and that are very spread on scientific field and applied in energy sector. Among these, the most common are: MAUT, AHP, ELECTRE, PROMETHEE and OMADM.

5.1.2 Selection of MCDA approach

As described in paragraph 5.1.1, MCDA is of course the most widely spread technique with many different fields of application and usefulness within the discipline of DA; the selection of the right approach for a specific issue is not trivial but fundamental because:

- It has to face with the major peculiarities of the problem considered;
- It has to provide the outputs required;
- The availability of techniques is huge.

The paper [69] suggests as method to guide in the choice of a multicriteria decision aiding method a list of questions, presented in a hierarchical order, that the analyst has to ask himself when the knowledge of the problem is almost completely defined. The key question is the first one, that will be reported and discussed below [66].

> *"Taking into account the context of the decision process, what type(s) of results the method is expected to bring, so as to allow elaboration of relevant answers to questions asked by the decision maker?"*

The question and the possible answers are reported in the same article but actually the method chosen comes from the second group of questions and of course from the analyst's experience. Five types of possible objective outcome from the analysis are considered, recalling the possible issues of MCDA community listed in the anthem of Chapter 5:

a) A *numerical value* (utility, score) to each potential action listed. This requires that the scale for the evaluation (i.e. the pairwise comparison usually) is numeric;
b) The *set of actions is ranked* (without associating a numerical value to each of them) as a complete or partial weak order. This requires the prior knowledge of potential actions;

c) A *subset of actions*, as small as possible, is selected in view of a final choice of one or, at first, few actions. Even in this case a missing knowledge of action a priori makes these methods unappropriated. This result is also relevant for the "portfolio problem" where additional costs and constraints are added.
d) Each action is assigned to one or *several categories*, given that the set of categories is defined a priori. In this case, the application of the methods is useful to presort the large number of potential actions that are listed at the starting point of the decision process;
e) A *subset of potential* actions enjoying some remarkable properties is provided to serve as a base in the following stage of the decision aiding process (for this purpose, a set of evolutionary algorithm is used to select the best actions among the alternatives where they are more than an hundred) [69].

For every one of these expected outputs, the same source reports the methods specifically implemented, reported in Table 37, that are commonly applied in DA field.

Table 37 – Suggested methods corresponding to the kind of output, according to [69]

(a)	(b)	(c)	(d)	(e)
MAVT, MAUT, UTA, MACBETH, AHP, SMART, TOPSIS, Choquet Integral	ELECTRE, PROMETHEE, ROR, UTA, GRIP, ERA, RUTA, DRSA, Machine Learning approach	ELECTRE, IS, PROMETHEE, Rubis	DRSA, UTADIS, PREFDIS, UTADIS, ELECTRE, PROAFTN, TRINOMFC, PAIRCLASS, THESEUS	Complex interactive multi-objective optimization

5.2 Portfolio Decision Analysis framework [70]

Portfolio Decision Analysis (PDA) can be seen as a subfield of DA because it concerns only the "choice problem type" in case of multiple selection that is to select a subset of projects, called portfolio, from a large set of alternatives considered. Once again, this discipline has a theoretical, methodological and practical base and is particular contributing into the optimization of resource allocation.

The definition of PDA remarks well the usefulness and the goal of this discipline that has historical roots back to the 50s:

> *"By Portfolio Decision Analysis (PDA) we mean a body of theory, methods, and practice which seeks to help decision makers make informed multiple selections from a discrete set of alternatives through mathematical modelling that accounts for relevant constraints, preferences, and uncertainties* [70]*"*

From such definition, three voices can be highlighted:

- Theory, of course the foundation of PDA, postulates axioms that translate the rational decision making that has to be followed;
- Methods that fit the problem type and axioms aiding the decisional process to gain quality;

- Practice that consists in applications where these methods and real decision problems, involving DMs, are deployed as in this thesis work.

Portfolio Decision Analysis, derived from the Italian word "portafoglio", which is derived from Latin "portare" and "folium" (i.e. carry sheets), follows the history of decision analysis and operations research but differs because opposes a choice of a single alternative with a set of actions, plans, or projects considering even the distribution of good performances on the whole set of considered criteria. This approach may provide a more realistic representation of projects, hence decision actions or suggestions, because it accounts for possible interconnections between alternatives and possible shared benefits and risks. PDA involves more cases than in a single choice problem because alternatives are analyzed together even though resources are limited, for instance a limited budget, forcing to consider the meaningful portfolio possible.

As in multi-criterial analysis, PDA tries to increase the transparency of the decision making because the use of a methodology allows to structure the decisional process for external actors or stakeholders. As every methodological approach, the portfolio selection can be divided into stages regardless of the specific algorithm: strategic consideration, evaluation of individual projects and portfolio selection [71].

The kind of problem solved by PDA is once again very common in real life application and especially in industry sectors, for instance where all organizations and individuals have the goal of allocate optimally sources or standardize the investments. In Research and Development (R&D) many strains are afforded to choose the better area of investigation or introduce the better products to generate profits or increase productivity. Municipalities allocate public funds to the better social and educational initiatives for their citizens. Manufacturing plants dealing with optimal configuration of their product lines in order to decide which products to make or a manager involved into the selection of football players for a new football team [72].

> *"The availability of resources is typically limited by constraints while the desirability of consequences depends on preferences concerning the attainment of multiple objectives* [70]*"*

In PDA literature, resources refer to financing, time, space or personnel that can have quantitative limits (i.e. constraints), the consequences instead are output of the projects as compromise between benefits and risks, both accepted according to the human preferences of the decision maker. MCDA methods often play a vital role in supporting the portfolio decisional process or for the weighting of criteria: traditionally such problems were solved by MAVT [72].

The paper [73] identifies five portfolio modelling approaches in literature that can aid to best meet multiple objectives while satisfying the problem constraints of resource allocation:

- The "value-cost approach" that is a simple portfolio generation method where the costs of projects are estimated. The actions are then ranked in a descending order of cost and selected until the budget limit is reached, meaning that the optimal use of resources (almost the whole budget) corresponds to the optimal selection.
- The "modern portfolio approach" where the portfolio is achieved with a balance between benefits and risks. The first is measured with a score-based approach, the

second as a variance from such benefit value. The analysis ends with a “frontier”, showing for each benefit the risk expected.

- The **“multi-objective optimization approach”** where the goal is to identify non-dominated portfolio through the interaction with a DM and the setting of portfolio constraints. The subset chosen can be updated on the base of preference information and presented back until a satisfying solution is attained. A portfolio dominated is when another, better in some attribute and at least equally good for the remaining criteria, exist (of course not exceeding the budget).
- The “portfolio decision analysis approach” that combines multi-criteria evaluation and mathematical optimization because of multiple objectives, interactions and resource constraints. The decision makers‘ preferences are obtained with a MAVT function and thank to a ‘what-if’ analysis one can test the robustness of the code.
- “PDA with incomplete information” uses intervals to describe the consequences (for example qualitative thresholds) and related weights in the value model. Optimization is used to identify the non-dominated portfolio of actions with the incomplete information given, where the dominance now includes the weighting process.

5.2.1 Evolution and history of PDA

“Portfolio” is often associated with finance and with optimization models for making external investments (introduced with the Markowitz mean-variance model in the 50s) but PDA uses even no-quantitative data, for example binary variables or qualitative indices (i.e. scores or degree).

Afterward these approaches were used in the 60s for capital budgeting that is intra-organizational investment with antecedents dating the Second World War. Simultaneously, PDA was used for operations research, in environment R&D, in order to plan the optimal distribution of fund for projects or activities and maximize the attainment of predetermined scopes.

Later, in the mid-70s, DA, PDA, MCDA and multi-objective approaches slowed markedly because perhaps organizations became less centralized with less formal planning cycles or because the methods became too much complex to implement and time-consuming: at that time the power of computers was yet too low to manage the high degree of mathematical sophistication behind the complex optimization algorithms. In the late 70s two studies formulated resource allocation decisions as non-linear optimization problems with uncertainty, where the objective function could be assessed as MAUT with mixed integer programming in the framework of major governmental organizations.

In the 80s and 90s, more approaches were developed that exploited differently and heuristically the scoring of projects and DA started to be used by firms, consultants and specialists for real case application in enterprises. Especially in the 90s the portfolio approach gained importance at several major corporations in pharmaceutical industry and oil and gas industry. Large corporations formalized some sort of DA planning process and related DA training and General Motors established PDA as common management, R&D and business units practice. Meanwhile during this period, from a computation point of view, PDA became widespread and user-friendly thanks to the implementation on spreadsheets. From the theoretical point of view, the first forms of "interactivity" with the DM were introduced as fundamental constraints to the optimization problems, starting the approaches of Interactive Multi-objective Optimization (IMO): the paper [71] reported the concept of DSS as translator of DM's preferences and DA's interface throughout the stages of decisional process.

At the turn of 2000, the MCDA and PDA expanded in both public and private sector, of course derived by computer science developments. In particular, it is worth mentioning the usefulness of computing power and visualization technology that permitted a near real-time approach to the portfolio decisional process. New PDA approaches grew as combination of assessment techniques, MCDA, decision trees, optimization algorithms and interactive software for stakeholders' involvement.

5.2.2 Future perspectives and area of improvement

Beyond the large number of applications, the book [70] highlights where scientific community is setting attention for the methodological development and real case applications of portfolio analysis. Actually, the real value of PDA will be realized where organizations institutionalize the use of portfolio analysis as common practice and deliver it by training without the diluting by data management. The topics for future activities can be:

- Transcending levels of organizational decision making: this affects the aspects of intra-enterprise environment where the fragmentation of duty and responsibility leads to a no-interlinked optimization in resource allocation. PDA shall help into define long term strategic investment by "top-down" approach (where the starting point is the description of overall problem and goals [73]) or "bottom-up" perspective that, in turn, is based on the experience on already existing available actions. The second point, starting from departments' issues, inputs are generated and taken forward to higher levels of decision management teams. The tasks of **prioritization, resource allocation, capital budgeting** are closely linked to the managerial decision making and many issues of intra-enterprise tissue: an approach beyond operation research, corporate finance and decision analysis will help into balancing costs, risks and multiple benefits and PDA clearly arises as a transparent methodology based on human judgment to align such requirements [28].
- Interlinking organizations with outer environment to enhance competitiveness towards innovative sectors.
- Advances in IT and software tools: to increase the spreading of these methods in new areas, for instance, to elicit and synthesize information from stakeholder groups. Similarly, PDA can be integrated with IT systems already available.
- Pursuing behavioral research advancement because DA in general is linked with many disciplines: psychology, decision theory, social psychological issues, behavioral biases.
- Enhance facilitation in the use and practice of the methods because the utility is often a significant part of PDA interventions. For these purposes, facilitation skills are already studied with "decision conferences" or workshop setting in many works.

5.3 Dominance-based Rough Set Approach for optimization of multiple satisfaction levels [72]

In this sub-paragraph, one introduces briefly the approach, applied in the next chapter, to solve the portfolio type problem analyzed in this thesis. The method, that is reported in the article in press [72], is implemented in collaboration with the "Department of Economics and Business, University of Catania" and chosen because of its degree of novelty and easiness of application with intra-enterprise environment to solve portfolio type decision making process. The approach enables the decision maker to control the distribution of good evaluations on different criteria over the portfolio considering qualitative satisfaction degrees, allowing to exploit the features of MCDA to portfolio problem type. After the setting of multi-objective optimization problem and a soft screening of the portfolios by DM, iteratively a set of decision rules are induced by Dominance-based Rough Set Approach (DRSA) that can be used to progressively focus the search on the non-dominated portfolios better fitting DM's preferences during the interactive phase. The use of decision rules simplifies the interactive phase because no technical parameters as weights are required and being an understandable form of communication for a real decisional process.

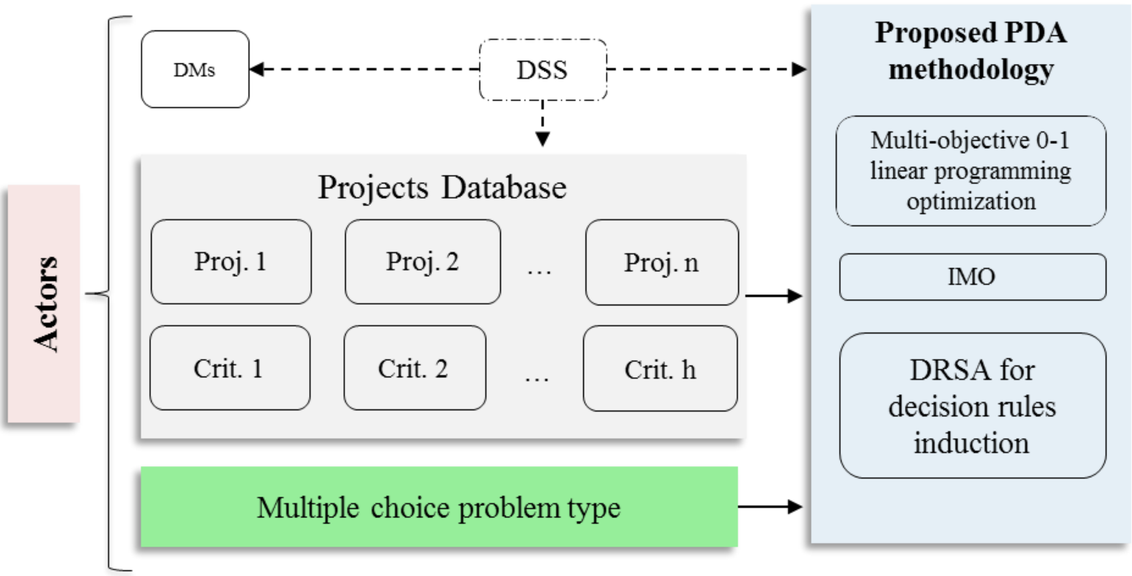

Figure 64 - Diagram of methodological framework for PDA approach

As shown in the scheme of Figure 64, the inputs of such proposed methodology are provided by the physical actor referred as DSS (i.e. the author) that, interactively, behaves as an interface between the decisional tool, the DMs and the preparation of the problem (i.e. calibration of thresholds and satisfaction classes). The four tags reported in the blue box summarize the main features of the mathematical part of the algorithm:

- Multi-objective 0-1 linear programming optimization because in turn the projects will create portfolios under the budget constraints;
- Interactive Multi-objective Optimization (IMO): because the mathematical optimization is supported by soft iterations with DMs through the addition of constraints that iteratively call back the optimizing creation of portfolios;

- DRSA: that is the mathematical foundation of the entire approach, allows the induction of consistent decision rules on the base of non-dominated portfolios previously built. Such "if … then" rules can be added as constraints to the optimization problem if they match the DMs' preferences.

The **symbology** used below is that of the paper and will be reported separately in the thesis nomenclature because all the theoretical aspects will be extinguished in this chapter.

5.3.1 Definition of multi-objective optimization problem

The starting point for the mathematical translation of the problem is of course the definition of the main sets. Firstly, the set of projects to create the portfolios $A=\{a_1,\dots,a_j,\dots a_n\}$ and the related costs $c_j \in R^+$ (in €); each project $a_j \in A$ is evaluated on a set of criteria $G=\{g_1,\dots,g_i,\dots g_h\}$ supposing that all criteria $g_i \in G$ are monodirectional, meaning that if $g_i(a_j)>g_i(a_k)$ project a_j is preferred to project a_k for each criterion i.

For each criterion defined, the algorithm requires a suitable granulation, so a fix set of quality thresholds L_i is introduced, consisting in G(i) elements: the calibration of the thresholds is performed and, in case, later adjusted by the DSS considering the case application:

$$L_i = \{l_{1,i}; \dots; l_{G(i),i}: l_{1,i} < l_{2,i} < \dots < l_{G(i),i}\} \tag{66}$$

Such thresholds allow the identification of G(i)+1 qualitative satisfaction classes for each criterion i, so that the higher is the class $\varsigma_{t,i}$ of a project (with t=1,…,G(i)+1) the more it is preferred on that criterion.

$$C_i = \{\varsigma_{1,i}, \dots, \varsigma_{G(i)+1,i}\} \tag{67}$$

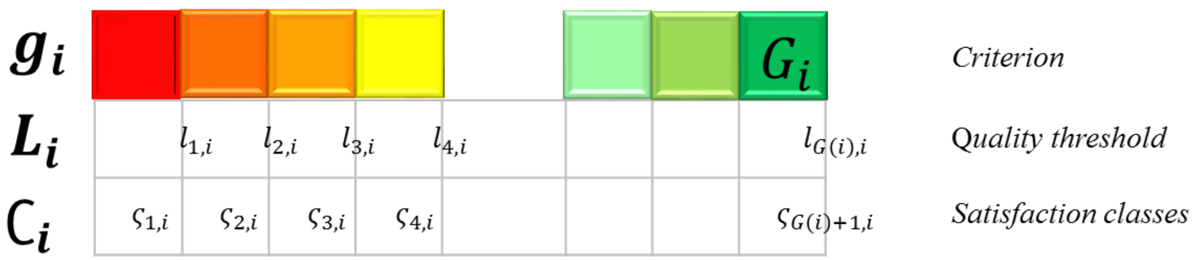

Figure 65 - Visual scheme of thresholds $l_{t,i}$ and satisfaction classes $c_{t,i}$ for criterion g_i

Of course, each project $a_j \in A$ can be assigned to a class $\varsigma_{t,i}$ comparing the value of $g_i(a_j)$ with the thresholds $l_{t,i}$ assuming again scalar ordering as represented in Figure 65 (i.e. fixed preferential direction for the criterion i). The rules can be formalized as follow:

- Project a_j belongs to the first class $\varsigma_{1,i}$ if $g_i(a_j)<l_{1,i}$;
- Project a_j belongs to class $\varsigma_{t,i}$ if $l_{t-1,i} \leq g_i(a_j)<l_{t,i}$;
- Project a_j belongs to the last class $\varsigma_{G(i)+1,i}$ if $l_{G(i),i} \leq g_i(a_j)$;

The mathematical translation of the problem depends on how the DM selects the "marks" to assign for each criterion and threshold levels corresponding to the satisfaction levels expected with the intervention. During the decision process, with the understanding of the decision procedure, the DM can set better the thresholds in order to spread the most equally possible the projects in classes and find satisfactory solutions easily.

Below the definition of the potential portfolio $P \subseteq A$ through the introduction of vector $\mathbf{x}=[x_1,\ldots,x_j,\ldots,x_n]$ such that $\forall a_j \in A$:

$$x_j = \begin{cases} 1, & if\ a_j \in A\ is\ contained\ in\ P \\ 0, & otherwise \end{cases} \tag{68}$$

One can indicate the number of projects included in a portfolio **x** attaining, for criterion $g_i \in G$, the threshold level $l_{t,i} \in L_i$ with the variable $F_{t,i}(\mathbf{x})$ defined as follows:

$$F_{t,i}(\boldsymbol{x}) = \left|\{a_j \in P: g_i(a_j) \geq l_{t,i}\}\right| \tag{69}$$

With this scalar quantity, the optimization problem can be postulated as follows:

$$\begin{aligned} &\max(F_{t,i}) \quad \forall g_i \in G,\ \forall l_{t,i} \in L_i \\ &subject\ to: \\ &\sum_{a_j \in A} c_j \cdot x_j \leq B \end{aligned} \tag{70}$$

The problem is a multi-objective 0-1 linear programming optimization scheme with a fundamental constraint, that is the limiting budget B for each project contained. In words, the algorithm is looking at a portfolio maximizing each satisfaction levels introduced with $l_{t,i}$, meaning that there are overall $\sum_{i=1}^{h} G(i)$ objectives (i.e. the sum of thresholds $\forall g_i \in G$).

5.3.2 IMO-DRSA procedure and decision rules

The first step of the optimization technique is computational, where the goal is to discover a set of $\sum_{i=1}^{h} G(i)$ (not necessarily distinct) weakly non-dominated portfolios that maximize individually each objective $F_{t,i}$ and are guaranteed to be Pareto-optimal, still attaining the budget constraint. Therefore, the final output of this step is the obtaining of a set of $\sum_{i=1}^{h} G(i)$ portfolios that are proposed to the DM: now, the computing phase is suspended and the interactive procedure starts (dialogue phase) so to allow a convergence to the final satisfactory solution. On the base of the searched portfolios the DM can:

- Chose the best portfolio and stop the procedure;
- There is no satisfactory solution in the problem setting, so one proposes to reformulate from the beginning the PDA;
- DM detects some portfolios that are good, so he is asked to classify them into "good" and "others".

In the last case, the algorithm proceeds with the application of DRSA theory to build decision rules so that the DM can selects the ones that best reflect her/his preferences. Such rules include additional constraints to be added to the definition of the main problem. These rules are induced from non-dominated portfolios, for which few words will be devoted below.

The conventional Rough Set Theory (RST) can be applied to "preference modelling" as a set of decision rules obtained by induction. But this classical approach can be used only to solve sorting and ranking problems and not choice problems like PDA because it does not consider preferences. For this purpose, the Dominance-based RSA is introduced as answer to the indiscernibility principle of RST stating that: if project x_a is at least as good as x_b with respect to all relevant criteria considered, then x_a should be classified at least as good as x_b [74]. DRSA, differently from RST, handles better preferences ordered data and real-world decision problem's inconsistencies, due to uncertainty and granularity of the information.

To get closer to the decisional rules, one introduces the concept of dominance for a sorting problem starting from the definition of a finite set of portfolios $\mathbf{X}=\{\mathbf{x}_1,\ldots,\mathbf{x}_j,\ldots,\mathbf{x}_n\}$ and a finite set of criteria $G=\{g_1,\ldots,g_i,\ldots,g_h\}$. For a criterion $g_i \in G$ and two portfolios $\mathbf{x}_j$ and $\mathbf{x}_k \in \mathbf{X}$ one can indicate the marginal preference with the binary relation below.

$$g_i(\boldsymbol{x}_j) \geq g_i(\boldsymbol{x}_k) \tag{71}$$

This expression can be read as "$\mathbf{x}_j$ is at least as good as $\mathbf{x}_k$ with respect to criterion g_i". In addition, one considers a finite set of preference ordered decision classes $\mathbf{Cl}=\{Cl_1,\ldots,Cl_z\}$ such that for all r,s=1…z, if r>s then portfolios from Cl_r are preferred to the portfolios from Cl_s. The number of classes is higher than two (i.e. the right setting for a choice problem) because we are considering as example to discuss on DRSA a sorting problem type.

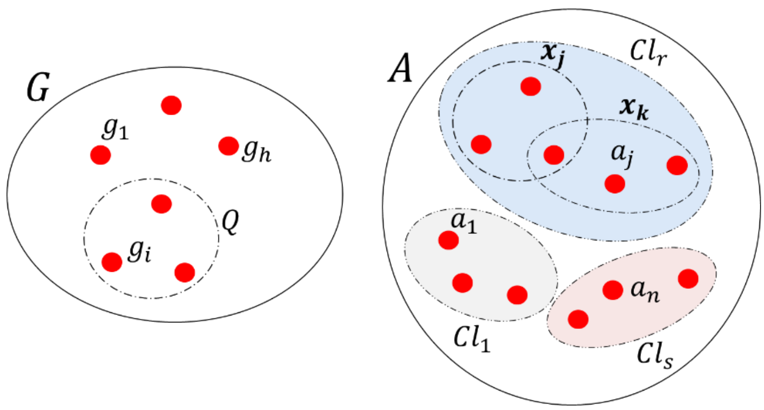

Figure 66 - Graphical visualization of the sets considered for IMO-DRSA procedure

In this perspective, we consider the dominance principle[33]: assuming a subset of criteria $Q \subseteq G$, with the expression $\mathbf{x}_j D_Q \mathbf{x}_k$ one states that portfolio $\mathbf{x}_j$ Q-dominates portfolio $\mathbf{x}_k$ if $\mathbf{x}_j$ is at least as good as $\mathbf{x}_k$ for every criterion of Q, that is $\forall g_i \in Q$, $g_i(\mathbf{x}_j) \geq g_i(\mathbf{x}_k)$. This concept can be extended to all portfolios: for each portfolio respecting the budget constraint $\mathbf{x}_j \in \mathbf{X}$, one can define a set of portfolios Q-dominating with the expression $D_Q^+(\boldsymbol{x}_j) = \{\boldsymbol{x}_k \in \boldsymbol{X}: \boldsymbol{x}_k D_Q \boldsymbol{x}_j\}$ or a set of portfolios Q-dominated with $D_Q^-(\boldsymbol{x}_j) = \{\boldsymbol{x}_k \in \boldsymbol{X}: \boldsymbol{x}_j D_Q \boldsymbol{x}_k\}$.

[33] The dominance indicates how much the portfolio contains good projects on a subset of criteria, formally: portfolio $\mathbf{x}_j$ dominates on $\mathbf{x}_k$ if it is at least good as $\mathbf{x}_k$ for criterion g_i so that $F_i(\mathbf{x}_j) \geq F_i(\mathbf{x}_k)$.

The subset Q of G is introduced because at each iteration a different set **X** of portfolios is evaluated on criteria from a set before the addition of preference information in terms of classification from the DM, allowing the DRSA to elaborate the decision rules.

The next point of dominance theory introduces the concept of lower and upper approximations of a class (i.e. the class good) with respect to a set of criteria $Q \subseteq G$. The lower approximation of class Cl_{good} denoted with $\underline{Q}(Cl_{good})$ is composed of all portfolios $\mathbf{x}_j \in Cl_{good}$ which are not Q-dominated by any portfolio belonging to class Cl_{others}.

$$\underline{Q}(Cl_{good}) = \{\boldsymbol{x}_j \in \boldsymbol{X}: D_Q^+(\boldsymbol{x}_j) \subseteq Cl_{good}\}; \tag{72}$$

Similarly, the upper approximation of class Cl_{good} denoted with $\overline{Q}(Cl_{good})$ is composed of all portfolios which Q-dominate any portfolio with at least one belonging to class Cl_{good}.

$$\overline{Q}(Cl_{good}) = \{\boldsymbol{x}_j \in \boldsymbol{X}: D_Q^-(\boldsymbol{x}_j) \cap Cl_{good} \neq 0\}; \tag{73}$$

With the mathematical setting of the approximations, DRSA can define the "if … then" decision rules that basically describe the **conditions of assignment** of the portfolios to class Cl_{good}. These rules are an aggregator operator and a scenario of causal relationship that, using the DM judgment, drive the analysis:

- Connect the complex interactions among considered criteria;
- Are non-compensatory;
- Come from ordinal scales but do not convert ordinal evaluations into cardinal ones [75].

There are two main types of decision rules that can be used in this algorithm:

- *Certain decision rules* that describe the minimum performances owned by portfolios on selected criteria, in order to assign with certainty them to class good. These rules are induced from the lower approximation class $\underline{Q}(Cl_{good})$ and are of the type "if $g_i(\mathbf{x}) \geq \alpha_i$ and $g_j(\mathbf{x}) \geq \alpha_j$, then portfolio **x** is certainly good";
- *Possible decision rules,* where the same assignment is achieved with doubt. Consequently, these rules are induced by upper approximation $\overline{Q}(Cl_{good})$.

The method elaborates all potential decision rules with the induction procedure that are exponential in the number of criteria, number that, for the application in real decisional context, could be difficult for the DM to handle. For this reason, this algorithm shows only consistent and the **certain decision rules**. The inconsistent rules have a limited impact, in fact they can occur when some portfolios dominated are assigned to Cl_{good} but later, by the procedure, they are automatically assigned to the upper approximation for which are not used to generate certain rules, leading to a correct next presentation of non-dominated portfolios with the remaining information.

With such rules, the DM can select the most representative of his/her preferences and from each one of them a constraint is added to the computational optimization phase, where a new sample **X** of portfolios is generated. The constraints derive from the selected rules chosen and are in the form of "$g_i(\mathbf{x}) \geq \alpha_i$".

Overall, the entire PDA approach is divided in the steps reported in Figure 67 alternating computational phase to the dialogue with DM(s) but remembering that a considering setting of the problem in terms of criteria, thresholds and alternatives has to be addressed a priori. In the flow chart, the red boxes correspond to a computational phase, whereas the blue ones refer to interactive actions to be performed by the DM on the base of the computational outputs.

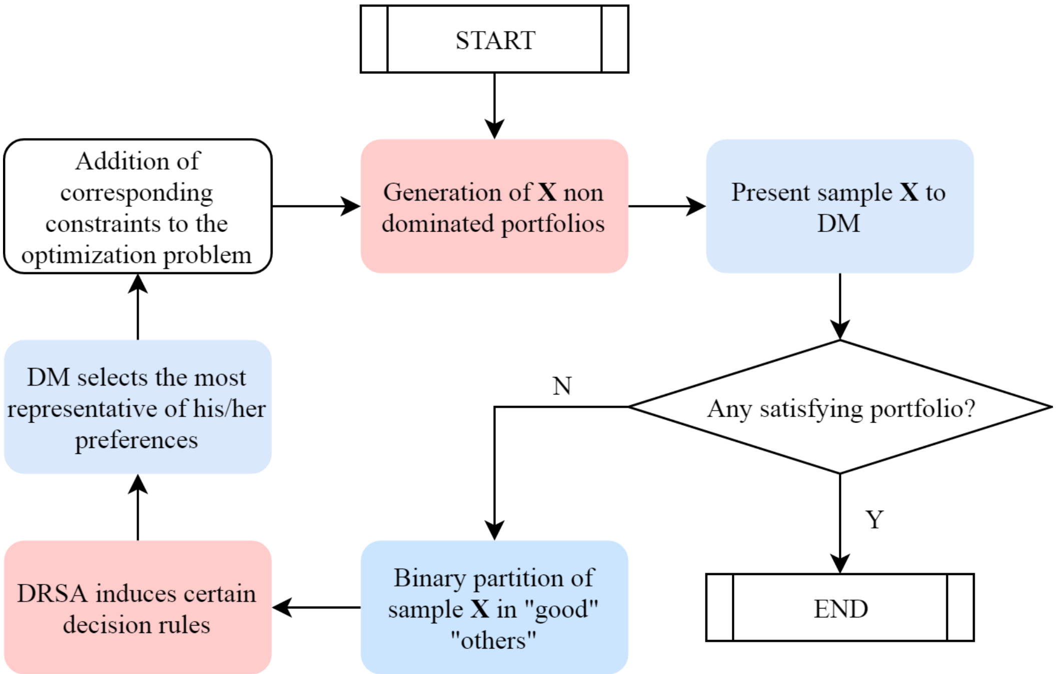

Figure 67 – Flowchart of the algorithm based on IMO-DRSA iteration

The multi-objective optimization procedure in 0-1 linear programming generates an optimal portfolio for each of the $\sum_{i=1}^{h} G(i)$ functions respecting the budget constraint and the qualitative or quantitative score assigned to each project for any criterion. The sample space is presented to the DM who can chose whether stop the analysis because a satisfactory portfolio is detected or indicate which are good.

According to the selection of DM, the DRSA analyses the dominance relations among portfolios belonging to lower approximation of class "good" and elaborates consistent decision rules, that can be in part chosen by the DM as representative of his/her preferences. The chosen rules are translated into mathematical constraints and added to the optimization procedure again, where the reduction of the solution space summarizes the DM's decisional path. The strong interactivity with the DM, so, allows the knowledge and the transposition of preferences.

6 Decisional flow of Retrofit strategy

In this chapter the application of the PDA approach, explained in paragraph 5.3, will be executed to select the best portfolios in accordance to the dataset output of retrofitting projects of Chapter 4. The first part contains the problem setting, allowing the technical aspects analyzed previously to fit the method's constraints: these limits will automatically give a logic shape to the interactive workflow because they consider data collected, solution designed and client's knowledge. The budget equation will be set with a didactic value chosen according to the measures presented, because of low disclosability on company's investments.

Such anticipation elicits that the optimization will be divided in four parallel parts, showing how DM's preferences head the optimum in different directions according to the considered criteria displayed. A final comparison about the portfolios output achieved will highlight more the best projects under different perspectives.

6.1 Optimization problem's setting

Firstly, the threshold levels for quantitative classes are introduced so to spread uniformly the number of projects in classes and avoid imbalances: the PDA approach is able to compare evenly the portfolios and reach earlier a satisfactory solution. As reported in Table 38, the number of thresholds for variation of OPEX are five, four for Emission of CO_2, three for technical life and two for PBT and Lead Time. Considering the thresholds setup for both quantitative and qualitative[34] criteria, one can calculate 57 overall **thresholds** $\mathbf{l}_{t,i}$ $\sum_{i=1}^{h} G(i)$, number that leads to an impacting re-sizing of the problem. With such dimensionality, the problem is not easy to handle by both human and computational part because:

- During the interactive choice of 'good' portfolios, the DM(s) will receive a matrix with 57 columns, compromising the capability to compare the set of projects;
- From a computational point of view, the implementation of DRSA requires the "power sets" of criteria (i.e. the combination of all possible sub-criterion for threshold) that is a set with cardinality 2^{57}, number that raises too much computational costs because corresponds to the dominance checks to be done at each iteration.

The solution to such problem can be to split the optimization into parallel procedures so, in order to have a maximum of 20 thresholds each, the analysis will be conducted by optimizing a subset of criteria per time and the division in clusters will allow a first detection of such drivers. The sub-criteria chosen for each optimization are reported in Table 38 marked with a "X", keeping the sum of total $F_{t,i}$ below 20 (see last row of the table). In detail, the economy optimization considers all the economic criteria in the cluster "economy" whereas, for the other three procedures, an additional direction is added.

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[34] Excluding the investment cost, the overall number of criteria is 15 for 57 thresholds instead of 65, because some projects does not use all the classes initially considered for "scores" type

The comfort decision-process includes even the people's satisfaction as general expression of appreciation for the proposed scenario. "External image" optimization considers all criteria concerning the possible interactions with outer factors, for example people's satisfaction because of trade union aspects, much felt within manufacturing environment, and technical reliability of the action adopted as meter of progress among the wide common and standard solutions. The technical optimization includes even the maintenance impact as intensifier of technical reliability.

Table 38 - Optimization drivers to face dimensionality issue

									Optimization drivers			
Clusters	**Criteria**	**Objective**	**T1**	**T2**	**T3**	**T4**	**T5**	$l_{t,i}$	**Economic**	**Comfort**	**External.**	**Technical**
ECONOMY	**Variation of operational costs**	min	-15000	-5000	0*[35]	1000	7000	5	X			
	Pay Back Time	min	10	30				2	X			
	Variation of maintenance operation	A	A	B	C*	D		4	X			X
	Impact of the installation phase	VL	VL	L	M	H	VH	5	X			
COMFORT	**Visual comfort**	A	A	B	C*	D		4		X		
	Thermal comfort (heating season)	A	A	B	C*	D		4		X		
	Thermal comfort (cooling season)	A	A	B	C*	D		4		X		
	Indoor air quality	A	A	B	C*			3		X		
SOCIAL & SUSTAINABILITY	**People's satisfaction**	A	A	B	C*			3		X	X	
	Visual impact	A	A	B	C*	D	E	5			X	
	Emission CO_2	max	-15	0*	10	50		4			X	
TECHNICAL	**Reliability**	VH	VH	H	M	L	VL	5			X	X
	Technical Life	max	5	10	20			3				X
	Duration of the work (Lead Time)	min	5	15				2				X
	Layout flexibility	A	A	B	C*	D		4				X
								57	*16*	*18*	*17*	*18*

[35] The asterisk "*" means that the value considered is a tradeoff point, for example a 0 for quantitative approaches or a neutral value for qualitative.

The **budget constraint** is satisfied assuming a didactic cost book in view of the overall projects' costs depicted in Figure 68. The first diagram is obtained sorting in increasing order the costs of the 20 measures, while the second calculating the cumulative of the previous chart. Having the most expensive project a cost of 260'000 €, such value must be used as down limiting value for the total cost book, while 1'500'000 € as up value, being the sum of all projects costs.

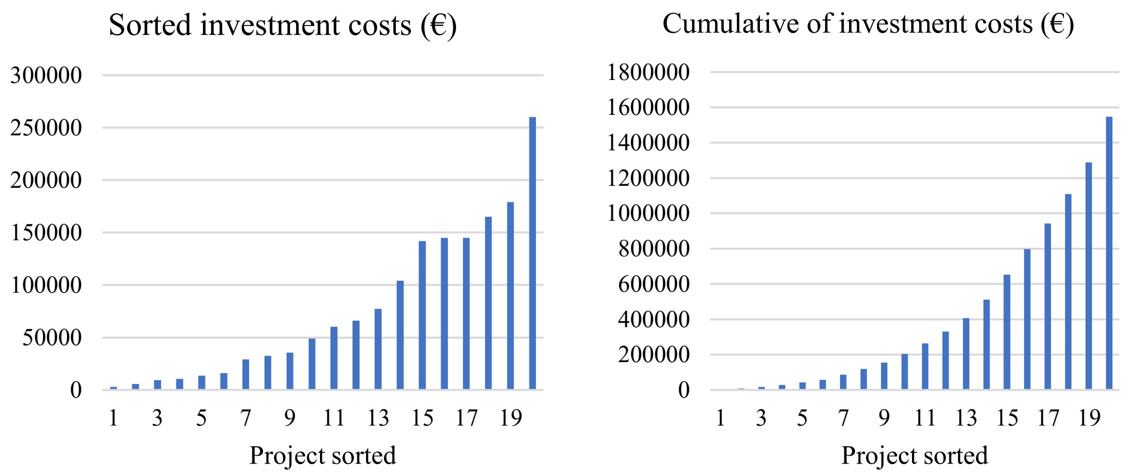


Figure 68 – Bar charts showing the costs state of all projects

The **budget** initially chosen is 400'000 €, covering the 60% of cumulative, that is 12 projects with the lowest costs; to support the DM during the analysis few adroitness are taken:

- Each project is coded with a reference number and a mnemonic name reported in Table 39;
- The equal portfolios generated are not shown for brevity, but only the different ones with the name and overall cost;
- At each iteration is shown a table with the satisfaction thresholds attained by different portfolios and its visual chart with an asterisk "*" indicating the neutral threshold (tradeoff point), if any.

Being the procedure finalized to didactic scope, the interactive phase of the algorithm was executed with the support of supervisors of building engineering, referred later as DMs, by short sessions where the outputs were shown, and decisions gathered. In detail, to avoid influences and interferences among the four optimizations (in terms of criteria) each request was separated temporally, e.g. during the morning the inputs for economic analysis were requested while during the afternoon the inputs for the comfort optimization. The DMs were aware of the single projects because of knowledge of the whole Mirafiori plant and improvement measures necessary for each area.

The four optimizations are offered separately up to the final convergence, while in the last chapter a discussion about the optimal measures is presented.

Table 39 - Coding of projects for interactive phase

Type	Name	Number	Simultaneity[36]	Code	Cost (€)
Thermal projects	Insulation of the confining wall with La Caverna	1		Ins. Caverna	66’000
	Insulation of perimetric wall	2		Ins. Perimetric	15’980
	Insulation shop office roof	3	A	Ins. Roof	179’157
	Insulation paint central roof	4		Ins. PC roof	9’438
	Cool roof	5		Cool roof	77’266
	Installation of delayers	6		Delayers	165’000
	Adiabatic cooler for microcooling	7		Coolers	13’680
	Radiant heaters for microheating	8		Heaters	2’795
	Substitution glass for sheds	9		Glass	142’000
Lighting projects	Substitution environment lighting with LED	10		Env. light	145’000
	Upgrade process lighting increasing lux	11	B	Add pro. light	10’506
	Upgrade existing process lighting with LED	12	B	Up. pro. light	60’252
Logistics projects	Demolition of hanging conveyors	13		Demolition	145’000
	Refurbishment doorway south	14	C	Doorway	29’000
	New warehouse layout	15	C	Layout	35’518
Liveability projects	Roof waterproofing refurbishment	16	A	Waterproofing	104’000
	Increase of Air Change Rate	17		ACR	5’670
	Refurbishment dressing rooms	18		Dressing room	260’000
	Refurbishment bathrooms	19		Bathroom	32’500
	Adding a smoking room	20		Smoking room	49’000

6.2 Starting optimization

6.2.1 Economic optimization

The analysis started with the presentation to the DMs of the visual satisfaction achievements for the first iteration reported in Figure 69. The DMs in this case, as in all the next analysis, stopped on the most relevant criteria after understanding the meaning of the charts, that to clarify the procedure will be explained below.

[36] The projects marked with the same letter cannot be in the same portfolio because represent contrasting alternatives. These constraints will be added in the optimization procedure.

The 3D charts show for each criterion, for each satisfaction class and thresholds $F_{t,i}$ reported in Table 38, the number of projects satisfying at least each level for any portfolio x_n generated during the multi-objective optimization. Originally, 16 portfolios were generated[37] but only 6 are different.

Throughout the economic analysis the DMs stopped on the first three criteria reported, that are 'Variation of OPEX', 'PBT' and 'Variation of maintenance operations'. From the chart and the corresponding matrix of Table 41, four projects were pointed out: x_1, x_2, x_3 and x_6, being the first and the last interesting under the perspective of maintenance (the second has even a flat behavior on PBT, meaning that all projects satisfy maximally the criterion).

After this step, the DMs was presented Table 40 where all the projects were shown and coded by symbols of Table 39, here reported just by numbers for brevity. Only portfolio x_2 and x_3 were chosen among the four initially considered.

Table 40 – First iteration economic optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	12	14	16	17	19	20	388'315	?[38]
x_2	1	2	4	7	8	10	12	15	17	19		386'833	good
x_3	2	4	6	7	8	10	11	14	17			397'069	good
x_4	1	2	4	5	7	8	11	14	16	17	19	366'835	
x_5	2	4	7	8	10	11	14	16	17	19		368'569	
x_6	2	4	5	7	8	12	14	16	17	19	20	399'581	?

The portfolios presented in the first iteration had a similar behavior under the point of view of installation impact, being even a not interesting criterion, whereas x_2 clearly showed as very well optimized by the point of view of PBT, and x_3 by OPEX. Projects x_6 perhaps was chosen because of its levels of PBT and maintenance but discarded later because it contains too much projects considering comfort (e.g. cool roof, coolers, heaters, doorway, waterproofing, ACR, bathroom and smoking room).

[37] At each iteration a set of portfolios is generated in number equal to the number of satisfaction thresholds. Iteration after iteration the number of different portfolios will be different up to a convergent solution satisfying all constraints, that stop the procedure.

[38] The question mark will be used in the table with optimized portfolios to indicate the discarded ones after the first visual screening.

Table 41 – First iteration economic optimization: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	**F_{11}**	**F_{21}**	**F_{31}***	**F_{41}**	**F_{51}**	**F_{12}**	**F_{22}**	**F_{13}**	**F_{23}***	**F_{33}**	**F_{43}**	**F_{14}**	**F_{24}**	**F_{34}**	**F_{44}**	**F_{54}**
x_1	10	9	7	1	0	4	2	11	7	5	3	11	11	7	2	1
x_2	9	8	7	3	1	6	4	10	6	4	1	10	9	6	2	1
x_3	8	6	5	2	2	4	3	9	5	4	1	9	9	6	2	1
x_4	9	7	6	0	0	3	1	11	8	5	3	11	11	6	3	1
x_5	9	7	6	1	1	3	2	10	7	6	3	10	10	6	2	1
x_6	9	8	6	1	0	3	2	11	7	5	3	11	11	8	3	1

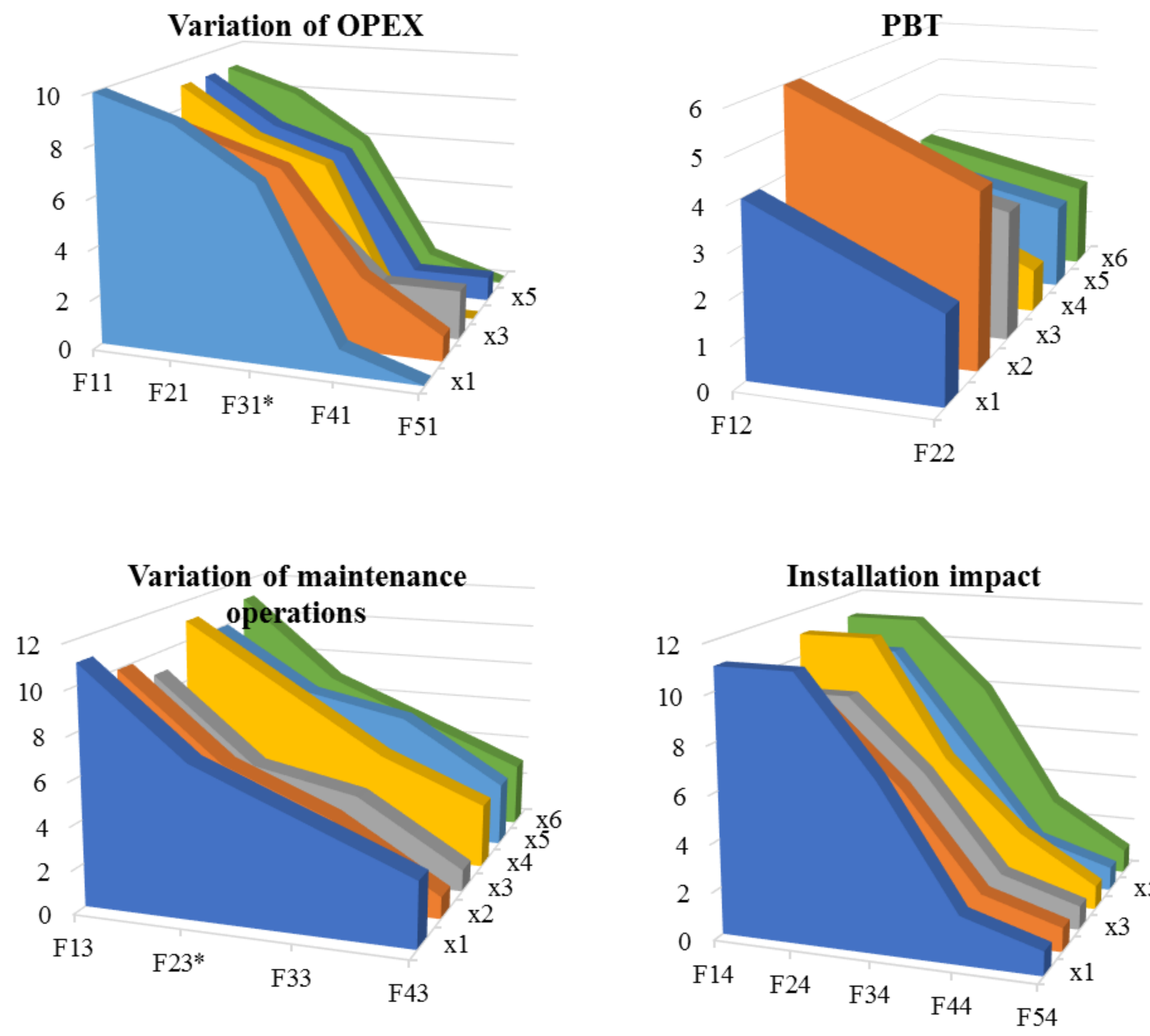


Figure 69 – Fist iteration economic optimization: visual satisfaction achievements

With the preferential portfolios chosen, six rules were generated by DRSA procedure and reported in Table 42: the DMs decided to keep no conservative limits to the procedure to slow it and better understand the algorithm in the next steps. Even on the rules, the most observed ones are on the three main criteria and, regarding OPEX, between rules #1 and #6 the first was chosen because less conservative and because the difference of threshold value F_{31} and F_{41} is just 1000 €.

Under the point of view of PBT, the two thresholds are far (10 vs 30 years) and this value summarizes the overall economic return. Rule #4 fits the preference of DMs better than rule #1, for this reason it is the law chosen. For maintenance, rules were not generated.

Table 42 - First iteration economic optimization: decision rules

Rules				Supported by	Chosen
#1	if $F_{41}\geq2$	then	GOOD	x_2, x_3	?
#2	if $F_{51}\geq2$	then	GOOD	x_3	
#3	if $F_{12}\geq6$	then	GOOD	x_2	
#4	if $F_{22}\geq3$	then	GOOD	x_2, x_3	X
#5	if $F_{21}\geq8$ and $F_{51}\geq1$	then	GOOD	x_2	
#6	if $F_{31}\geq7$ and $F_{51}\geq1$	then	GOOD	x_2	

Choosing the rule #4 the constraint $F_{22}\geq3$ was added to the optimization problem implying the generation of new portfolios satisfying this new limit. In fact, in Table 43 there were 8 different portfolios, indeed of the 6 in previous iteration, that were presented with Figure 70, visual translation of Table 44. The number of portfolios can increase maybe because multiple portfolios for each $l_{t,i}$ are offered at each iteration but, only the most repeated are finally included that, constraining the problem, can be afterwards deleted.

By OPEX and PBT, the portfolios x_2 and x_3 were shown and then the DMs skipped to the table with the portfolios‘ content of Table 43. Among x_2, x_3 and x_4 was chosen only x_2 because on lighting projects it does an upgrade rather than an addition of new bulbs for process line (so with an economic return) and, with respect to portfolio x_4, it changes the entire layout and not only the doorway. Note that portfolio x_2 is the same x_2 generated at the first iteration and already chosen as ‘good’. The DMs decided to consider even the portfolio x_6 because it contains the complete coating of workshop’s roof.

Table 43 - Second iteration economic optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	12	15	16	17	19	20	394’833	
x_2	1	2	4	7	8	10	12	15	17	19		386’833	good
x_3	2	4	6	7	8	10	11	14	17			397’069	
x_4	1	2	4	7	8	10	12	14	17	19		380’315	
x_5	4	7	8	10	12	14	16	19				396’665	
x_6	2	3	4	7	8	12	14	17	19	20		397’472	good
x_7	4	5	7	8	12	15	16	17	19	20		390’119	
x_8	2	4	5	7	8	10	12	14	17	19		391’581	

Table 44 - Second iteration economic optimization: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	10	9	7	2	0	5	3	11	6	4	2	11	10	7	2	1
x_2	9	8	7	3	1	6	4	10	6	4	1	10	9	6	2	1
x_3	8	6	5	2	2	4	3	9	5	4	1	9	9	6	2	1
x_4	9	8	7	2	1	5	3	10	7	5	2	10	10	6	2	1
x_5	8	7	6	2	1	3	3	8	6	6	3	8	8	6	1	1
x_6	9	8	6	2	1	4	3	10	6	5	3	10	10	7	2	1
x_7	8	7	5	2	0	3	3	10	5	4	2	10	9	8	3	1
x_8	8	7	6	2	1	4	3	10	7	5	2	10	10	7	3	1

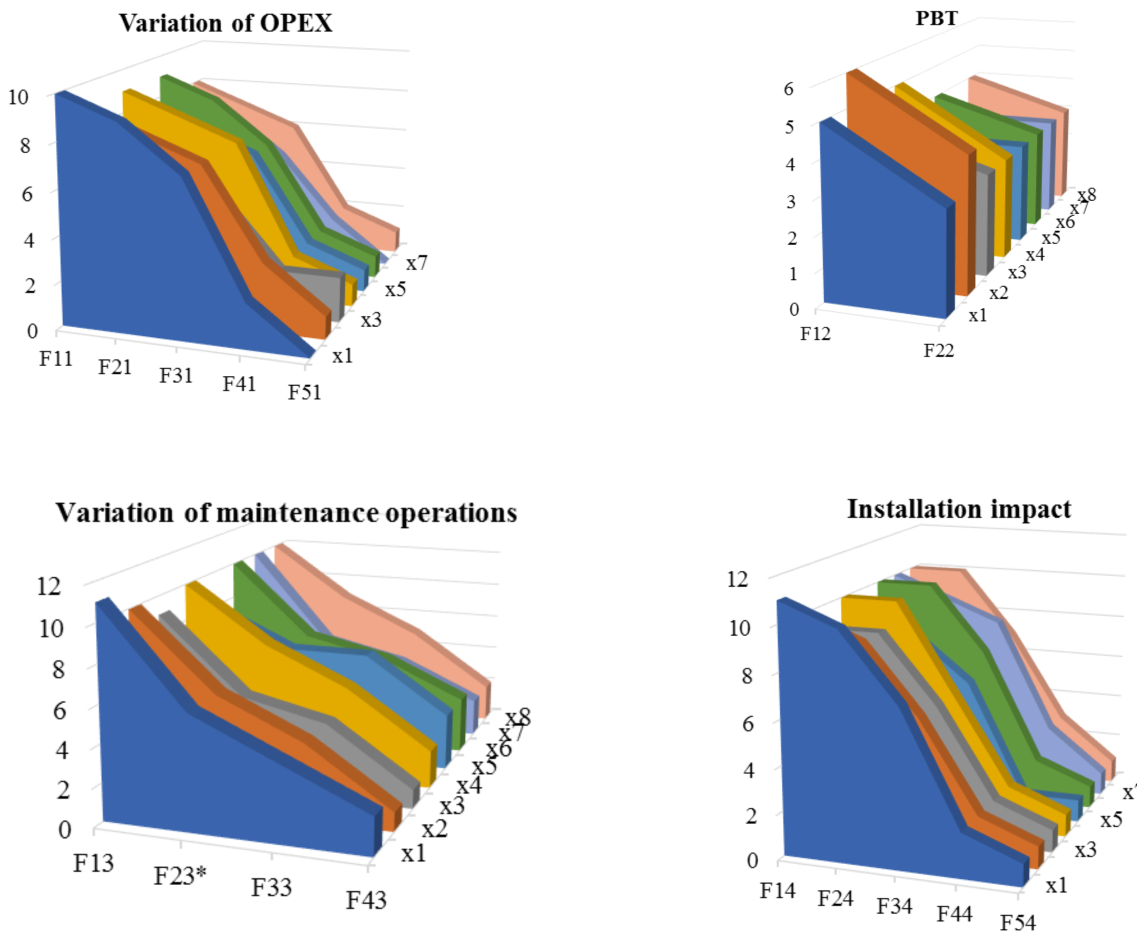


Figure 70 – Second iteration economic optimization: visual satisfaction achievements

The DMs was undecided between the rules #1 and #3, that for the second iteration are reported in Table 45, and both resemble the rules for the first iteration. Both rules are supported by x_2 and lead to the same set of portfolios of the third iteration in Table 46.

Table 45 - Second iteration economic optimization: decision rules

	Rules			Supported by	Chosen
#1	if $F_{41}\geq3$	then	GOOD	x_2	?
#2	if $F_{12}\geq6$	then	GOOD	x_2	
#3	if $F_{22}\geq4$	then	GOOD	x_2	X
#4	if $F_{11}\geq9$ and $F_{43}\geq3$	then	GOOD	x_6	
#5	if $F_{21}\geq8$ and $F_{43}\geq3$	then	GOOD	x_6	
#6	if $F_{12}\geq4$ and $F_{43}\geq3$	then	GOOD	x_6	
#7	if $F_{13}\geq10$ and $F_{43}\geq3$	then	GOOD	x_6	
#8	if $F_{43}\geq3$ and $F_{14}\geq10$	then	GOOD	x_6	
#9	if $F_{43}\geq3$ and $F_{24}\geq10$	then	GOOD	x_6	
#10	if $F_{43}\geq3$ and $F_{34}\geq7$	then	GOOD	x_6	
#11	if $F_{43}\geq3$ and $F_{44}\geq2$	then	GOOD	x_6	
#12	if $F_{11}\geq9$ and $F_{51}\geq1$ and $F_{34}\geq7$	then	GOOD	x_6	
#13	if $F_{11}\geq9$ and $F_{33}\geq5$ and $F_{34}\geq7$	then	GOOD	x_6	
#14	if $F_{21}\geq8$ and $F_{51}\geq1$ and $F_{34}\geq7$	then	GOOD	x_6	
#15	if $F_{21}\geq8$ and $F_{33}\geq5$ and $F_{34}\geq7$	then	GOOD	x_6	

The interactive phase was again constituted by satisfaction achievements in Table 47 and its visual presentation in Figure 71, the list of portfolios in Table 46 and the elaboration of decision rules of Table 48. The interesting portfolios were the first three, but DMs decided to delete x_1 and x_3 because they contain the project on ACR, resulting not requested for any aspects regarding this optimization. Portfolio x_4 was added because it was similar to x_2[39].

Table 46 - Third iteration economic optimization: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	10	12	15	17	19	386’833	
x_2	2	4	6	7	8	10	11	15			397’917	good
x_3	4	8	10	12	15	16	17	19			395’173	
x_4	2	3	4	7	8	12	15	19	20		398’320	good
x_5	4	5	7	8	10	12	15	17	20		398’619	
x_6	2	4	5	7	8	10	12	15	17	19	398’099	

[39] Note that the portfolios chosen as ‘good’ in the third iteration (i.e. x_2 and x_4) are different from the ones selected previously.

Table 47 - Third iteration economic optimization: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	9	8	7	3	1	6	4	10	6	4	1	10	9	6	2	1
x_2	8	6	5	3	2	5	4	8	4	3	0	8	7	5	1	1
x_3	7	6	6	3	1	4	4	8	5	5	2	8	7	6	1	0
x_4	9	8	6	3	1	5	4	9	5	4	2	9	8	6	1	1
x_5	7	6	4	3	1	4	4	9	4	3	0	9	8	8	3	1
x_6	8	7	6	3	1	5	4	10	6	4	1	10	9	7	3	1

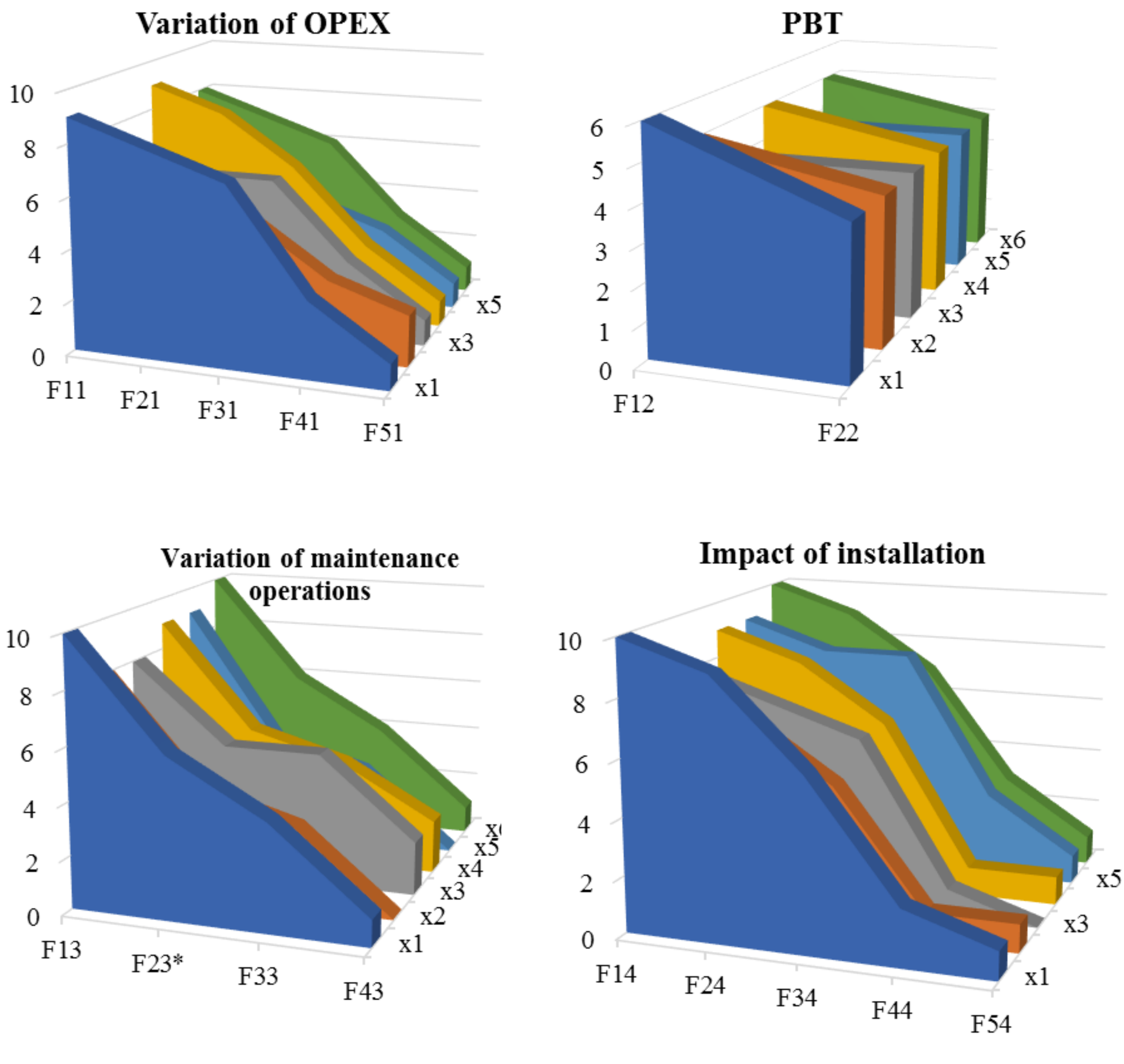


Figure 71 – Third iteration economic optimization: visual satisfaction achievements

The rule that best fits the DMs' preferences was #3, because it considers even the maintenance aspects.

Table 48 - Third iteration economic optimization: decision rules

Rules				Supported by	Chosen
#1	if $F_{51}\geq2$	then	GOOD	x_2	
#2	if $F_{11}\geq9$ and $F_{43}\geq2$	then	GOOD	x_4	
#3	if $F_{21}\geq8$ and $F_{43}\geq2$	then	GOOD	x_4	X
#4	if $F_{12}\geq5$ and $F_{43}\geq2$	then	GOOD	x_4	
#5	if $F_{13}\geq9$ and $F_{43}\geq2$	then	GOOD	x_4	
#6	if $F_{43}\geq2$ and $F_{14}\geq9$	then	GOOD	x_4	
#7	if $F_{43}\geq2$ and $F_{24}\geq8$	then	GOOD	x_4	
#8	if $F_{43}\geq2$ and $F_{54}\geq1$	then	GOOD	x_4	

The rule chosen brought to a unique portfolio that was the same marked as 'good' during the third iteration.

Table 49 - Fourth iteration economic optimization: optimized portfolios

Portfolio	Projects									Costs (€)	Preference
x_1	2	3	4	7	8	12	15	19	20	398'320	good

The author considers 'good' all the portfolios chosen by DMs during the procedure, even though in x_2 (third iteration) the project 'Add pro. lights' is not energy efficient nor useful for maintenance. The last portfolio obtained contains, over 9 projects, 5 that are very profitable, 2 that are positively impacting on maintenance and the last 2 that have not an economic return nor aid on maintenance (installation of additional coolers and heaters).

From an analytical perspective, this portfolio is good because has at least 1 project attaining the maximum satisfaction threshold for all criteria, and 4 projects with a PBT below 10 years.

6.2.2 Comfort optimization

The first iteration started showing the DMs the visual satisfaction classes of Figure 72 that plots the information of Table 51. Once again, the DMs used some relevant criteria to choose to best set from the visual charts:

- From People's satisfaction: x_1, x_4, x_6, x_8, x_9 because of highest satisfaction level;
- From thermal comfort (winter): x_1, x_4, x_5 and x_9 for at least neutral impact;
- From visual comfort: x_1 and x_3.

With such portfolios in mind, the DMs moved to Table 50 to assign the class 'good' and x_5 was discarded because of specific projects: thermal delayers because expensive and doorway because the entire layout was preferred.

Table 50 - First iteration comfort optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	9	11	15	17	19	20	383’087	good
x_2	1	2	4	5	11	14	16	17	19	20	0	399’360	
x_3	4	8	9	11	13	17	19	20	0	0	0	396’909	good
x_4	1	2	4	7	8	10	11	15	17	19	20	386’087	good
x_5	1	2	4	6	7	8	11	14	17	19	20	399’569	?
x_6	1	2	4	7	8	11	15	16	17	19	20	345’087	
x_7	1	2	5	7	9	15	20	0	0	0	0	399’444	
x_8	2	4	7	8	11	13	15	16	17	19	0	375’087	good
x_9	2	4	5	7	8	9	11	15	17	19	20	394’353	good

Table 51 - First iteration comfort optimization: matrix of satisfaction achievements

Portfolio	Visual comfort				Therm. comfort winter				Therm. comfort summer				Indoor quality			People's satisfaction		
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}*	F_{32}	F_{42}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}*	F_{24}	F_{34}	F_{15}*	F_{25}	F_{35}
x_1	11	9	4	2	11	9	5	1	11	10	6	1	11	3	1	11	8	6
x_2	10	10	3	2	10	7	3	0	10	9	4	0	10	3	1	10	7	4
x_3	8	7	5	2	8	6	2	1	8	7	2	0	8	2	1	8	7	4
x_4	11	9	4	3	11	9	4	1	11	10	5	1	11	3	1	11	8	6
x_5	11	8	3	2	11	9	5	2	11	10	5	1	11	4	1	11	7	5
x_6	11	9	3	2	11	9	4	1	11	10	5	1	11	4	1	11	8	7
x_7	7	6	2	0	7	5	4	0	7	7	7	1	7	2	0	7	5	2
x_8	10	8	3	2	10	9	3	1	10	9	3	1	10	5	1	10	8	7
x_9	11	9	4	2	11	8	4	1	11	10	6	1	11	3	1	11	9	6

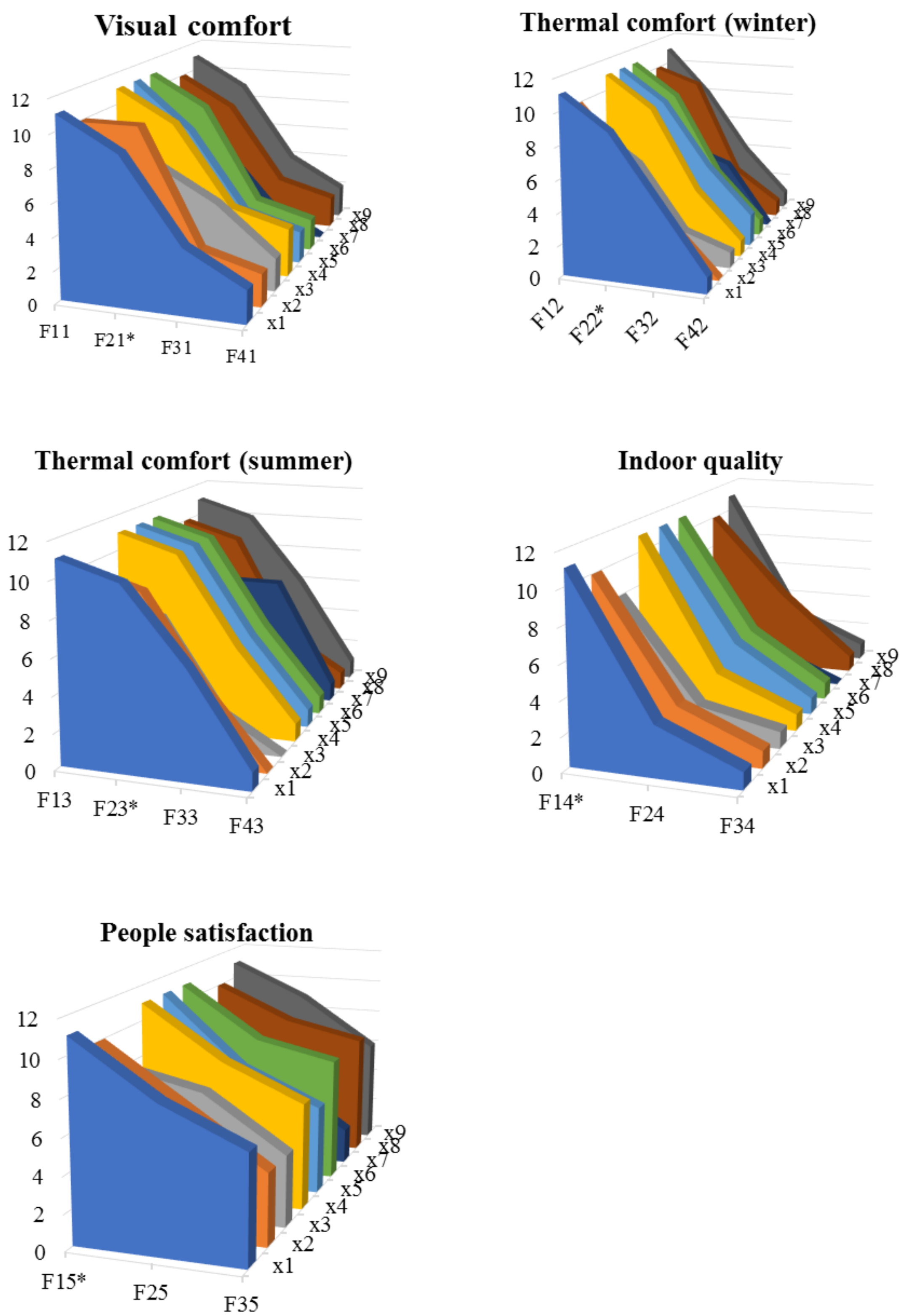


Figure 72 – First iteration comfort optimization: visual satisfaction achievements

Regarding the decision rules, only two criteria were considered (visual comfort and thermal heating) because the remaining had the tradeoff point yet satisfied by all projects.

The DMs looked for a rule satisfying both criteria, that was #6, that simultaneously was less conservative than rules #7 and #8. Including even the parameter "People's satisfaction" the alternative rule was the number #12: both #6 and #12 led to the same portfolio (the supported x_1), ending the procedure at the second iteration.

Table 52 – First iteration comfort optimization: decision rules

Rules				Supported by	Chosen
#1	if $F_{31}\geq4$	then	GOOD	x_1,x_3,x_4,x_9	
#2	if $F_{41}\geq3$	then	GOOD	x_4	
#3	if $F_{24}\geq5$	then	GOOD	x_8	
#4	if $F_{25}\geq9$	then	GOOD	x_9	
#5	if $F_{11}\geq11$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#6	if $F_{21}\geq9$ and $F_{32}\geq5$	then	GOOD	x_1	X
#7	if $F_{21}\geq9$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	?
#8	if $F_{41}\geq2$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	?
#9	if $F_{12}\geq11$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#10	if $F_{22}\geq8$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#11	if $F_{32}\geq5$ and $F_{33}\geq6$	then	GOOD	x_1	
#12	if $F_{32}\geq5$ and $F_{25}\geq8$	then	GOOD	x_1	?
#13	if $F_{32}\geq5$ and $F_{35}\geq6$	then	GOOD	x_1	
#14	if $F_{42}\geq1$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#15	if $F_{13}\geq11$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#16	if $F_{23}\geq10$ and $F_{33}\geq6$	then	GOOD	x_1, x_9	
#17	if $F_{33}\geq6$ and $F_{14}\geq11$	then	GOOD	x_1, x_9	
#18	if $F_{33}\geq6$ and $F_{24}\geq3$	then	GOOD	x_1, x_9	
#19	if $F_{33}\geq6$ and $F_{34}\geq1$	then	GOOD	x_1, x_9	
#20	if $F_{33}\geq6$ and $F_{15}\geq11$	then	GOOD	x_1, x_9	
#21	if $F_{33}\geq6$ and $F_{25}\geq8$	then	GOOD	x_1, x_9	
#22	if $F_{33}\geq6$ and $F_{35}\geq6$	then	GOOD	x_1, x_9	

The final portfolio was presented in Table 53: among the 11 solutions achieved, only the project 'Ins. PC roof' was useless for the purposes intended of improving comfort. Whereas the glass substitution was considered a good investment that can simultaneously improve both visual and thermal comfort during winter for reduced ex-filtration.

Table 53 - Second iteration comfort optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	9	11	15	17	19	20	383'087	good

This portfolio is good even from an analytical point of view because it has at least 1 project attaining the maximum satisfaction threshold for all criteria, and 6 criteria satisfying maximally the final users.

6.2.3 External image optimization

The optimization started showing the DMs the visual charts about satisfaction achievements of Figure 72 and the corresponding mother matrix in Table 55. The most observed criteria were:

- People's satisfaction because of trade union aspects, where portfolios x_3, x_5, x_8 and x_{10}, x_{11} were identified clearly;
- Emission CO_2: x_1, x_6, x_{11} because of the values at the tradeoff achievements.

Being the work without RES, the conflict among these two criteria were very remarked since sustainability cannot be matched always with users' expectation. Among the 7 portfolios detected, the DMs removed the ones with the project of glasses' substitution because of the low expectation as sustainable measures except for the portfolio x_6 where the glass 'substitution is coupled with 'cool roof' (i.e. it is appreciable to combine more than a work when the object is the roof). The final portfolios detected as 'good' are reported in Table 54.

Table 54 - First iteration ext. image optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	10	11	14	17	19	20	379'569	good
x_2	2	4	5	7	8	9	11	14	17	19	20	387'835	
x_3	1	2	4	7	8	11	15	16	17	19	20	345'087	good
x_4	1	2	4	5	11	14	16	17	19	20		399'360	
x_5	1	2	4	7	8	12	14	16	17	19	20	388'315	good
x_6	5	8	9	10	19							399'561	good
x_7	4	5	8	10	11	13	17					395'675	
x_8	1	2	4	7	8	9	11	14	17	19	20	376'569	?
x_9	1	2	9	11	14	16	19					399'986	
x_{10}	1	2	4	7	8	9	12	14	17	19		377'315	?
x_{11}	2	4	8	9	10	11	14	17	19			392'889	?
x_{12}	1	2	4	8	9	11	13	17				397'389	

Table 55 - First iteration ext. image optimization: matrix of satisfaction achievements

	People's satisfaction			Visual impact					Emission CO_2				Realiability				
Portfolio	F_{11}*	F_{21}	F_{31}	F_{12}	F_{22}	F_{32}*	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}*	F_{43}	F_{15}	F_{25}	F_{35}	F_{45}	F_{55}
x_1	11	8	5	11	9	7	2	1	10	6	2	1	11	11	11	5	3
x_2	11	9	5	11	9	7	3	1	9	5	1	1	11	10	10	4	3
x_3	11	8	7	11	9	6	1	0	10	6	1	0	11	11	11	5	3
x_4	10	7	4	10	10	8	2	1	8	6	1	0	10	9	9	5	3
x_5	11	7	5	11	9	8	1	0	10	6	2	0	11	11	11	6	3
x_6	5	5	2	5	4	4	4	2	4	3	2	2	5	4	4	2	1
x_7	7	6	3	7	6	5	3	3	5	3	1	1	7	6	6	4	2
x_8	11	8	5	11	9	7	2	0	10	6	2	1	11	11	11	5	4
x_9	7	5	3	7	7	6	2	0	7	7	2	1	7	7	7	4	3
x_{10}	10	6	4	10	8	8	2	0	9	6	3	1	10	10	10	6	4
x_{11}	9	7	4	9	8	7	3	1	8	6	2	2	9	9	9	5	3
x_{12}	8	5	3	8	7	6	2	1	7	5	2	1	8	8	8	6	5

The selection of decision rules for this interaction is critical because the optimization procedure assessed about 40 rules, reported in Table 56: this made the procedure complex to be applied directly by personal interview. This limit needed to be tackled by a logic screening of laws to present. This was done by selection of the rules that simultaneously cover three main criteria: Emission CO_2, Visual impact (at least on the tradeoff point) and People's satisfaction. Seven rules survived and only the #27 was chosen because less conservative on Visual impact (note the threshold F_{52}).

The second iteration showed only 3 portfolios (see Table 54) and the DMs decided to choose directly x_1 because from Table 58, and especially from its visual representation in Figure 74, the portfolios seemed comparable. The portfolio was chosen because the remaining two consider the addition of new process bulbs, whereas with an upgrade to LED of the same lamps maybe the appreciation is anyway large.

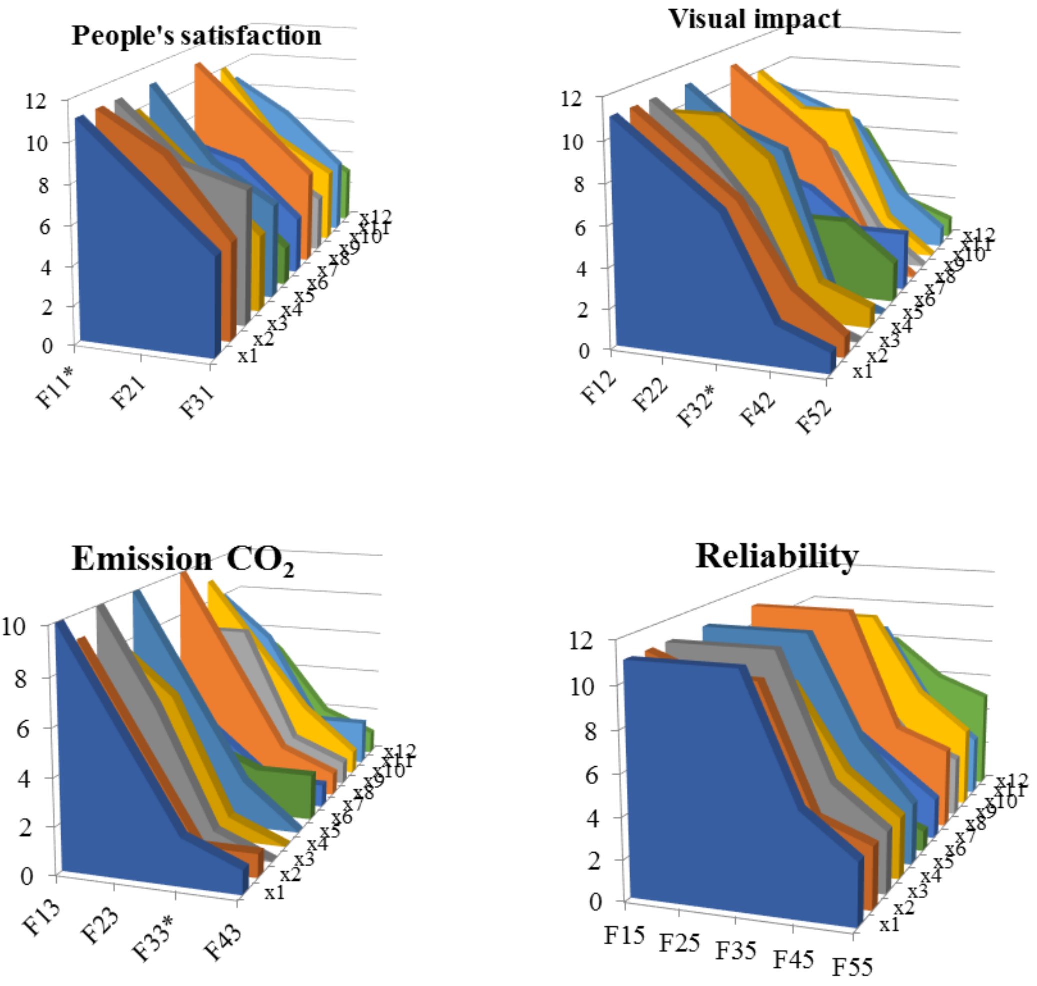


Figure 73 - First iteration ext. image optimization: visual satisfaction achievements

Table 56 - First iteration ext. image optimization: decision rules

	Rules			Supp. by	CO_2	P.'s s.	Visual.	Chosen
#1	if $F_{31}\geq7$	then	GOOD	x_3		?		
#2	if $F_{42}\geq4$	then	GOOD	x_6			?	
#3	if $F_{11}\geq11$ and $F_{32}\geq8$	then	GOOD	x_5		?	?	
#4	if $F_{11}\geq11$ and $F_{45}\geq6$	then	GOOD	x_5		?		
#5	if $F_{21}\geq7$ and $F_{45}\geq6$	then	GOOD	x_5		?		
#6	if $F_{31}\geq5$ and $F_{32}\geq8$	then	GOOD	x_5		?	?	
#7	if $F_{31}\geq5$ and $F_{45}\geq6$	then	GOOD	x_5		?		
#8	if $F_{12}\geq11$ and $F_{32}\geq8$	then	GOOD	x_5			?	
#9	if $F_{12}\geq11$ and $F_{45}\geq6$	then	GOOD	x_5				
#10	if $F_{22}\geq9$ and $F_{45}\geq6$	then	GOOD	x_5				
#11	if $F_{32}\geq8$ and $F_{13}\geq10$	then	GOOD	x_5			?	
#12	if $F_{32}\geq8$ and $F_{15}\geq11$	then	GOOD	x_5			?	

#13	if $F_{32}\geq 8$ and $F_{25}\geq 11$	then	GOOD	x_5			?	
#14	if $F_{32}\geq 8$ and $F_{35}\geq 11$	then	GOOD	x_5			?	
#15	if $F_{52}\geq 1$ and $F_{13}\geq 10$	then	GOOD	x_1			?	
#16	if $F_{52}\geq 2$ and $F_{33}\geq 2$	then	GOOD	x_6	?		?	
#17	if $F_{52}\geq 2$ and $F_{43}\geq 2$	then	GOOD	x_6	?		?	
#18	if $F_{52}\geq 1$ and $F_{25}\geq 11$	then	GOOD	x_1			?	
#19	if $F_{52}\geq 1$ and $F_{35}\geq 11$	then	GOOD	x_1			?	
#20	if $F_{13}\geq 10$ and $F_{45}\geq 6$	then	GOOD	x_5				
#21	if $F_{15}\geq 11$ and $F_{45}\geq 6$	then	GOOD	x_5				
#22	if $F_{25}\geq 11$ and $F_{45}\geq 6$	then	GOOD	x_5				
#23	if $F_{35}\geq 11$ and $F_{45}\geq 6$	then	GOOD	x_5		?		
#24	if $F_{11}\geq 11$ and $F_{52}\geq 1$ and $F_{23}\geq 6$	then	GOOD	x_1		?	?	!
#25	if $F_{11}\geq 11$ and $F_{52}\geq 1$ and $F_{33}\geq 2$	then	GOOD	x_1	?	?	?	!
#26	if $F_{11}\geq 11$ and $F_{52}\geq 1$ and $F45\geq 5$	then	GOOD	x_1		?	?	
#27	if $F_{21}\geq 7$ and $F_{32}\geq 8$ and $F33\geq 2$	then	GOOD	x_5	?	?	?	X
#28	if $F_{21}\geq 8$ and $F_{52}\geq 1$ and $F_{23}\geq 6$	then	GOOD	x_1	?	?	?	!
#29	if $F_{21}\geq 8$ and $F_{52}\geq 1$ and $F_{33}\geq 2$	then	GOOD	x_1	?	?	?	!
#30	if $F_{21}\geq 8$ and $F_{52}\geq 1$ and $F_{45}\geq 5$	then	GOOD	x_1		?	?	
#31	if $F_{31}\geq 5$ and $F_{52}\geq 1$ and $F_{23}\geq 6$	then	GOOD	x_1		?	?	!
#32	if $F_{31}\geq 5$ and $F_{52}\geq 1$ and $F_{33}\geq 2$	then	GOOD	x_1	?	?	?	!
#33	if $F_{31}\geq 5$ and $F_{52}\geq 1$ and $F_{45}\geq 5$	then	GOOD	x_1		?	?	
#34	if $F_{12}\geq 11$ and $F_{52}\geq 1$ and $F_{23}\geq 6$	then	GOOD	x_1			?	
#35	if $F_{12}\geq 11$ and $F_{52}\geq 1$ and $F_{33}\geq 2$	then	GOOD	x_1	?		?	
#36	if $F_{12}\geq 11$ and $F_{52}\geq 1$ and $F_{45}\geq 5$	then	GOOD	x_1			?	
#37	if $F_{22}\geq 9$ and $F_{32}\geq 8$ and $F_{33}\geq 2$	then	GOOD	x_5	?		?	
#38	if $F_{22}\geq 9$ and $F_{52}\geq 1$ and $F_{33}\geq 2$	then	GOOD	x_1	?		?	
#39	if $F_{52}\geq 1$ and $F_{23}\geq 6$ and $F_{15}\geq 11$	then	GOOD	x_1			?	
#40	if $F_{52}\geq 1$ and $F_{33}\geq 2$ and $F_{15}\geq 11$	then	GOOD	x_1	?		?	
#41	if $F_{52}\geq 1$ and $F_{15}\geq 11$ and $F_{45}\geq 5$	then	GOOD	x_1			?	
#42	if $F_{22}\geq 9$ and $F_{52}\geq 1$ and $F_{23}\geq 6$ and $F_{43}\geq 1$	then	GOOD	x_1			?	
#43	if $F_{22}\geq 9$ and $F_{52}\geq 1$ and $F_{43}\geq 1$ and $F_{45}\geq 5$	then	GOOD	x_1	?		?	

Table 57 - Second iteration ext. image optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	12	14	16	17	19	20	388’315	good
x_2	1	2	4	5	8	9	11	14	17	19		391’155	
x_3	1	2	4	5	8	10	11	14	17	19		394’155	

Table 58 - Second iteration ext. image optimization: matrix of satisfaction achievements

	People's satisfaction			Visual impact					Emission CO_2				Realiability				
Portfolio	F_{11}*	F_{21}	F_{31}	F_{12}	F_{22}	F_{32}*	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}*	F_{43}	F_{15}	F_{25}	F_{35}	F_{45}	F_{55}
x_1	11	7	5	11	9	8	1	0	10	6	2	0	11	11	11	6	3
x_2	10	7	4	10	9	8	3	1	8	6	2	1	10	9	9	5	4
x_3	10	7	4	10	9	8	3	2	8	6	2	1	10	9	9	5	3

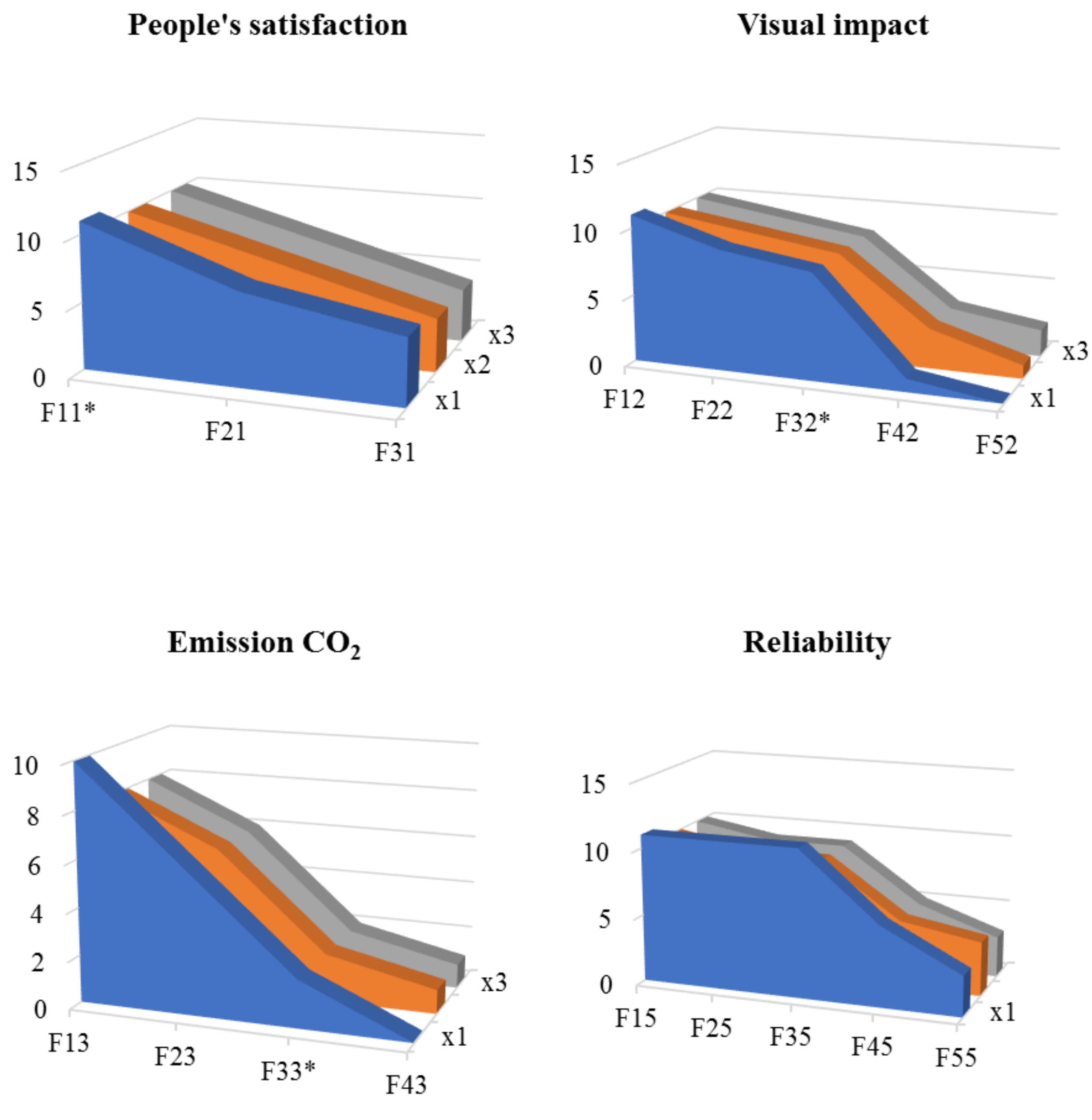


Figure 74 - Second iteration ext. image optimization: visual satisfaction achievements

From the portfolio selected, the 8 rules reported in Table 59 come out, all supported by the single choice. The DMs decided the rule #2 because of People's satisfaction that led again to portfolio x_1 in Table 57 and Table 60, ending the optimization.

Table 59 - Second iteration ext. image optimization: decision rules

Rules				Supported by	Chosen
#1	if $F_{11}\geq 11$	then	GOOD	x_1	
#2	if $F_{31}\geq 5$	then	GOOD	x_1	X
#3	if $F_{12}\geq 11$	then	GOOD	x_1	
#4	if $F_{13}\geq 10$	then	GOOD	x_1	
#5	if $F_{15}\geq 11$	then	GOOD	x_1	
#6	if $F_{25}\geq 11$	then	GOOD	x_1	
#7	if $F_{35}\geq 11$	then	GOOD	x_1	
#8	if $F_{45}\geq 6$	then	GOOD	x_1	

Table 60 - Third iteration ext. image optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	12	14	16	17	19	20	388'315	good

6.2.4 Technical optimization

In general, during this analysis, the most observed criteria were 'Variation of maintenance operation', 'Reliability' and 'Technical life'. The first optimization detected 18 portfolios, where the 8 different are reported in Table 61. At the presentation of the five charts of Figure 75, the portfolios selected are:

- x_2, x_3 and x_7 from 'Variation of maintenance';
- x_5 and x_6 from 'Technical life'.

These were the ones that best satisfy the highest threshold of criteria considered, as shown even in Table 62. After the diagrams, the DMs skipped to the matrix with optimized portfolios coded and discarded x_7 because of 'Cool roof', considered the worst project under the technical point of view.

Table 61 - First iteration technical optimization: optimized portfolios

Portfolio	Projects											Costs (€)	Preference
x_1	1	2	4	7	8	12	14	16	17	19	20	388’315	
x_2	1	2	4	5	7	8	11	14	16	17	19	366’835	
x_3	2	4	7	8	9	11	14	16	17	19		365’569	good
x_4	1	2	4	8	9	11	13	17				397’389	
x_5	1	2	4	7	8	12	15	16	17	19	20	394’833	good
x_6	1	2	4	7	8	9	11	15	17	19	20	383’087	good
x_7	2	4	5	7	8	12	14	16	17	19	20	399’581	?
x_8	2	4	5	7	8	10	11	14	17	19	20	390’835	

Table 62 - First iteration technical optimization: matrix of satisfaction achievements

Portfolio	Var. maint. Op.				Reliability					Technical life			Duration work		Layout flexibility			
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}	F_{32}	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}	F_{14}	F_{24}	F_{15}	F_{25}*	F_{35}	F_{45}
x_1	11	7	5	3	11	11	11	6	3	11	9	3	9	5	11	9	9	7
x_2	11	8	5	3	11	10	10	5	3	10	8	2	9	6	11	10	10	8
x_3	10	7	6	3	10	10	10	5	3	10	8	3	8	5	10	9	9	7
x_4	8	6	4	0	8	8	8	6	5	8	7	3	4	4	8	7	7	6
x_5	11	6	4	2	11	11	11	6	3	11	10	4	9	4	11	9	8	7
x_6	11	6	4	1	11	11	11	5	4	11	10	5	8	4	11	9	8	7
x_7	11	7	5	3	11	10	10	5	2	10	8	3	10	6	11	9	9	7
x_8	11	7	5	2	11	10	10	4	2	10	8	3	10	7	11	9	9	6

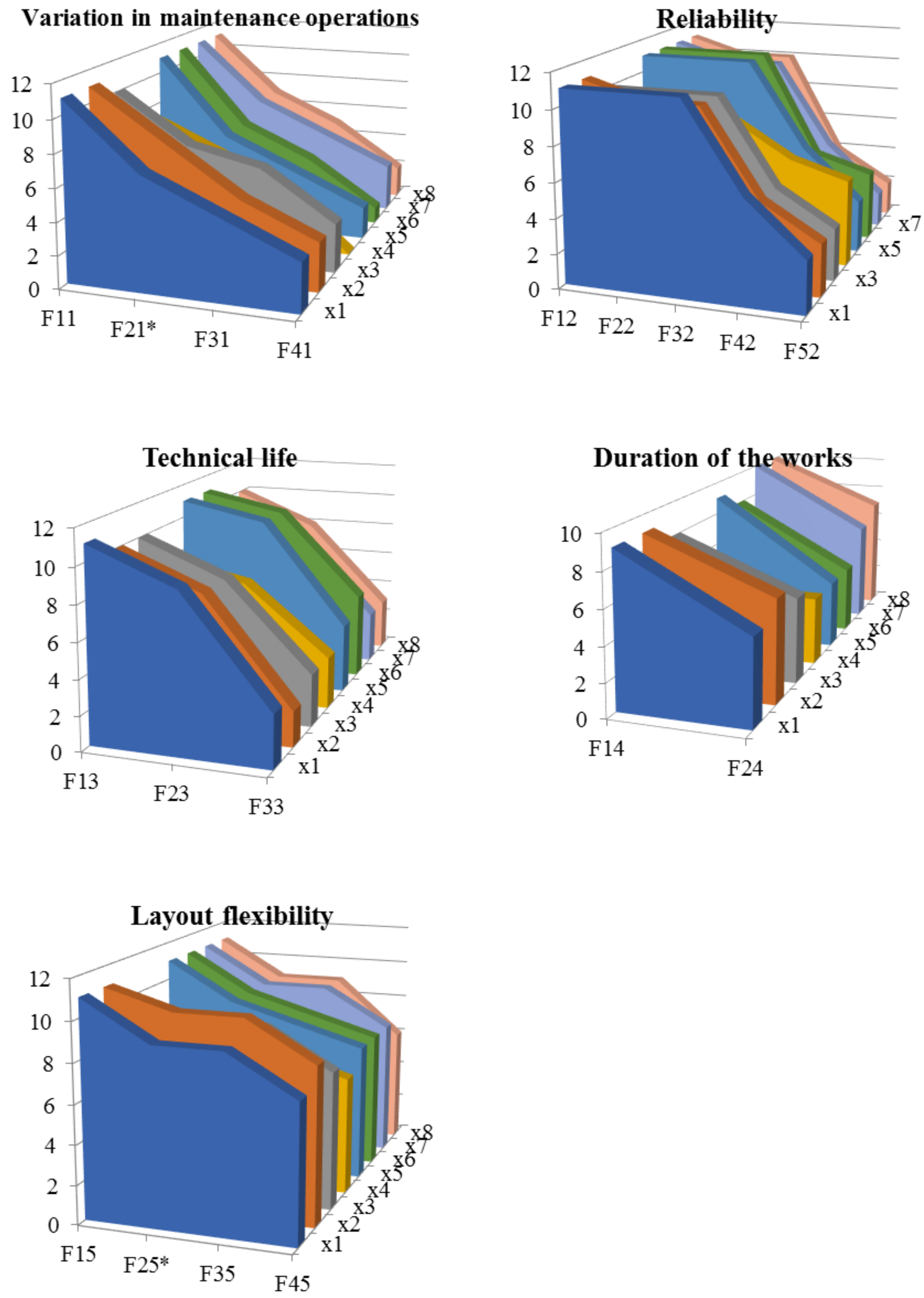


Figure 75 – First iteration technical optimization: visual satisfaction achievements

To select the best decision rule from Table 63, DMs looked for the one containing both indications about the criteria 'Variation of maintenance operation' and 'Technical life'. Since there were not intersections, the rule chosen was #1. Rule #5 was considered interesting also but not chosen because too conservative on technical reliability.

Table 63 - First iteration technical optimization: decision rules

Rules				Supported by	Chosen
#1	if $F_{31} \geq 6$	then	GOOD	x_3	X
#2	if $F_{23} \geq 10$	then	GOOD	x_5, x_6	
#3	if $F_{33} \geq 4$	then	GOOD	x_5, x_6	
#4	if $F_{11} \geq 11$ and $F_{52} \geq 4$	then	GOOD	x_6	
#5	if $F_{41} \geq 1$ and $F_{52} \geq 4$	then	GOOD	x_6	?
#6	if $F_{12} \geq 11$ and $F_{52} \geq 4$	then	GOOD	x_6	
#7	if $F_{22} \geq 11$ and $F_{52} \geq 4$	then	GOOD	x_6	
#8	if $F_{32} \geq 11$ and $F_{52} \geq 4$	then	GOOD	x_6	
#9	if $F_{52} \geq 4$ and $F_{13} \geq 11$	then	GOOD	x_6	
#10	if $F_{52} \geq 4$ and $F_{14} \geq 8$	then	GOOD	x_6	
#11	if $F_{23} \geq 4$ and $F_{15} \geq 11$	then	GOOD	x_6	
#12	if $F_{52} \geq 4$ and $F_{25} \geq 9$	then	GOOD	x_6	
#13	if $F_{52} \geq 4$ and $F_{35} \geq 8$	then	GOOD	x_6	
#14	if $F_{52} \geq 4$ and $F_{45} \geq 7$	then	GOOD	x_6	

The second iteration of the procedure ended suddenly because DMs, from satisfaction charts of Figure 76 and related Table 65, noted that the portfolio x_2 was the unique "flat" along the satisfaction direction and before the tradeoff for all criteria, meaning that it is at least good on neutral threshold. Reading the remaining portfolios, after the consultation of Table 64, DMs decided to confirm only x_2 because the other solutions added only additional equipment in the workshop hence higher maintenance.

Table 64 - Second iteration technical optimization: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	2	4	7	8	9	11	14	16	17	19	365’569	
x_2	2	4	9	12	14	16	17	19			398’840	good
x_3	2	4	8	9	11	13	14	17	19		392’889	
x_4	4	7	8	9	11	14	16	17	19	20	398’589	
x_5	2	4	7	8	10	11	14	16	17	19	368’569	

Table 65 - Second iteration technical optimization: matrix of satisfaction achievements

Portfolio	Var. maint. Op.				Reliability					Technical life			Duration work		Layout flexibility			
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}	F_{32}	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}	F_{14}	F_{24}	F_{15}	F_{25}*	F_{35}	F_{45}
x_1	10	7	6	3	10	10	10	5	3	10	8	3	8	5	10	9	9	7
x_2	8	7	6	3	8	8	8	6	3	8	7	3	6	4	8	7	7	6
x_3	9	7	6	2	9	9	9	5	4	9	7	4	6	5	9	8	8	6
x_4	10	6	6	3	10	10	10	4	2	10	8	4	9	5	10	8	8	6
x_5	10	7	6	3	10	10	10	5	2	10	8	2	9	6	10	9	9	6

From this choice, only one rule came from (see Table 66), supported by the chosen portfolio: this situation once again confirmed as optimized solution the unique portfolio of the third iteration, reported in Table 67.

Table 66 - Second iteration technical optimization: decision rules

Rules				Supported by	Chosen
#1	$F_{42} \geq 6$	then	GOOD	x_2	X

Table 67 - Third iteration technical optimization: optimized portfolios

Portfolio	Projects									Costs (€)	Preference
x_1	2	4	9	12	14	16	17	19	2	398’840	good

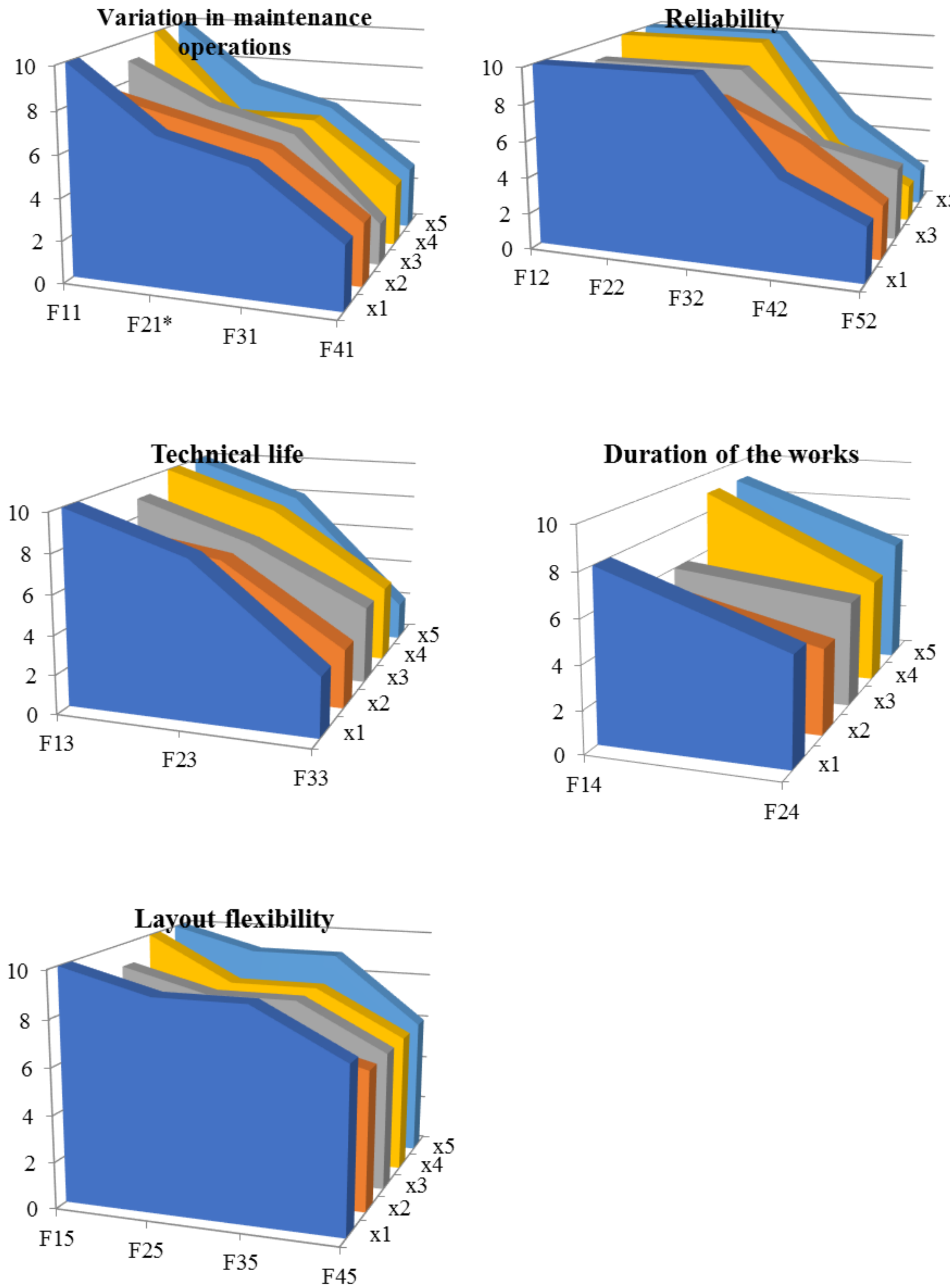


Figure 76 – Second iteration technical optimization: visual satisfaction achievements

6.2.5 Convergence of sharing functions

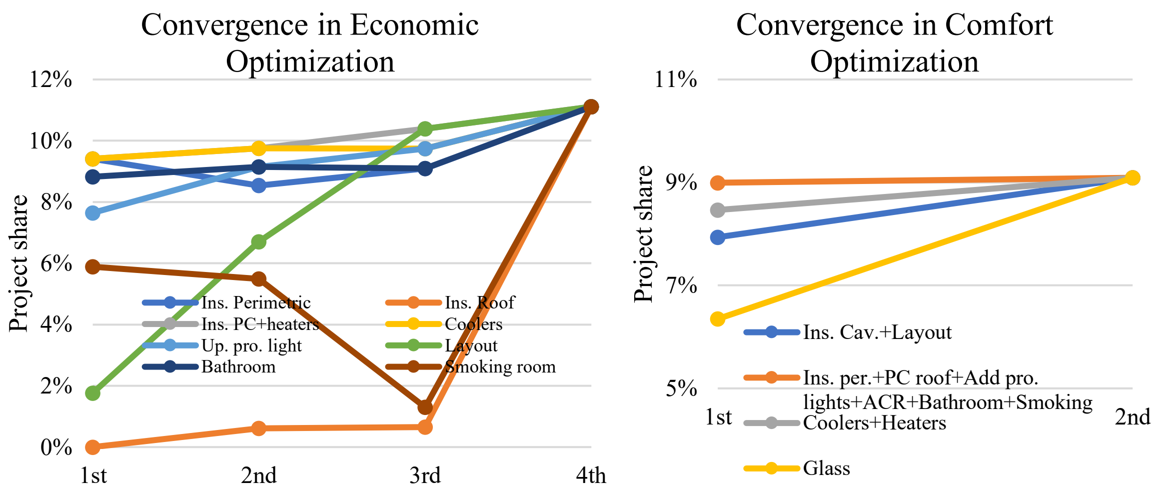
In Figure 77 it is shown the value of projects‘ share among the outputs of mathematical optimization at each iteration, highlighting how an expected convergence towards the results is weakly influenced by human errors of DMs.

For an assigned iteration ‘n’, the share[40] *f(x,n)* of project ‘x’, belonging to the ending optimal portfolio for an assigned optimization, is calculated with the following equation:

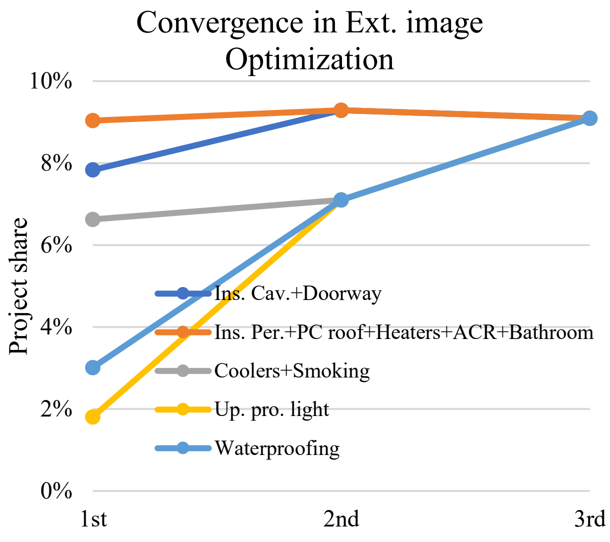
$$f(x,n) = \frac{'x'\ occurrences\ at\ iteration\ 'n'}{number\ projects\ in\ portfolios\ at\ iteration\ 'n'} \quad (\%) \qquad (74)$$

Where at the denominator there is the total number of projects contained among the optimized portfolios at iteration ‘n’ (with repetition), whilst the numerator expresses only the occurrences of the project ‘x’.

From these charts one can note that the function is almost stable for most projects, meaning that already with the first iteration the DMs and the procedure detected the best actions, while some of the most expensive (with a cost above 50’000 €) entered slowly to the final share.



40 I.e. the presence of the project ‘x’ among the $F_{t,i}$ optimized portfolios.



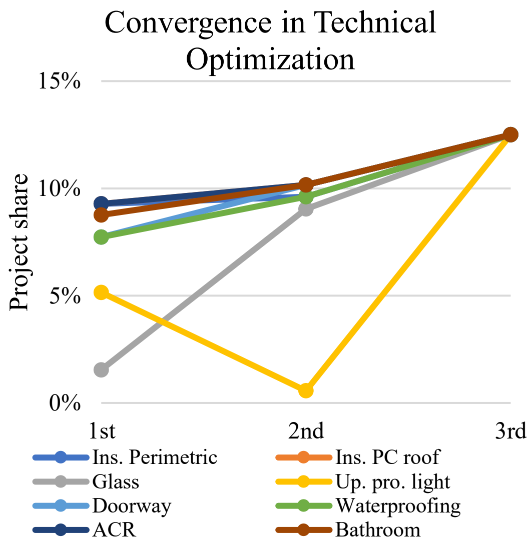


Figure 77 – Convergence of sharing functions for the four optimizations

6.3 New budget formulation

After the above shown optimizations with the budget sets at 400’000 €, the analyst decided to repeat the procedure with a lower budget, in order to:

- Filter more the subset obtained;
- Test the robustness of the algorithm;
- Check whether the procedure is easier to handle because of the expected decreased length of optimized portfolios;
- Revise generally the model as suggested in Figure 61;

The new budget chosen is 300’000 € that again is within the limits reported in the setting of paragraph 6.1, covering 11 projects (55% of cumulative).

6.3.1 Economic optimization

The optimized portfolios in the first iteration are reported in Table 68, while the number of projects attaining a determined threshold in Table 69. The DMs starting from its visual representation of Figure 78, selected:

- x_2 because of results on ‘Variation of Operation costs’;
- x_2 and x_4 for ‘PBT’;
- Whereas for maintenance x_3 and x_5 because of F_{43} equal to 3.

Observing the projects contained, the projects x_3 and x_5 were removed because they contain many projects without economic return.

Table 68 - First iteration economic optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	12	14	17	19	20	284’315	
x_2	2	4	7	8	10	12	15	17			288’333	good
x_3	2	3	4	7	8	11	14	17	19		298’726	?
x_4	1	2	4	7	8	12	15	17	19	20	290’833	good
x_5	1	2	4	7	8	11	14	16	17	19	289’569	?
x_6	2	4	5	7	8	12	14	17	19	20	295’581	

Table 69 – First iteration economic optimization bis: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	9	8	6	1	0	4	2	10	6	4	2	10	10	6	2	1
x_2	7	6	5	3	1	5	4	8	4	3	0	8	7	6	2	1
x_3	8	6	5	1	1	3	2	9	6	5	3	9	9	5	2	1
x_4	9	8	6	2	0	5	3	10	5	3	1	10	9	6	2	1
x_5	9	7	6	0	0	3	1	10	7	5	3	10	10	5	2	1
x_6	8	7	5	1	0	3	2	10	6	4	2	10	10	7	3	1

Finally the DMs chose x_2 because of high number of efficiency projects and x_4 that has 6 projects over 9 useful either for economic and maintenance purposes, even though in both cases ACR is not requested.

Among the decision rules, listed in Table 70, the DMs chose the first because less conservative and allowing the persistence of more portfolios.

The second iteration proposed 8 different portfolios instead of the 6 reported in the first. Among these, listed in Table 71 and classified in Table 72, the decisional flow follows:

- From Figure 79 DMs chose x_3, x_4, and x_5 for maintenance and x_2 for PBT;
- Later, by checking on the projects’ name, DMs discarded x_3 for the project ‘Add process light’ and x_5 because x_2 was favorite.

Eight rules are offered by DRSA and reported in Table 73, the last was chosen because it sets constraints on the three most relevant criteria.

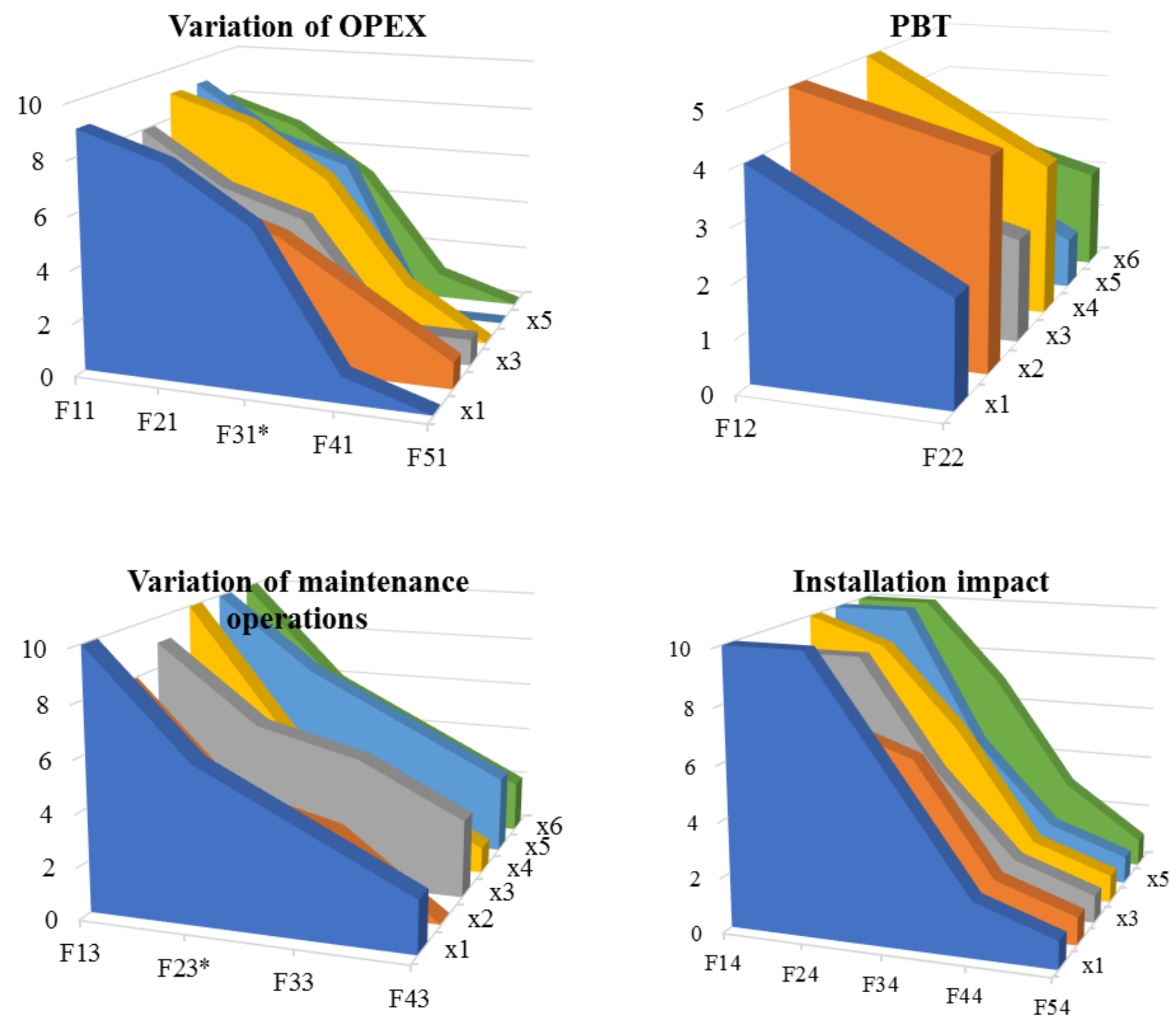


Figure 78 – Fist iteration economic optimization bis: visual satisfaction achievements

Table 70 - First iteration economic optimization bis: decision rules

Rules				Supported by	Chosen
#1	if $F_{41} \geq 2$	then	GOOD	x_2, x_4	X
#2	if $F_{12} \geq 5$	then	GOOD	x_2, x_4	
#3	if $F_{22} \geq 3$	then	GOOD	x_2, x_4	
#4	if $F_{51} \geq 1$ and $F_{34} \geq 6$	then	GOOD	x_2	

Table 71 - Second iteration economic optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	12	15	17	19	20	290’833	
x_2	2	4	7	8	10	12	15	17			288’333	good
x_3	2	4	7	8	10	11	15	17	19		271’087	?
x_4	2	4	10	12	14	17	19				297’840	good
x_5	4	7	8	10	12	14	17	19			298’335	?
x_6	2	4	7	8	12	15	16	17	19		279’833	
x_7	2	4	7	8	12	15	16	17	20		296’333	
x_8	2	4	5	7	12	15	17	19	20		299’304	

Table 72 – Second iteration economic optimization bis: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	9	8	6	2	0	5	3	10	5	3	1	10	9	6	2	1
x_2	7	6	5	3	1	5	4	8	4	3	0	8	7	6	2	1
x_3	8	6	5	2	1	4	3	9	5	4	1	9	8	5	2	1
x_4	6	6	6	2	1	4	3	7	6	5	2	7	7	4	1	0
x_5	7	6	5	2	1	3	3	8	5	5	2	8	8	6	2	1
x_6	8	7	6	2	0	4	3	9	5	4	2	9	8	6	2	1
x_7	8	7	5	2	0	4	3	9	4	3	1	9	8	7	2	1
x_8	7	7	5	2	0	4	3	9	5	3	1	9	8	6	3	1

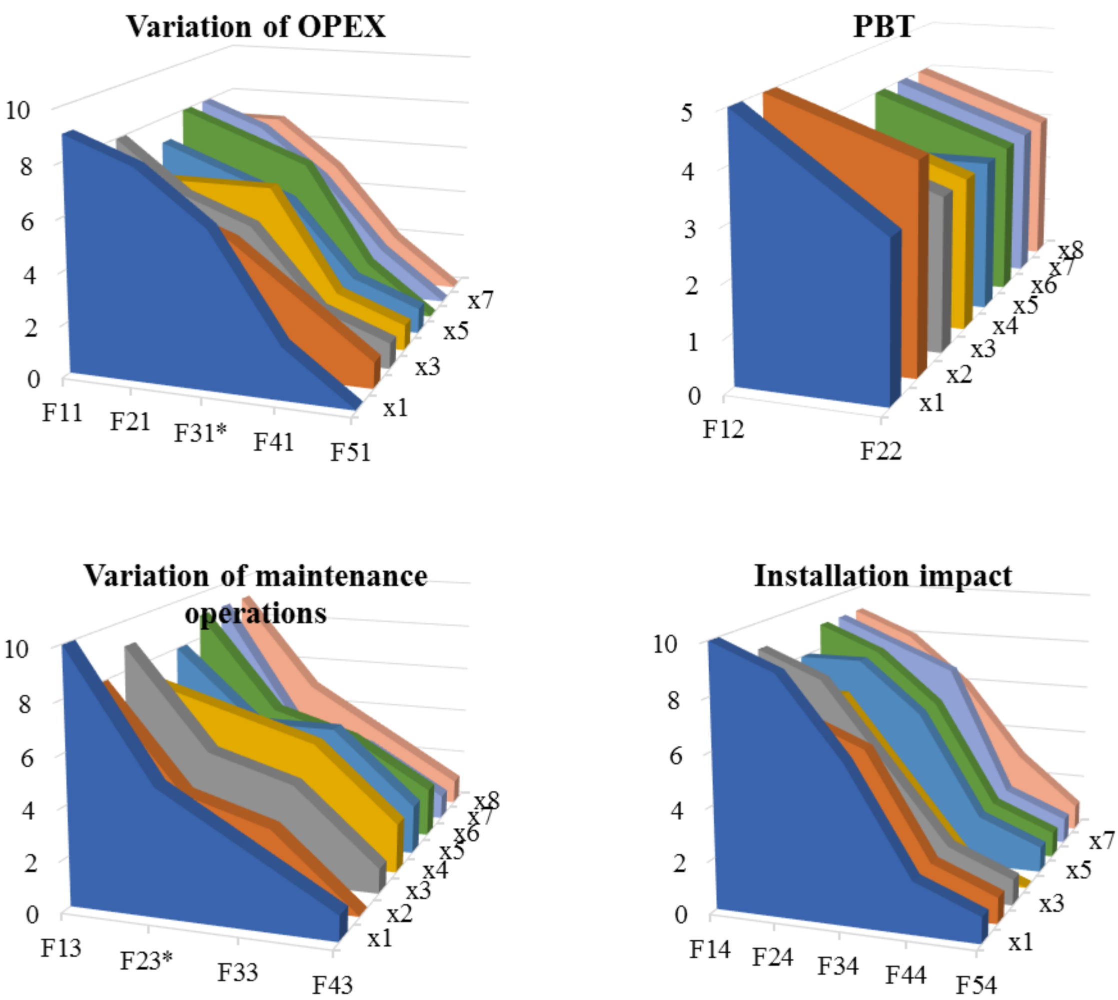


Figure 79 – Second iteration economic optimization bis: visual satisfaction achievements

Table 73 - Second iteration economic optimization bis: decision rules

	Rules			Supported by	Chosen
#1	if $F_{41} \geq 3$	then	GOOD	x_2	
#2	if $F_{22} \geq 4$	then	GOOD	x_2	
#3	if $F_{23} \geq 6$	then	GOOD	x_4	
#4	if $F_{31} \geq 6$ and $F_{51} \geq 1$	then	GOOD	x_4	
#5	if $F_{31} \geq 6$ and $F_{33} \geq 5$	then	GOOD	x_4	
#6	if $F_{51} \geq 1$ and $F_{12} \geq 5$	then	GOOD	x_2	
#7	if $F_{12} \geq 4$ and $F_{33} \geq 5$	then	GOOD	x_4	
#8	if $F_{51} \geq 1$ and $F_{12} \geq 4$ and $F_{43} \geq 2$	then	GOOD	x_2	X

Table 74 - Third iteration economic optimization bis: optimized portfolios

Portfolio	Projects								Costs (€)	Preference
x_1	2	3	4	7	8	11	15	19	299'574	
x_2	2	4	8	10	12	14	19		294'965	good
x_3	2	3	4	7	8	15	17	19	294'738	good

Table 75 – Third iteration economic optimization bis: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	8	6	5	2	1	4	3	8	5	4	2	8	7	4	1	1
x_2	7	6	6	2	1	4	3	7	6	5	2	7	7	4	0	0
x_3	7	6	5	2	1	4	3	8	4	3	2	8	7	5	2	1

The third iteration brought to 3 optimized portfolios, reported in Table 74 and in Table 75. By aid of visual representation in Figure 80, the DMs indicated as 'good' portfolios x_2 and x_3 (the last because of roof's insulation and new layout).

Among the rules obtained by DRSA and listed in Table 76, the #3 was chosen as better representative of DMs preferences.

Table 76 - Third iteration economic optimization bis: decision rules

Rules				Supported by	Chosen
#1	if $F_{31}\geq6$	then	GOOD	x_2	
#2	if $F_{23}\geq6$	then	GOOD	x_2	
#3	if $F_{33}\geq5$	then	GOOD	x_2	X
#4	if $F_{34}\geq5$	then	GOOD	x_3	
#5	if $F_{44}\geq2$	then	GOOD	x_3	

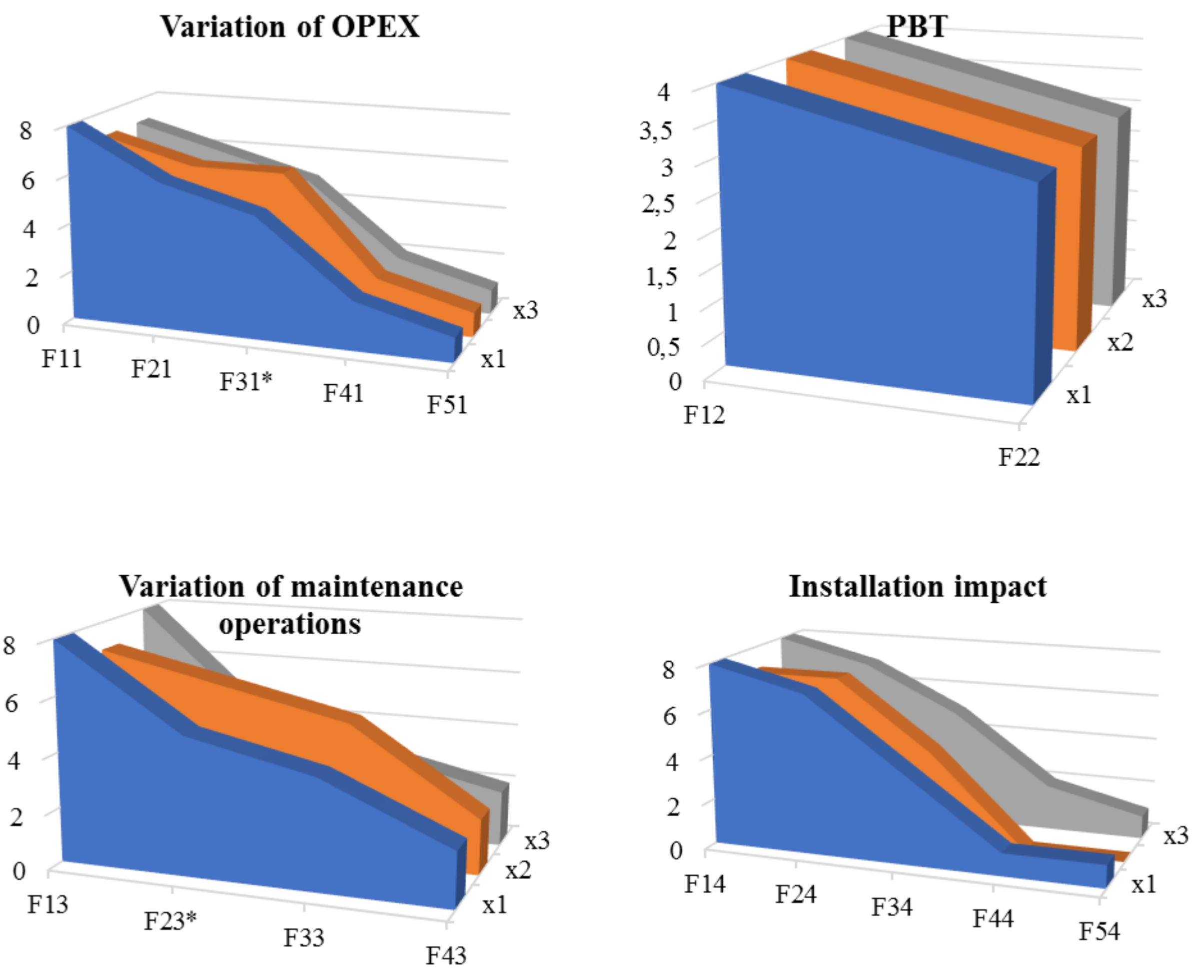


Figure 80 – Third iteration economic optimization bis: visual satisfaction achievements

Table 77 - Fourth iteration economic optimization bis: optimized portfolios

Portfolio	Projects							Costs (€)	Preference
x_1	2	4	8	10	12	14	19	294’965	good
x_2	2	4	10	12	14	17	19	297’840	

Table 78 – Fourth iteration economic optimization bis: matrix of satisfaction achievements

	Variation of OPEX					PBT		Variation maint. op.				Installation impact				
Portfolio	F_{11}	F_{21}	F_{31}*	F_{41}	F_{51}	F_{12}	F_{22}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}	F_{24}	F_{34}	F_{44}	F_{54}
x_1	7	6	6	2	1	4	3	7	6	5	2	7	7	4	0	0
x_2	6	6	6	2	1	4	3	7	6	5	2	7	7	4	1	0

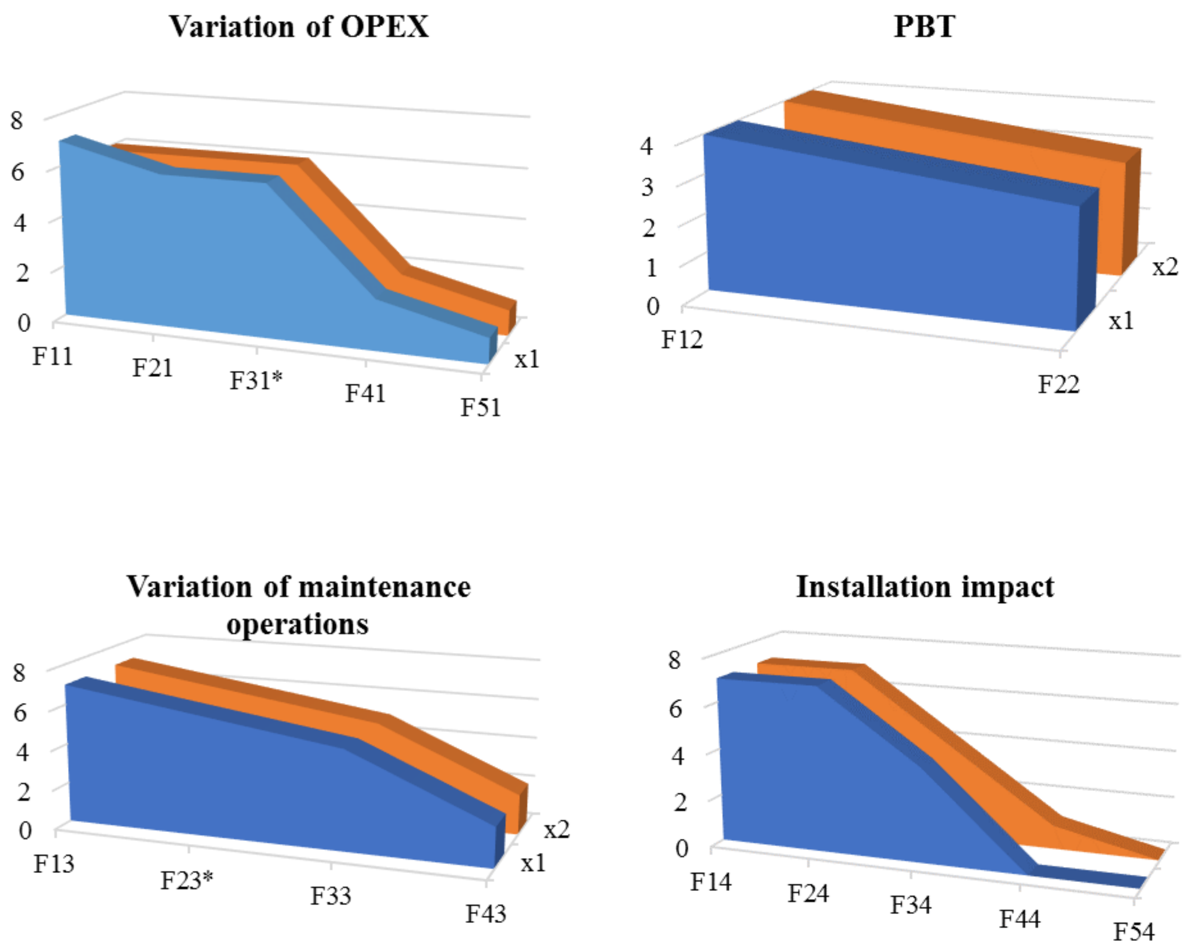


Figure 81 – Fourth iteration economic optimization bis: visual satisfaction achievements

The fourth iteration offered only two portfolios, reported again in Table 77 Table 78 and Figure 81, but the DMs chose the first because less impacting on overall OPEX. In fact x_1 contained the project on ‘Heaters’ while x_2 the project on ‘ACR’, that is expected to be less profitable.

The fourth iteration ended with one decision rule, reported in Table 79, confirming in the next optimization the portfolio x_1 as optimal.

Table 79 - Fourth iteration economic optimization bis: decision rule

	Rules			Supported by	Chosen
#1	if $F_{11} \geq 7$	then	GOOD	x_1	X

6.3.2 Comfort optimization

The first iteration started showing the DMs the 9 optimized portfolios reported in Table 80 and classified in Table 81 and graphically in Figure 82. Firstly, analyzing the figures, the DMs selected:

- x_3 and x_4 for visual comfort profile;
- x_8 for thermal summer comfort;
- x_1 for people satisfaction.

Later the project x_4 was removed because the opportunity on building's lighting is very expensive and x_9 because too imprinted towards indoor quality, while x_5 was added.

Table 80 - First iteration comfort optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	2	4	7	8	11	15	16	17	19	20	279'087	good
x_2	1	2	4	5	8	11	14	17	19	20	298'155	
x_3	4	7	8	9	11	14	17	19	20		294'589	good
x_4	2	4	7	8	10	11	15	17	19		271'087	?
x_5	1	2	4	7	8	11	15	16	17	19	296'087	good
x_6	1	2	4	7	8	9	11	14	17		295'069	
x_7	2	4	6	7	8	11	15	17	19		291'087	
x_8	1	2	4	5	7	8	11	15	17	20	285'853	good
x_9	7	13	14	16	17						297'350	

Table 81 - First iteration comfort optimization bis: matrix of satisfaction achievements

Portfolio	Visual comfort				Therm. comfort winter				Therm. comfort summer				Indoor quality			People's satisfaction		
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}*	F_{32}	F_{42}	F_{13}	F_{23}*	F_{33}	F_{43}	F_{14}*	F_{24}	F_{34}	F_{15}*	F_{25}	F_{35}
x_1	10	8	3	2	10	8	3	1	10	9	4	1	10	4	1	10	8	7
x_2	10	9	3	2	10	7	4	1	10	9	4	0	10	2	1	10	7	4
x_3	9	7	4	2	9	7	3	1	9	8	3	1	9	3	1	9	8	5
x_4	9	7	3	3	9	8	3	1	9	8	3	1	9	3	1	9	7	6
x_5	10	8	2	2	10	9	4	1	10	9	4	1	10	4	1	10	7	7
x_6	9	7	2	1	9	8	5	1	9	8	4	1	9	3	1	9	6	4
x_7	9	6	2	2	9	8	4	2	9	8	4	1	9	4	1	9	6	6
x_8	10	8	2	1	10	7	4	1	10	9	6	1	10	3	1	10	7	5
x_9	5	4	1	0	5	4	1	0	5	4	1	1	5	5	1	5	5	3

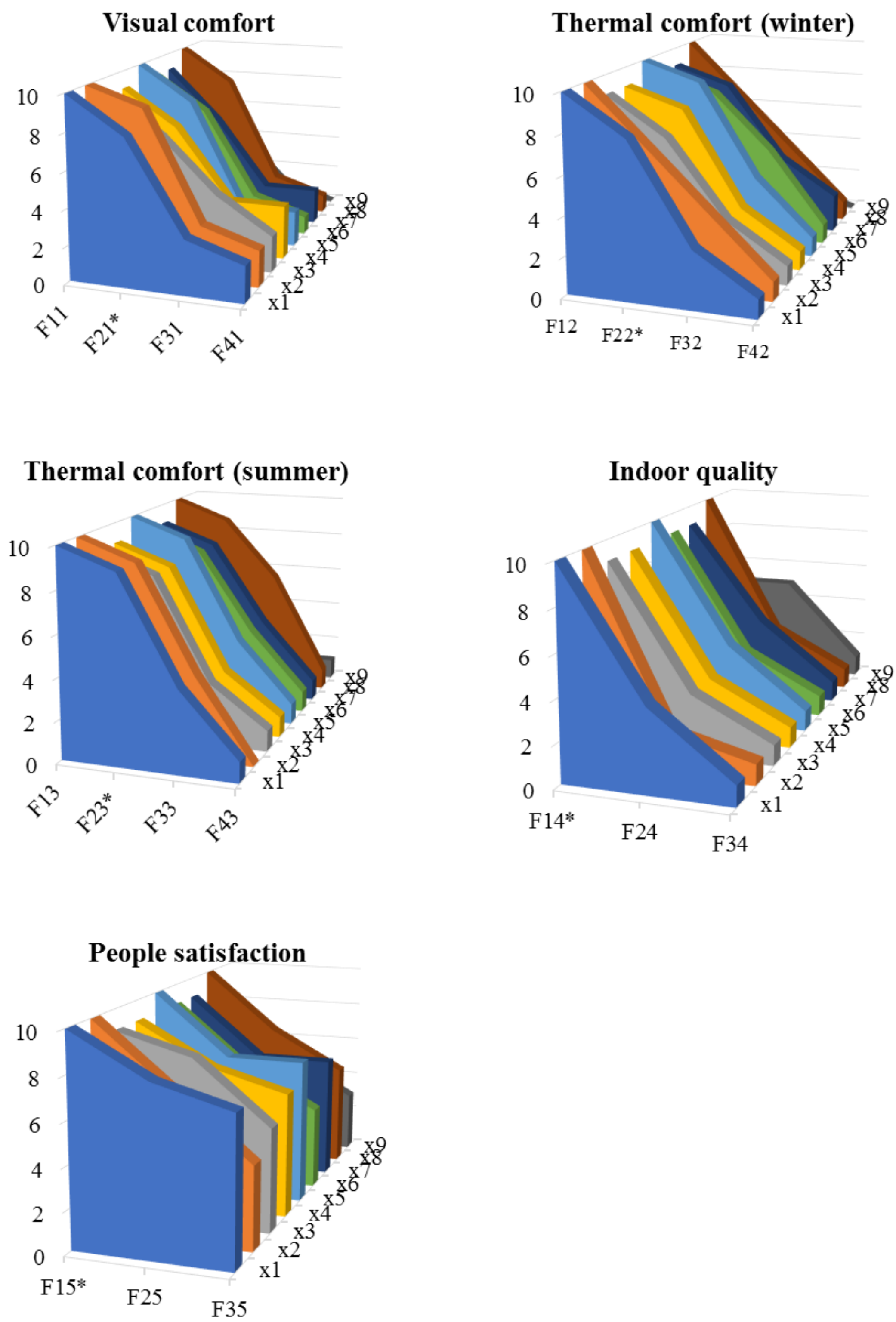


Figure 82 – First iteration comfort optimization bis: visual satisfaction achievements

Table 82 - First iteration comfort optimization bis: decision rule

	Rules			Supported by	Visual	Th. heat	Satisf.	Chosen
#1	if $F_{31}\geq4$	then	GOOD	x_3	?			
#2	if $F_{22}\geq9$	then	GOOD	x_5		?		
#3	if $F_{33}\geq6$	then	GOOD	x_8				
#4	if $F_{25}\geq8$	then	GOOD	x_1, x_3			?	
#5	if $F_{35}\geq7$	then	GOOD	x_1, x_5			?	
#6	if $F_{11}\geq10$ and $F_{22}\geq8$	then	GOOD	x_1, x_5		?		
#7	if $F_{11}\geq10$ and $F_{43}\geq1$	then	GOOD	x_1, x_5, x_8				
#8	if $F_{11}\geq10$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8				
#9	if $F_{11}\geq10$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#10	if $F_{21}\geq8$ and $F_{22}\geq8$	then	GOOD	x_1, x_5	?	?		?
#11	if $F_{21}\geq8$ and $F_{43}\geq1$	then	GOOD	x_1, x_5, x_8	?			
#12	if $F_{21}\geq8$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8	?			
#13	if $F_{21}\geq8$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8	?		?	
#14	if $F_{31}\geq3$ and $F_{24}\geq4$	then	GOOD	x_1	?			
#15	if $F_{12}\geq10$ and $F_{22}\geq8$	then	GOOD	x_1, x_5		?		
#16	if $F_{12}\geq10$ and $F_{43}\geq1$	then	GOOD	x_1, x_5, x_8				
#17	if $F_{12}\geq10$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8				
#18	if $F_{12}\geq10$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#19	if $F_{22}\geq8$ and $F_{13}\geq10$	then	GOOD	x_1, x_5		?		
#20	if $F_{22}\geq8$ and $F_{23}\geq9$	then	GOOD	x_1, x_5		?		
#21	if $F_{22}\geq8$ and $F_{14}\geq10$	then	GOOD	x_1, x_5		?		
#22	if $F_{22}\geq8$ and $F_{15}\geq10$	then	GOOD	x_1, x_5		?	?	X
#23	if $F_{13}\geq9$ and $F_{43}\geq1$	then	GOOD	x_1, x_3, x_5, x_8				
#24	if $F_{13}\geq10$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8				
#25	if $F_{13}\geq10$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#26	if $F_{23}\geq9$ and $F_{43}\geq1$	then	GOOD	x_1, x_5, x_8				
#27	if $F_{23}\geq9$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8				
#28	if $F_{23}\geq9$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#29	if $F_{43}\geq1$ and $F_{14}\geq10$	then	GOOD	x_1, x_5, x_8				
#30	if $F_{43}\geq1$ and $F_{15}\geq10$	then	GOOD	x_1, x_5, x_8			?	
#31	if $F_{14}\geq10$ and $F_{24}\geq3$	then	GOOD	x_1, x_5, x_8				
#32	if $F_{14}\geq10$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#33	if $F_{24}\geq3$ and $F_{15}\geq10$	then	GOOD	x_1, x_5, x_8			?	
#34	if $F_{24}\geq4$ and $F_{25}\geq7$	then	GOOD	x_1, x_5			?	
#35	if $F_{15}\geq10$ and $F_{35}\geq5$	then	GOOD	x_1, x_5, x_8			?	
#36	if $F_{31}\geq3$ and $F_{22}\geq8$ and $F_{33}\geq4$	then	GOOD	x_1	?	?		?
#37	if $F_{31}\geq3$ and $F_{33}\geq4$ and $F_{43}\geq1$	then	GOOD	x_1	?			
#38	if $F_{32}\geq4$ and $F_{43}\geq1$ and $F_{25}\geq7$	then	GOOD	x_5, x_8		?	?	?

#39	if $F_{32} \geq 4$ and $F_{24} \geq 3$ and $F_{25} \geq 7$	then	GOOD	x_1, x_5, x_8	?	?	?
#40	if $F_{32} \geq 4$ and $F_{25} \geq 7$ and $F_{35} \geq 5$	then	GOOD	x_5, x_8	?	?	?
#41	if $F_{33} \geq 4$ and $F_{43} \geq 1$ and $F_{25} \geq 7$	then	GOOD	x_1, x_5, x_8		?	

Table 83 - Second iteration comfort optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	2	4	7	8	11	15	16	17	19	20	279’087	
x_2	1	2	4	7	8	11	15	16	17	19	296’087	
x_3	1	2	4	7	8	11	15	17	19	20	241’087	good

Table 84 - Second iteration comfort optimization bis: matrix of satisfaction achievements

Portfolio	Visual comfort				Therm. comfort winter				Therm. comfort summer				Indoor quality			People's satisfaction		
	F_{11}	**F_{21}***	**F_{31}**	**F_{41}**	**F_{12}**	**F_{22}***	**F_{32}**	**F_{42}**	**F_{13}**	**F_{23}***	**F_{33}**	**F_{43}**	**F_{14}***	**F_{24}**	**F_{34}**	**F_{15}***	**F_{25}**	**F_{35}**
x_1	10	8	3	2	10	8	3	1	10	9	4	1	10	4	1	10	8	7
x_2	10	8	2	2	10	9	4	1	10	9	4	1	10	4	1	10	7	7
x_3	10	8	3	2	10	8	4	1	10	9	5	1	10	3	1	10	7	6

The first optimization brought too many rules (exactly 41 and reported in Table 82) to be presented to the DMs. For this reason, one decided to screen the options looking for multiple satisfaction of the three most relevant considered criteria: ‘Visual comfort’, ‘Thermal comfort heating’, ‘People’s satisfaction’. There are no triple intersections but 6 rules are filtered and only 2 are limited to the above mentioned criteria.

DMs decided the rule #22, involving thermal heating and people’s satisfaction.

The outputs of the second iteration are reported in Table 83 and Table 84. From a first view on Figure 83, the projects seemed all similar in terms of satisfaction achievement, for this reason the driver for the selection was the contents of portfolios. x_1 was not chosen because of roof’s insulation, whilst x_3 was preferred to x_2 for smoking room.

DRSA elaborated two rules for the second iteration, both reported in Table 85, and the last was chosen because optimizing both the first two criteria.

Selecting that decision rule, a single portfolio was generated in the third iteration, shown in Table 86, ending the procedure.

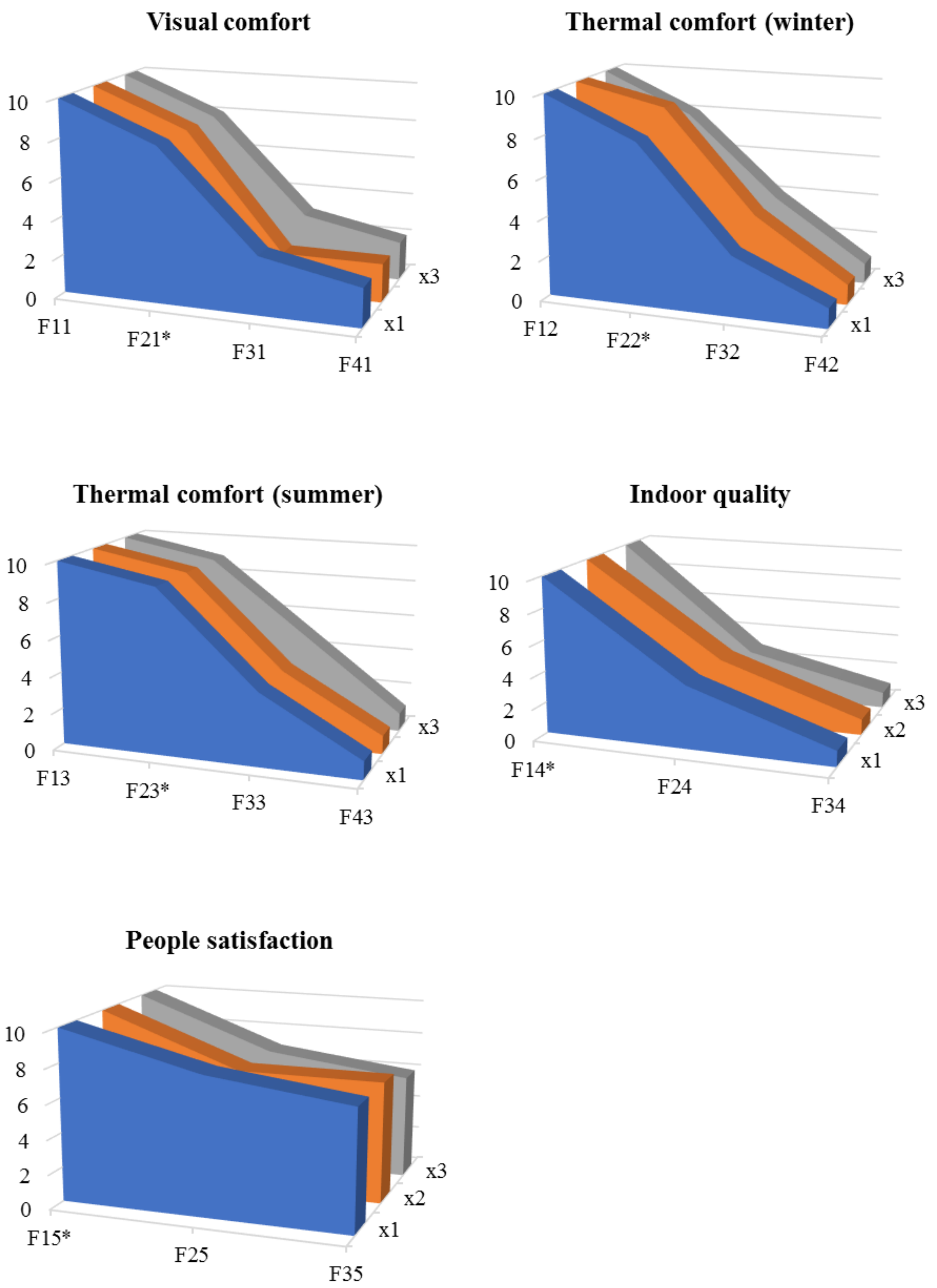


Figure 83 – Second iteration comfort optimization bis: visual satisfaction achievements

Table 85 – Second iteration comfort optimization bis: decision rules

	Rules			Supported by	Chosen
#1	if $F_{33} \geq 5$	then	GOOD	x_3	
#2	if $F_{31} \geq 3$ and $F_{32} \geq 4$	then	GOOD	x_3	X

Table 86 - Third iteration comfort optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	11	15	17	19	20	241'087	good

6.3.3 External image optimization

Considering the 11 optimized portfolios of the first iteration, shown in Table 87 and classified Table 88, the DMs considered initially portfolios x_1, x_2 and x_3 for people's satisfaction and x_8 and x_9 for CO_2 emission helped by illustrations of Figure 84. Later, subset x_1 and x_2 were substituted with x_3 because it considered the new layout and less projects on comfort. Portfolio x_9 was chosen because of high saving and comfort due to expensive projects.

The decision rules induced from the class 'good' and reported in Table 89 were just three, and the third is suddenly considered too extreme. Between #1 and #2 the choice fell on the first because less conservative.

Table 87 - First iteration ext. image optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	11	14	16	17	19	289'569	
x_2	2	4	7	8	11	14	16	17	19	20	272'569	
x_3	1	2	4	7	8	11	15	16	17	19	296'087	good
x_4	1	2	4	5	8	11	14	17	19	20	298'155	
x_5	1	2	4	5	8	12	14	17	19		298'901	
x_6	2	4	5	8	9	11	17	19			296'155	
x_7	2	4	5	8	10	11	17	19			299'155	
x_8	1	4	7	8	9	12	17				299'835	good
x_9	8	9	10	17							295'465	good
x_{10}	1	2	4	8	12	16	17	19			296'635	
x_{11}	1	2	4	7	8	9	11	17	19		298'569	

Table 88 - First iteration ext. image optimization bis: matrix of satisfaction achievements

	People's satisfaction			Visual impact					Emission CO_2				Reliability				
Portfolio	**F_{11}***	**F_{21}**	**F_{31}**	**F_{12}**	**F_{22}**	**F_{32}***	**F_{42}**	**F_{52}**	**F_{13}**	**F_{23}**	**F_{33}***	**F_{43}**	**F_{15}**	**F_{25}**	**F_{35}**	**F_{45}**	**F_{55}**
x_1	10	7	6	10	8	7	1	0	9	6	1	0	10	10	10	5	3
x_2	10	8	6	10	8	6	1	0	9	5	0	0	10	10	10	4	2
x_3	10	7	7	10	8	6	1	0	9	6	1	0	10	10	10	5	3
x_4	10	7	4	10	9	7	2	1	8	5	1	0	10	9	9	4	3
x_5	9	5	3	9	8	8	2	1	7	5	2	0	9	8	8	5	3
x_6	8	6	4	8	7	6	3	1	6	4	1	1	8	7	7	4	3
x_7	8	6	4	8	7	6	3	2	6	4	1	1	8	7	7	4	2
x_8	7	4	3	7	5	5	1	0	6	3	3	1	7	7	7	5	3
x_9	4	4	2	4	3	3	2	1	3	2	2	2	4	4	4	3	1
x_{10}	8	4	4	8	7	7	1	0	7	5	2	0	8	8	8	6	3
x_{11}	9	6	5	9	7	6	2	0	8	5	2	1	9	9	9	5	4

Table 89 – First iteration ext. Image optimization bis: decision rules

Rules				**Supported by**	**Chosen**
#1	if $F_{31} \geq 7$	then	GOOD	x_3	?
#2	if $F_{33} \geq 3$	then	GOOD	x_8	good
#3	if $F_{43} \geq 2$	then	GOOD	x_9	

Table 90 - Second iteration ext. image optimization bis: optimized portfolios

Portfolio	**Projects**							**Costs (€)**	**Preference**
x_1	1	4	7	8	9	12	17	299'835	?
x_2	1	2	4	9	12	17		299'340	
x_3	1	2	8	10	12	17		295'697	good

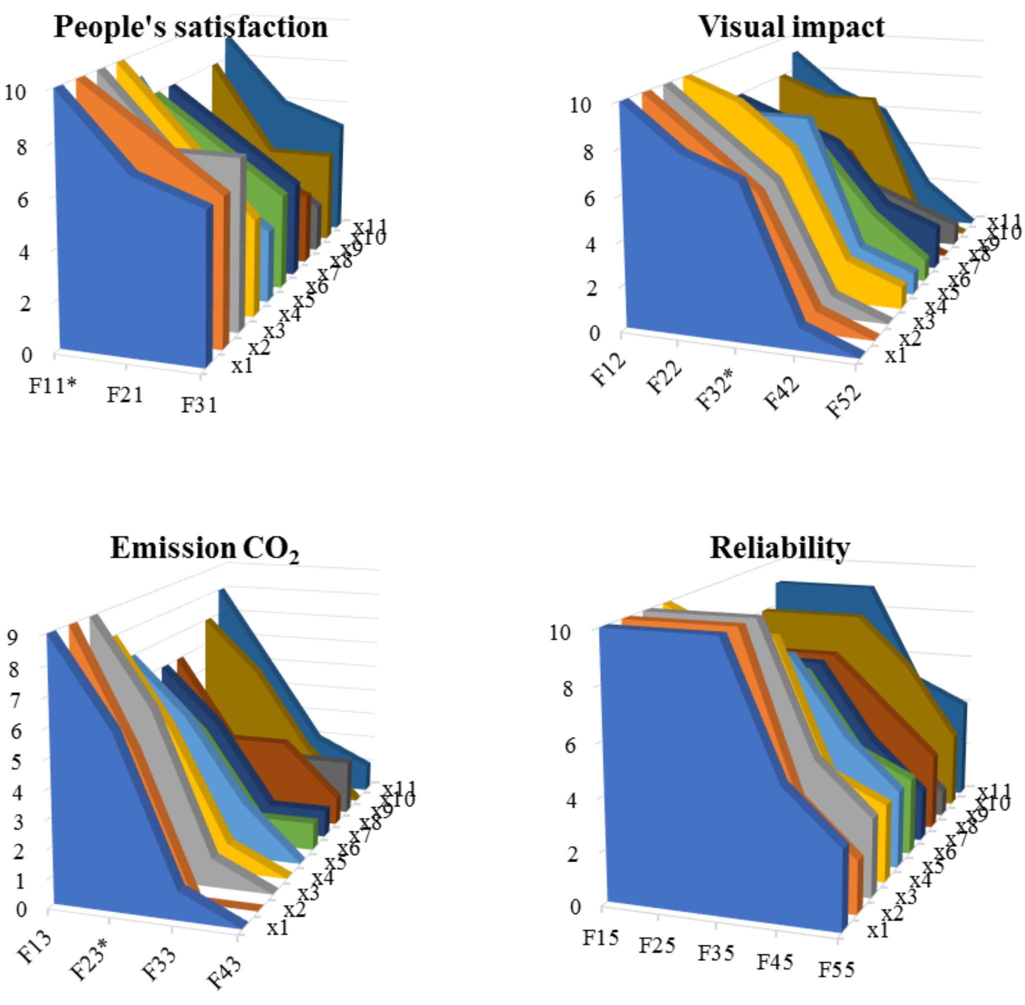


Figure 84 - First iteration ext. image optimization bis: visual satisfaction achievements

The constraint brought to only three portfolios at the second iteration, when the DMs chose the project x_1 from the visual expression of satisfaction achievements in Figure 85, derived from Table 91. After the sight of the projects in Table 90, DMs changed x_1 for x_3 because of comfort and for the sake of image of energy saving (correctly x_3 indicates more projects decreasing CO_2 emissions).

Table 91 - Second iteration ext. image optimization bis: matrix of satisfaction achievements

	People's satisfaction			Visual impact					Emission CO_2				Reliability				
Portfolio	F_{11}*	F_{21}	F_{31}	F_{12}	F_{22}	F_{32}*	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}*	F_{43}	F_{15}	F_{25}	F_{35}	F_{45}	F_{55}
x_1	7	4	3	7	5	5	1	0	6	3	3	1	7	7	7	5	3
x_2	6	2	1	6	6	6	1	0	5	4	3	1	6	6	6	6	4
x_3	6	3	2	6	5	5	1	1	5	4	3	1	6	6	6	5	2

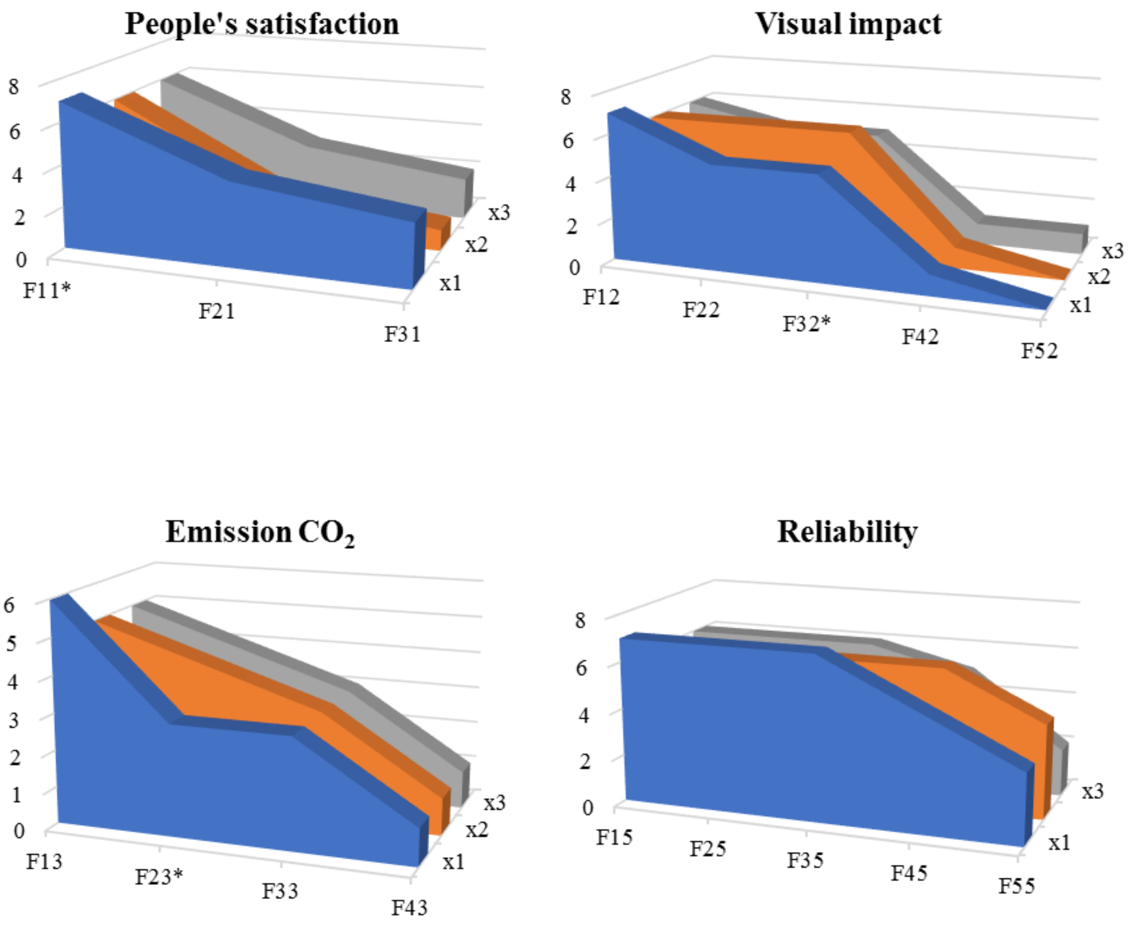


Figure 85 - Second iteration ext. image optimization bis: visual satisfaction achievements

The decision rule most representative of DMs' preferences is #2 of Table 92, remarking again the interest towards the same criteria of the first iteration.

Table 92 – Second iteration ext. Image optimization bis: decision rules

Rules				Supported by	Chosen
#1	if $F_{52}\geq1$	then	GOOD	x_3	
#2	if $F_{21}\geq3$ and $F_{23}\geq4$	then	GOOD	x_3	good
#3	if $F_{31}\geq2$ and $F_{23}\geq4$	then	GOOD	x_3	

Table 93 - Third iteration ext. image optimization bis: optimized portfolios

Portfolio	Projects						Costs (€)	Preference
x_1	1	2	8	9	12	17	292'697	
x_2	1	2	8	10	12	17	295'697	good

Table 94 - Third iteration ext. image optimization bis: matrix of satisfaction achievements

	People's satisfaction			Visual impact					Emission CO_2				Reliability				
Portfolio	**F_{11}***	**F_{21}**	**F_{31}**	**F_{12}**	**F_{22}**	**F_{32}***	**F_{42}**	**F_{52}**	**F_{13}**	**F_{23}**	**F_{33}***	**F_{43}**	**F_{15}**	**F_{25}**	**F_{35}**	**F_{45}**	**F_{55}**
x_1	6	3	2	6	5	5	1	0	5	4	3	1	6	6	6	5	3
x_2	6	3	2	6	5	5	1	1	5	4	3	1	6	6	6	5	2

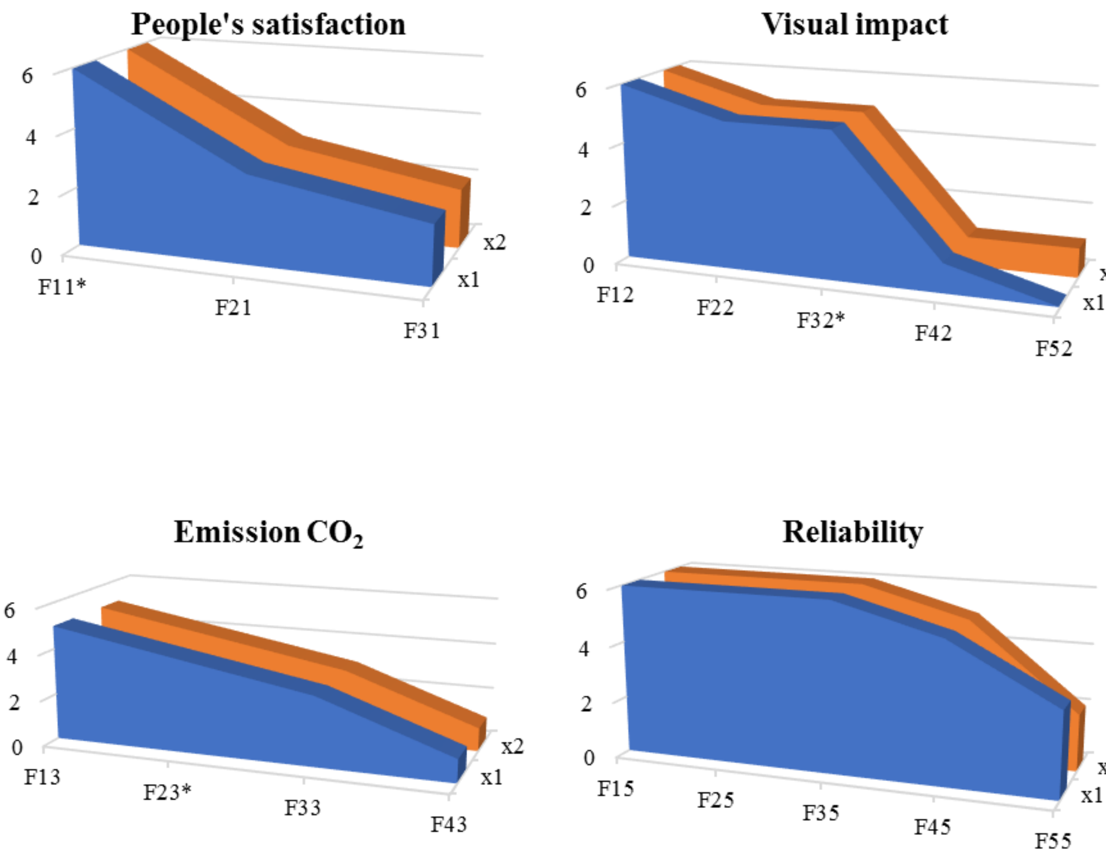


Figure 86 - Third iteration ext. image optimization bis: visual satisfaction achievements

The outputs of the third iteration are shown in Table 93, Table 94, Figure 86 and Table 95. Only two portfolios are considered and the second entered in the class 'good' because of the high-cost project: one assumed that the external image has more benefits from upgrade of environmental lighting than glasses' substitution. The single decision rule confirmed the portfolio supported at the fourth iteration.

Table 95 - Third iteration ext. Image optimization bis: decision rules

Rules				Supported by
#1	if $F_{52} \geq 1$	then	GOOD	x_2

6.3.4 Technical optimization

The number of different portfolios optimized at the first iteration is 7 and they are reported in Table 96 whereas the satisfaction thresholds are in Table 97 and Figure 87.

From an initial sight on visual achievement, DMs noted that from the perspective of 'layout flexibility' all collections are similar, for maintenance standed out x_1 and x_6 while for technical life x_5. Later, the list of projects is considered and x_1 was discarded because similar to x_5, adding 3 new systems to the building so increasing the maintenance requirements. x_2, x_3 and x_6 were added to class 'good' because the high number of projects with considerable technical life.

Table 96 - First iteration technical optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	1	2	4	7	8	11	14	16	17	19	289'569	
x_2	1	2	4	8	12	16	17	19			296'635	good
x_3	1	2	4	7	8	9	11	17	19		298'569	good
x_4	1	2	4	7	8	11	15	16	17	19	296'087	
x_5	2	4	8	9	15	17	19	20			292'901	good
x_6	2	4	7	8	11	14	16	17	19	20	272'569	good
x_7	2	4	5	8	10	11	14	17			295'655	

Table 97 - First iteration technical optimization bis: matrix of satisfaction achievements

Portfolio	Var. maint. Op.				Reliability					Technical life			Duration work		Layout flexibility			
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}	F_{32}	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}	F_{14}	F_{24}	F_{15}	F_{25}*	F_{35}	F_{45}
x_1	10	7	5	3	10	10	10	5	3	10	8	2	8	5	10	9	9	7
x_2	8	6	4	2	8	8	8	6	3	8	7	2	6	4	8	7	7	6
x_3	9	6	4	1	9	9	9	5	4	9	8	3	6	4	9	8	8	7
x_4	10	6	4	2	10	10	10	5	3	10	9	3	8	4	10	9	8	7
x_5	8	4	3	1	8	8	8	4	3	8	7	5	6	3	8	7	6	5
x_6	10	6	5	3	10	10	10	4	2	10	8	3	9	5	10	8	8	6
x_7	8	6	4	1	8	7	7	4	2	7	5	1	7	7	8	7	7	4

Among the seven decision rules obtained by the 4 portfolios in the class 'good', reported in Table 98, the DMs detected only two considering the two most assessed criteria (i.e. variation of maintenance operations and technical life), then selected the less conservative.

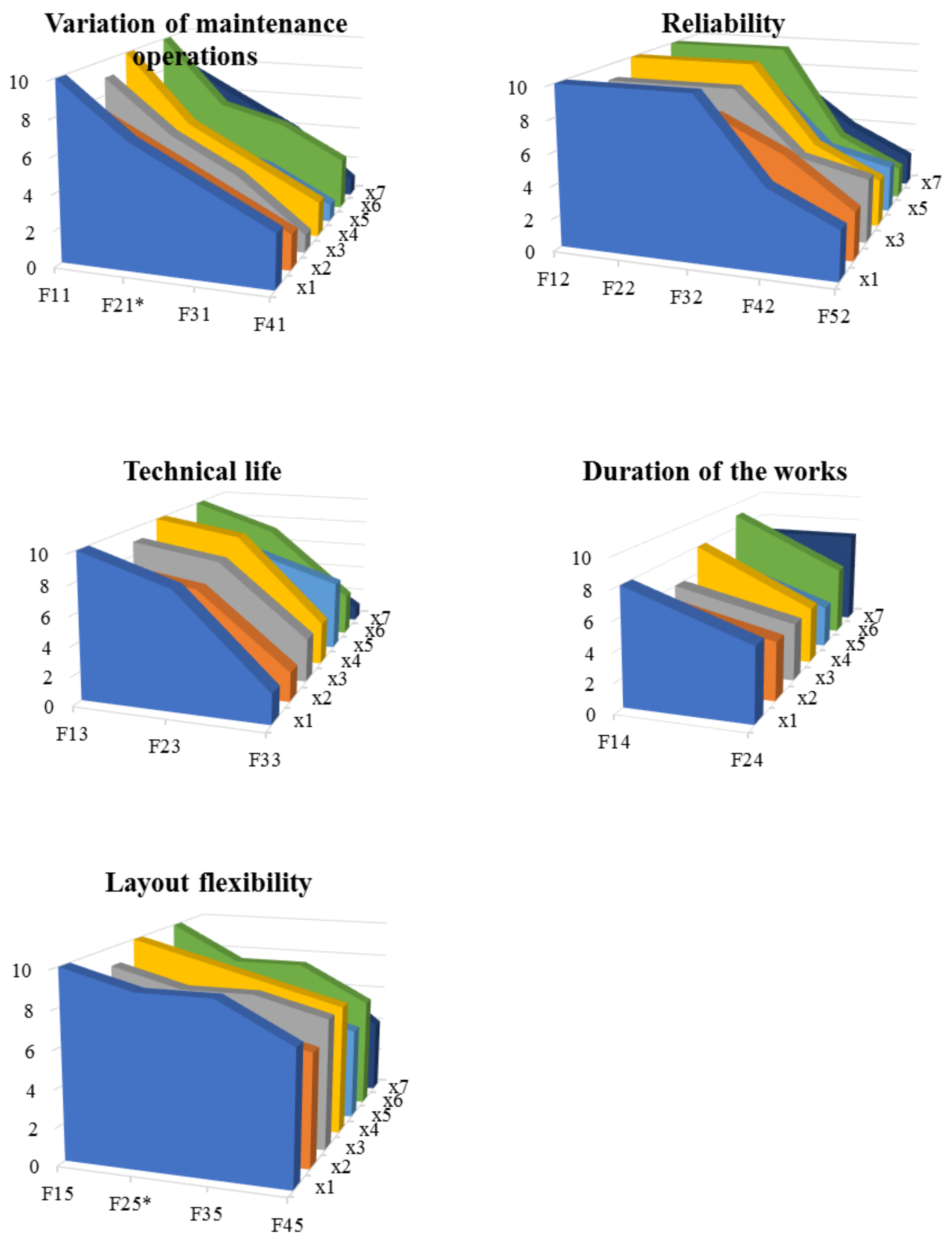


Figure 87 – First iteration technical optimization bis: visual satisfaction achievements

Table 98 - First iteration technical optimization bis: decision rules

	Rules			Supported by	Chosen
#1	if $F_{42}\geq6$	then	GOOD	x_2	
#2	if $F_{52}\geq4$	then	GOOD	x_3	
#3	if $F_{33}\geq5$	then	GOOD	x_5	
#4	if $F_{14}\geq9$	then	GOOD	x_6	
#5	if $F_{31}\geq5$ and $F_{33}\geq3$	then	GOOD	x_6	X
#6	if $F_{41}\geq3$ and $F_{33}\geq3$	then	GOOD	x_6	?
#7	if $F_{33}\geq4$ and $F_{24}\geq5$	then	GOOD	x_6	

Table 99 - Second iteration technical optimization bis: optimized portfolios

Portfolio	Projects										Costs (€)	Preference
x_1	2	4	7	8	11	14	16	17	19	20	272’569	
x_2	2	4	8	9	12	14	17	19			297’635	good
x_3	2	4	7	8	9	11	14	17	19		261’569	
x_4	2	4	8	9	11	14	17	19	20		296’889	
x_5	2	4	8	10	11	14	17	19	20		299’889	

Table 100 - Second iteration technical optimization bis: matrix of satisfaction achievements

Portfolio	Var. maint. Op.				Reliability					Technical life			Duration work		Layout flexibility			
	F_{11}	F_{21}*	F_{31}	F_{41}	F_{12}	F_{22}	F_{32}	F_{42}	F_{52}	F_{13}	F_{23}	F_{33}	F_{14}	F_{24}	F_{15}	F_{25}*	F_{35}	F_{45}
x_1	10	6	5	3	10	10	10	4	2	10	8	3	9	5	10	8	8	6
x_2	8	6	5	2	8	8	8	5	3	8	6	3	6	5	8	7	7	5
x_3	9	6	5	2	9	9	9	4	3	9	7	3	7	5	9	8	8	6
x_4	9	6	5	2	9	9	9	4	3	9	7	4	7	5	9	7	7	5
x_5	9	6	5	2	9	9	9	4	2	9	7	3	8	6	9	7	7	4

The second iteration offered 5 optimized portfolios, reported in Table 99 and Table 100. The DMs, after the consultation of the satisfaction classes in Figure 88, detected the portfolio x_1 because of a light prevalence on ‘variation in maintenance operations’ and ‘Technical life’, but later changed for x_2 because the unique that does not add new machines.

The DRSA detected a single rule confirming the same portfolio in the next iteration.

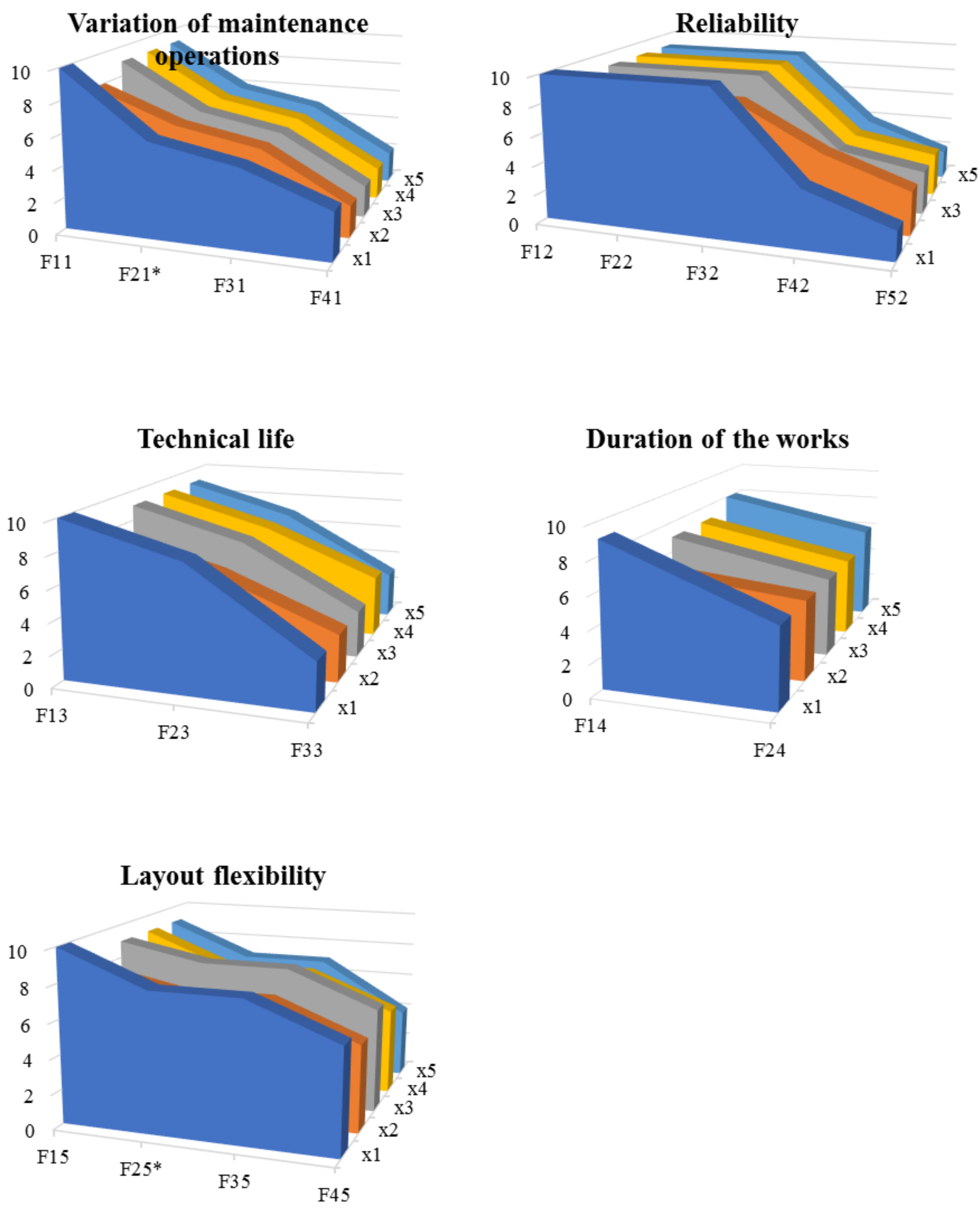


Figure 88 – Second iteration technical optimization bis: visual satisfaction achievements

Table 101 - Second iteration technical optimization bis: decision rules

Rules				Supported by	Chosen
#1	if $F_{42} \geq 5$	then	GOOD	x_2	

6.3.5 Convergence of sharing functions

As in the first set of optimization, the convergence of the share of optimal projects is shown in plots of Figure 89 for any optimization. Again the preferences and the consistent rules, proposed by DRSA approach, promoted projects with low cost from the first iterations while others more expensive entered slowly (e.g. Env. Lighting and Glass substitution). The shape of the comfort optimization shows how the resources were already well distributed at the first iteration (except for the project 'ACR' indeed of great importance for comfort).

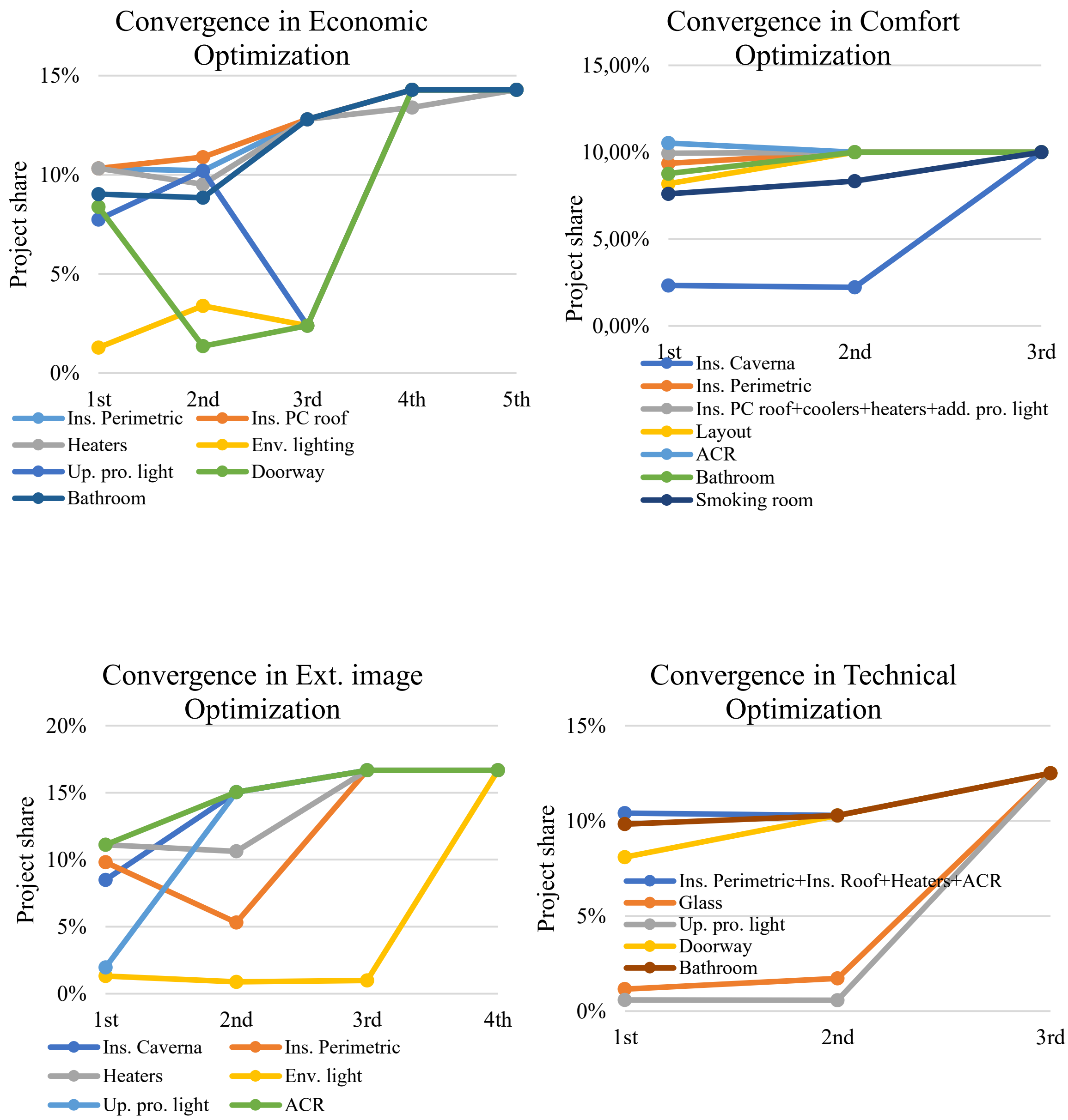


Figure 89 – Convergence of sharing functions for the new four optimizations

Conclusions

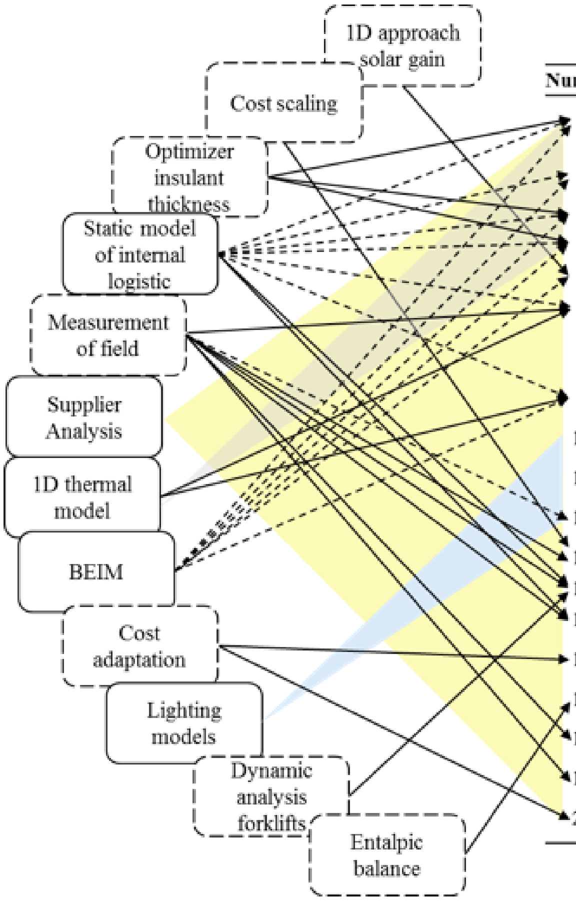
In this work of thesis, a methodology was proposed to develop a possible retrofit program for an industrial building of an important car manufacturer. In the bibliographic context of limited availability of studies and analysis for this type of client, the steps of the retrofit program proposed in Figure 1 were adapted up to a preliminary planning phase.

The pre-retrofit moment clarified the subject and the scope of the investigation that is the facility where preparation and painting of bumpers is executed, processes requiring a high degree of occupancy resulting so in many critical operational and maintenance understandings, reported in Chapter 1, and extending the boundary of the classic retrofit analysis to liveability and services improvements. The **diagnosis** and auditing phase, object of Chapter 2, was assessed by personal interviews with most supervisors involved in the product's transformation and building's investments, though a bibliographic review aided to determine standard measures concerning common problems of industrial assets. A screening procedure of such problems collected was performed, in order to reduce the relevant number of possible improvement's actions to investments regarding the building and the occupants, being the interventions of processes controlled by power over the facility managers. The resulting analysis focused on thermal, lighting, logistic and liveability improvements, developing a tool that could potentially be applied for other industrial customers.

The identification of retrofit options was driven by suggestions collected during the previous phase, together with the data on building relevant to design and valorise the possible improvement projects through feasibility studies: this chapter ended listing the projects considered profitable for the industrial client and the identification of potential criteria involved in a decisional step from a bibliographic review on renovation's literature. The remaining chapters of the thesis complete this pre-commissioning step: in Chapter 3 the design methodologies, used to develop the feasibility studies of retrofit measures, were described and later applied in Chapter 4. In Figure 90, the interactions between these two chapters are shown: with solid arrows or coloured beams the direct footprints of the methodological approach into a single project, whereas the dotted lines indicate a necessary contribution but not a direct application, for example a validation or a check by measurement of the real method concerned.

To sum up, the analysis of suppliers in the local and available market aided to determine the investment costs of each option, being a characterizing influence for the planning ahead. The building energy aspects were developed by 1D thermal approach, supported by a validation on EnergyPlus and a seasonal balance, and used to determine the economic return of traditional classical retrofit‘s measures. The static modelling of logistics helped the other analyses thanks to scheduling, internal handling and the estimation on opening‘s frequency of doorways. A general aid was given by measurements on field: inspection by infrared camera for the installation of delayers determining the vertical temperature gradient, timing during the product's chain, lengths and dimensions of areas. Chapter 4 ended with the presentation of a **database** obtained filling for each project the impact on a single criterion with a mark of simple granularity: this matrix will be the input for the choice problem ahead.

The completion of **prioritize the retrofit's investments** was executed by analysing the best combination of the 20 projects under the perspective of satisfy a financial constraint and the criteria' conflicts: this problem was addressed towards the discipline of Decision Analysis, introduced in Chapter 5. In detail, the branch that best fits the problem's setting is the **Portfolio Decision Analysis** placing as solution for the theme of resource allocation for no-strategic investments in a company's environment, as already suggested by [28]. A nouvelle approach based on dominance [72] was presented from a theoretical sight and later applied in collaboration with the "Department of Economics and Business, University of Catania", offering the possibility to implement a new model of top-down investments for vertical organizations: centralizing the power of choices with a transversal knowledge on parallel retrofit plans, under the point of view of conflictual criteria and departments seeking for individual benefits. By this method, the centralization of the decisional-flow in few figures with a better understanding of areas' limits and technically experienced or informed on projects, even though designed by external consultants, led to a 'transparent' prioritization of investments and a better collective choice, because the projects of different nature are presented on the base of common criteria.



Number	Code	Cost (€)	Name
1	Ins. Caverna	66'000	Insulation of the confining wall with La Caverna
2	Ins. Perimetric	15'980	Insulation of permetric wall
3	Ins. Roof	179'157	Insulation shop office roof
4	Ins. PC roof	9'438	Insulation paint central roof
5	Cool roof	77'266	Cool roof
6	Delayers	165'000	Installation of air delayers
7	Coolers	13'680	Adiabatic cooler for microcooling
8	Heaters	2'795	Radiant heaters for microheating
9	Glass	142'000	Substitution glass for sheds
10	Env. light	145'000	Substitution environment lighting with LED
11	Add pro. light	10'506	Upgrade process lighting increasing lux
12	Up. pro. light	60'252	Upgrade existing process lighting with LED
13	Demolition	145'000	Demolition of hanging conveyors
14	Doorway	29'000	Refurbishment doorway south
15	Layout	35'518	New warehouse layout
16	Waterproofing	104'000	Roof waterproofing refurbishment
17	ACR	5'670	Increase of Air Change Rate
18	Dressing room	260'000	Refurbishment dressing rooms
19	Bathroom	32'500	Refurbishment bathrooms
20	Smoking room	49'000	Adding a smoking room

Figure 90 – Design methodologies' footprint to sustain projects' development

The application of this method and the related interactions, throughout the decisional flow, with Decision Makers were reported in Chapter 6, noting how the technical sensibility on some criteria drove the analysis towards a clear convergence. Because of the quantity of overall criteria considered during the problem's setup, the algorithm made necessary the separation of the optimization into 4 parallel parts, each one following a determined subset of criteria. For each procedure, the DMs was asked to indicate preferences and to add new constraints at the problem on the criteria, directions of the optimization, without influences from the others considered in the database. The criteria most assessed, so optimized, were variation of operational costs, Pay Back Time, impact on maintenance, users‘ satisfaction, thermal and visual comfort, that were seen separately for each procedure showing sometimes the conflictual nature (e.g. in external image optimization one seeks the reduction of consumption and the people’s satisfaction simultaneously).

Table 102 – Resulting portfolios after the 8 optimizations

Type	Code	Cost (€)	Economic optimization		Comfort optimization		External Image optimization		Technical optimization		Occurrences
			300 k€	400 k€	300 k€	400 k€	300 k€	400 k€	300 k€	400 k€	
Thermal projects	Ins. Caverna	66’000	✗	✗	✓	✓	✓	✓	✗	✗	4
	Ins. Perimetric	15’980	✓	✓	✓	✓	✓	✓	✓	✓	8
	Ins. Roof	179’157	✗	✓	✗	✗	✗	✗	✗	✗	1
	Ins. PC roof	9’438	✓	✓	✓	✓	✗	✓	✓	✓	7
	Cool roof	77’266	✗	✗	✗	✗	✗	✗	✗	✗	0
	Delayers	165’000	✗	✗	✗	✗	✗	✗	✗	✗	0
	Coolers	13’680	✗	✓	✓	✓	✗	✓	✗	✗	4
	Heaters	2’795	✓	✓	✓	✓	✓	✓	✓	✗	7
	Glass	142’000	✗	✗	✗	✓	✗	✗	✓	✓	3
Lighting projects	Env. light	145’000	✓	✗	✗	✗	✓	✗	✗	✗	2
	Add pro. light	10’506	✗	✗	✓	✓	✗	✗	✗	✗	2
	Up. pro. light	60’252	✓	✓	✗	✗	✓	✓	✓	✓	6
Logistics projects	Demolition	145’000	✗	✗	✗	✗	✗	✗	✗	✗	0
	Doorway	29’000	✓	✗	✗	✗	✗	✓	✓	✓	4
	Layout	35’518	✗	✓	✓	✓	✗	✗	✗	✗	3
Liveability projects	Waterproofing	104’000	✗	✗	✗	✗	✗	✓	✗	✓	2
	ACR	5’670	✗	✗	✓	✓	✓	✓	✓	✓	6
	Dressing room	260’000	✗	✗	✗	✗	✗	✗	✗	✗	0
	Bathroom	32’500	✓	✓	✓	✓	✗	✓	✓	✓	7
	Smoking room	49’000	✗	✓	✓	✓	✗	✓	✗	✗	4
			7	9	10	11	6	11	8	8	

After a first optimization with a fixed budget of 400 k€, the analyst decided to revisit the model by reducing the available budget of 100 k€ and repeated the procedure again in order to test the robustness of the results.

The **outputs** of the optimizations are reported in Table 102 with the green cells meaning that the project belongs to the final portfolio: one can note that the 50% of projects chosen improve thermal aspects of the building, whereas 27%[41] only the liveability and occupants' comfort. Noting that each optimization included at least one project on lighting, the most welcomed is the upgrade of process lighting. Regarding the logistic, as expected, the demolition project was not chosen and had a limited impact during the optimization. In the liveability area, instead, the refurbishment of bathroom and the increase of air change rate are the most considered opportunities for the occupants.

A result to comment is the large acceptance of traditional retrofit's projects, i.e. renovation of building's envelope, that can be justified as a direct effect on positive setting of both economic and thermal comfort criteria. Some among the most expensive opportunities instead are never considered in the ending portfolio, as expected, but only the installation of air delayers is reputed interesting: this result is direct effect of the algorithm that is based on the quantities of projects attaining a determined satisfaction level, so low-cost interventions are favored.

The impact of a second optimization with a **lower budget** confirmed the projects of the first, prioritizing mainly a subset. The average size of the ending portfolios indeed decreased largely for the 'External image optimization', while in the 'Technical optimization' the substitution of waterproofing layer was replaced with the installation of heaters, a mathematical effect, because of the budget difference. The economic optimization at low budget preferred the less expensive project of 'doorway' for the new layout and the substitution of environmental bulbs to the new roof's insulation, more profitable in financial terms and obtained as new proposal even in 'External image optimization' with 300 k€ as budget.

Table 103 – Degree of priority of projects after the optimization

Priority	Progressive cost (€)	Projects			
1°	15'980	Ins. Perimetric			
2°	60'713	Ins. PC Roof	Heaters	Bathroom	
3°	126'635	Up. proc light	ACR		
4°	284'315	Ins. Caverna	Coolers	Doorway	Smoking room
5°	461'833	Glass	Layout		
6°	721'339	Env. light	Add pro. light	Waterproofing	
7°	900'496	Ins. Roof			

Summing up the **occurrences** of projects among the ending eight portfolios of the optimization, one can classify the prioritizing measures in Table 103 as last output of this work before the site implementation and commissioning: from this rank, one can appreciate how projects of different nature can be finally chosen according to the cumulative of available resources. In addition, the first three degrees of priority consider 3 projects strongly

[41] Actually this value is 31% for budget 400 k€ and 23% for the low budget, meaning that the class of problems of 'liveability' is more effected by resource reduction.

characterized by an economic return and 3 acting positively on occupants, even though the measure of 'Heaters' is favored because of its lowest cost among the treated: attribute that proves again that the resources are separately allocated.

Overall, the **limits** of the methodology proposed can be summarized in the following bullets:

- The diagnosis phase can be very time-consuming if the work is entrusted especially to external actors because, in a framework of a conspicuous manufacturing site to reach the right people of the organization may be difficult or dispersive if the final users are many and the model area wide.
- The use of simple design methodologies is useful and sometime forced because of uncertainty on data and effectiveness of an industrial reality.
- The creation of scenarios, object of further studies, is directly linked to the options and availability of the local market and favored supplier, making necessary an historical knowledge of the customer.
- The variety of projects and criteria leads to a database difficult to set correctly in order to have a fair judgement during the optimization procedure. A clear understanding of customer's technical knowledge, expectation and goals is important to calibrate the problem suitably and possibly guess multiple executions.
- The use of innovative tools, like PDA, to face common choice problems, requires the presence and attention of an analyst which is well informed about the outputs, client's availability and procedure's limits.
- Even though the DRSA procedure uses simple inputs of the DMs, sometimes it brings too much data that cannot be welcomed with attention, for this reason a screening on the most addressed ones previously is necessary.
- The IMO optimization becomes clear by visual aids though the attention of the DMs is devoted towards a limited set of criteria considered most relevant.

A **future perspective** of this work may be:

- developments on the topic of data collection and database's setting;
- revise the quality and quantity of criteria;
- insertion of the engineer in organization's network to achieve optimally the resources needed.

Nomenclature

Roman symbols

A	Surface of the element	m^2
B	Coefficient for electric Battery calculations	
BF	Burden Factor for means timing	-
C	Cost	€
c	Unit cost	€/unit
E	Energy consumption for general carrier	
ef_{CO2}	Emission factor for CO_2 per unit energy	
f	Frequency	times/h
F_{CO2}	Emission of CO_2 associated to the energy utilization	ton_{CO2}
G	Mass flow rate	kg/s
Gr	Grashof number	-
g_n	Solar transmittance of the fenestration element	-
H	Height	M
h	Convective coefficient	$W/m^2/K$
I	Illuminance	Lux
l	Thickness of the material in the stratigraphy	m
L	Length	m
n	Number of quantities considered	-
Nu	Nusselt number	-
P	Power	W
Pr	Prandtl number	-
Q	Thermal energy to the building or to the grid yearly	GJ
$\dot{Q}$	Thermal heat flux	W
q	Thermal heat flux per unit surface	W/m^2

R	Thermal resistance of the element	$K \cdot m^2/W$
r	Economic rates for insulant optimizer	-
r	Radius	m
s	Spacing	m
SF	Saturation Factor of the mean considered	-
T	Air space temperature	°C
t	Time	s
U	Thermal transmittance of the element	$W/m^2/K$
v	Velocity of the mean or of productive flow	m/s
$\dot{V}$	Volumetric Flow Rate	m^3/h
X	Fraction	-

Greek symbols

β	Coefficient of thermal volumetric dilatation	1/K
ε	Emissivity of the surface	-
ς	Solar reflectance of the surface	-
η	Efficiency of the system	-
Θ_i	Turn-on hours for heating system in the month "i"	H
λ	Thermal conductivity	W/m/K
μ	Dynamic viscosity	μPa·s
Φ	Lumen flux of the bulb(s)	lumen
ρ	Density	kg/m^3
σ_0	Stefan-Boltzmann constant	$W/m^2/K^4$
χ	Coefficient for lighting systems calculations	
Ψ	Linear transmittance of the pipeline	W/m/K

IMO-DRSA symbols

A; a_j[42]	Set of projects 'j'	
c_j	Cost of project 'j'	€
G; g_i	Set of criteria 'i'	
Li; $l_{G(i),i}$	G(i) quality thresholds level for criterion 'i'	
C_i; $\varsigma_{G(i)+1,i}$	G(i)+1 qualitative satisfaction classes for criterion 'i'	
P	Subset of projects and potential Portfolio	
x; $\mathbf{x_j}$	Vector identifying portfolio P	
$F_{t,i}(\mathbf{x})$	Number of satisfactory projects of portfolio **x** on the threshold level $l_{t,i}$ of criterion 'i'	
X; $\mathbf{x_j}$	Finite set of portfolios	
Cl; Cl_z	Set of preference ordered decision classes	
Q	Subset of criteria	
D_Q	Dominance operator on the subset of criteria Q	
$D_Q^+(\boldsymbol{x}_j)$	Q-dominating portfolios on subset of criteria Q	
$D_Q^-(\boldsymbol{x}_j)$	Q-dominated portfolios on subset of criteria Q	
$\underline{Q}(Cl_{good})$	Lower approximation of class 'good'	
$\overline{Q}(Cl_{good})$	Upper approximation of class 'good'	

[42] The semicolon separates the elements from the set/vector

Glossary

1D	Mono-dimensional approach
3D	Three-dimensional approach
ACR	Air Change Rate
ACS	Sanitary Hot Water
AGV	Automated Guided Vehicle
APE	Attestato di Prestazione Energetica
ASH	Superheated water (140 °C)
ATU	Air Treatment Unit
BEIM	Building Energy Information Modelling
BPS	Bumper Paint Shop
CAPEX	Capital costs
CDC	Centro Di Consolidamento (Ex-Imbutiti)
CMDPA	Continuous or Mixed Decision Problem Approaches
CTV	Air Treatment Unit
DA	Decision Analysis
DM(s)	Decision Maker(s)
DRSA	Dominance-based Rough Set Approach
DSS	Decision Support System
E+	EnergyPlus software
EDF	Edison Fenice
EHS	Environment Health and Safety
FCA	Fiat Chrysler Automobiles
FEM	Electromotive force
FIAT	Fabbrica Italiana Automobili Torino
GS	General Services
GUI	Graphic User Interface

HDD	Heating Degree Days
HVAC	Heating Ventilation and Air Conditioning System
IEA	International Energy Agency
IMO	Interactive Multi-objective Optimization
KPI	Energy Key Performance Indicator
LED	Bulb technology
LEV	Maserati Levante
MADM	Multiple attribute decision making
MAUT	Multiple Attribute Utility Theory
MCDA	Multi Criteria Decision Analysis
MCDA	Multi Criteria Decision Analysis
MCDM	Multi Criteria Decision Making
MITO	Alfa Romeo Mito
MODM	Multiple Objective Decision Making
OPEX	Operation costs
PBT	Pay Back Time (years)
PDA	Portfolio Decision Analysis
PLC	Programmable Logic Controller
R&D	Research and Development
RES	Renewable Energy Sources
RST	Rough Set Theory
SODM	Single Objective Decision Making
U.M.	Unit of measure
VOC	Volatile Organic Compounds
WCM	World Class Manufacturing

Figure index

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Attachments

Attachment A.

In the first table there are the thermal data of the opaque elements of the envelope, whereas, in the second the transparent ones. The inner elements of stratigraphy are listed first, and the value reported in the second-last column is the overall transmittance (U_{strata}), calculated with Equations 6 and 7.

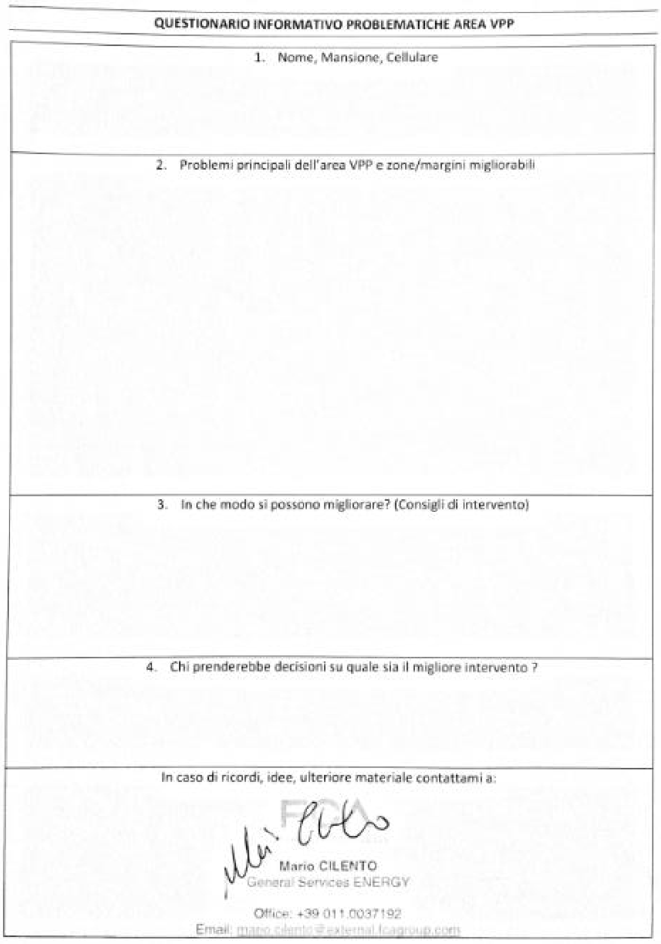
Type	Element	Stratigraphy	Conductivity λ W/m/K	Thickness l m	Transmittance U $W/m^2/K$	Area A m^2
Wall	Confining wall with "La Caverna"	Intonaco di gesso e sabbia	0.8	0.015	2.010	1920
		Blocco semipieno	0.424	0.195		
		Intonaco di calce e sabbia	0.8	0.015		
Wall	Perimetric wall	Intonaco di gesso e sabbia	0.8	0.02	1.1	799
		Muratura in laterizio pareti interne	0.5	0.12		
		Intercapedine non ventilata AV<500 mm^2/m	0.556	0.1		
		Muratura in laterizio pareti esterne	0.6	0.25		
		Muratura in laterizio pareti esterne	0.41	0.02		
Roof	Workshop roof	Impermeabilizzazione con bitume	0.17	0.004	2.488	10261
		Massetto ripartitore in calcestruzzo con rete	1.49	0.06		
		Soletta in laterizio spessore 20	0.66	0.2		
		Intonaco di gesso	0.57	0.02		
Roof	Paint shop roof	Impermeabilizzazione con bitume	0.17	0.005	2.259	550
		Sottofondo cemento magro	0.9	0.06		
		Soletta in laterizio spess. 16 interasse 50	0.61	0.2		
		Intonaco di gesso e sabbia	0.8	0.015		

Floor	Workshop floor	Cemento in genere	0.19	0.02	1.989	9945
		Sottofondo cemento magro	0.9	0.07		
		Cemento di sabbia e ghiaia	2.15	0.15		
		Ghiaia grossa senza argilla (um 5%)	1.2	0.3		

	Solar transmittance	Emissivity	Transmittance	Area
	g_n	ε	U_w	A
Element	-	-	W/m²/K	m²
East window	0.85	0.837	2.83	240
Nord window	0.85	0.837	2.818	81
Skylight	0.85	0.837	3.115	2717

Attachment B.

Photo of blank questionnaire survey used during the interview phase of paragraph 2.1.1.



QUESTIONARIO INFORMATIVO PROBLEMATICHE AREA VPP

1. Nome, Mansione, Cellulare

2. Problemi principali dell'area VPP e zone/margini migliorabili

3. In che modo si possono migliorare? (Consigli di intervento)

4. Chi prenderebbe decisioni su quale sia il migliore intervento ?

In caso di ricordi, idee, ulteriore materiale contattami a:

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Attachment C.

Reports from the interviews on fields.

Position	Problems	Solutions	DM	Type
GS Maintenance Head	Sinks in dressing rooms: pedals not running and oversized for the number of worker in BPS.	Repair or change only the sinks in the sufficient quantity.	GS manager	Liveability
GS Maintenance Head	South doorway: in poor condition and requires a lot of maintenance. It blocks several times and anyway for the logistic of the plant it is used too much and so stressed. Related problems: continuous deterioration, dust income in the plant from the external (this decreases the quality of the product and compromises an aseptic environment), energy losses and further discomfort.	Air blade and a relè.	GS manager/investment plant	Logistic
Environmental engineer	Tub paint collection: discomfort during the substitution because not well sized.			Process
Environmental engineer	CO_2 emission very high for the process.			Process
Environmental engineer	Overconsumption of paint in the cabin that leads to: economic losses, evaporation, discomfort (VOC presence).			Process
Risk manager	Flame cabin: jet fire risk if fire detection systems fails when paint is applied via spray.	1. Remove paper parts around the bumper (done) 2. Add additional sensors and flame detectors 3. Add a pergola air pusher.	Technology/ different offices	Process
Production utilities specialist	The half of the light in the plant are energy-saving bulbs (with dimmed), the rest just traditional incandescence bulbs (roof lights).	Substitution with LED of 4th generation and dimmed, especially for traditional bulbs.	Plant manager/GS manager depending on the cost	Lighting
GS Maintenance Head	Windows: not well kept, hazardous during maintenance and block continuously. They lead to energy losses problems and air tightness. Lubrification brings deterioration.	Lubrification, automation, optimization of sensors.		Thermal
GS Maintenance Head	Doorway blocks and fails continuously. Sensors are too close to the doorway and so moving driver hits the door.	Turn away the sensors from the doorway.		Logistic
GS Maintenance Head	Ceiling in bad condition and bad kept.			Liveability
GS Maintenance Head	Workers and users behaviour careless of the building and utilities.	Training.		Liveability

Environmental specialist (outdoor quality)	Internal emission of VOC from the ground.	Intervention on the sealing (?).		Process
Environmental specialist (outdoor quality)	Emissions from chimney 2.267 2.268 2.269 2.700 high for VOC and CO and NO_x.			Process
Worker	Cold spot in area close to the doorway (3642 probe).			Thermal
Worker	Excessive hot climate during the summer, no inner ventilation nearby the coffee machine.			Thermal
BPS supervisor	Dressing room in poor condition.	Refurbishment.		Liveability
BPS supervisor	Hot microclimate during summer.			Thermal
BPS supervisor	Absence of pedestrian road to reach the canteen.			Liveability
BPS supervisor	Absence of smoking room.			Liveability
BPS supervisor	Presence of lofts unused because for old models not produced anymore.			Logistic
BPS supervisor	Painting and refurbishment of several areas to improve the visual comfort.			Liveability
BPS supervisor	Moving truck entering from the external shall not pass because reduce the quality of the final product.	Change logistic of the area.		Logistic
BPS supervisor	Rain infiltration from the ceiling.			Liveability
BPS Maintenance specialist	Personal insufficient during productive peaks.			Process
BPS Maintenance specialist	Flame cabin: the skid has not to pass if wrong detection of the idem processed realises. This causes problem and accidents.	Add a camera to solve the visual misunderstanding.		Process
BPS Maintenance specialist	Carts not well balanced that compromises the quality of the product because spray robots are not well set.	Add a "DIME" to control skid load.		Process
Worker, revisionist	Hot microclimate during summer.			Thermal
Worker, revisionist	Cold spot during winter if heating system fails.			Thermal
BPS shift manager	Layout of the warehouse: too short whilst other areas are not utilized.			Logistic
BPS shift manager	Fenestration blocks, height building, floor with no gum but concrete.			Thermal
BPS shift manager	Economy losses for refuse because of human mistake during movimentation (poor space).			Logistic
BPS shift manager	Poor illumination (500 lux instead of 1000 lux). This does not lead to distinguish the colours of bumpers.			Lighting

Worker	Infiltration from the ceiling during the winter.			Liveability
Worker	Broken doorway and corresponding potholes on the ground. They break because of movement frequency and carts' hits.			Logistic
Worker	Logistic: for Levante arrival, vacant spaces removed at south-west.	New layout.		Logistic
BPS supervisor	Bathroom of BPS: old.			Liveability
BPS supervisor	Flame plant too aged.			Process
BPS supervisor	Transportation systems old and break often.			Logistic
BPS supervisor	Bumper waste because of dirt after the washing machine because the system is depressurized, and dust can enter.			Process
BPS supervisor	As above with the line after the primer (out-cabin).			Process
BPS supervisor	Poor illumination and several bulls are turned off (even the contrary is true).			Lighting
BPS supervisor	Logistically speaking the layout shall be redone.			Logistic
Forklift driver	Doorway and potholes: stun and block carts from "La Caverna".			Logistic
Forklift driver	Cavern's temperature because there is not a clear logistic and gather pieces to be worked is not easy and immediate.			Logistic
Forklift driver	Temperature and air flows caused by doorways.			Thermal
BPS Logistic head	Wrong layout for the limited number of resources (logistic).	New layout proposed to logistic engineering office.		Logistic
BPS Logistic head	Doorway: broken sensors or locked. Drivers' work compounded.	New larger doorway to facilitate manoeuvres and protecting sensors.		Logistic
EDF maintenance head	Stressed heating pipeline (more leakages) because of space/process heating modulation.			Thermal
Worker	Bathroom old and clogged.			Liveability
Worker	Discomfort (cold) in change room.			Liveability
Worker	Discomfort: women change room at the 3rd floor.			Liveability
Painting (selection) specialist	VOC's smells out of the cabin.			Process
Painting (selection) specialist	Poor air change rate inside the building.			Liveability

Painting (selection) specialist	Hot spot in the corridor beyond the primer (bad air balancing in new HVAC installation).			Thermal
Production utilities specialist	Lighting very bad designed with energy wastes and dark spot.	Engineering of lighting.		Lighting
Production utilities specialist	Air velocity in cabin too high, but the risk is for an inefficient process.	Test and modelling: act on the QE.		Process
Production utilities specialist	Single plenum in the cabin: it is not possible to differentiate the velocity in the three cabins.	Aeraulic analysis of the cabin.		Process
EDF CTV Maintenance Head	During winter season workers suffer for high temperature in the centre of the building whereas cold spot along the perimetric sides.			Thermal
Environmental specialist (indoor quality)	Noise level in the cabin higher than elsewhere though below 85 dB.			Liveability
BPS Maintenance specialist	High maintenance in the cabin.			Process
BPS Maintenance specialist	Poor air change rate.			Liveability
Production utilities specialist	High thermal losses via roof and perimetric area.	Improve insulation		Thermal
Production utilities specialist	Hot climate during the summer.	Adiabatic cooler where there are workers		Thermal
Production utilities specialist	Thermal layering that increases the upper losses.	Air delayers		Thermal

Attachment D.

Problem	Solution	Source	Type
Leakages in compressed air line.	Detect with ultrasonic detector and intervention.	[37]	Process
High pressure in the compressed air line.	Reduce pressure as much as possible.	[37]	Process
High pressure drops on the compressed air line	Re-design the pipeline.	[37]	Process
High consumption for lighting	Upgrade to LED dimmed light the whole factory.	[37]	Lighting
Low amount of natural daylight.	Rooflight edification and natural ventilation via ridge.	[41]	Lighting
	Change the ratio WWR of the building and introduce a control strategy for lighting.	[76]	Lighting
Building depressurized.	Pressurize the building via HVAC and reduce air tightness to improve indoor quality.	[37]	Thermal
High cooling load	Cooling roof (painting).	[40]	Thermal
	Roof garden: reduce cooling load, pollution and dust, increase life of the roof.	[37]	Thermal
	Shading trees on the southwest side.	[37]	Thermal
	Mixing Ventilation System (MSV), or even better the Hybrid solution (RHDVS).	[11]	Thermal
	Natural ventilation through ridge openings on the roof.	[41]	Thermal

High energy losses via wind	Shading trees on north side, they protect the building from the wind.	[37]	Thermal
Low quantity of natural daylight.	Change the ratio WWR of the building and introduce a control strategy for lighting.	[76]	Lighting
Ground thermal losses: slab on grade.	Utilization of a vertical footer insulation instead of a horizontal one.	[42]	Thermal
Wall thermal losses.	External over cladding with polystyrene.	[39]	Thermal
	Selection of suitable insulant via MCDA.	[43]	Thermal
Roof thermal losses.	Over cladding insulant and aluminium sheets.	[39]	Thermal
	Change skylight glass.	[9]	Thermal
	Several proposals of insulant sandwiches.	[9]	Thermal
Windows losses.	Complete renovation required.	[9]	Thermal
Natural air tightness	Shading trees that reduce the air infiltration because they stop the wind.	[37]	Thermal
	Over cladding of seals coupled with monitoring and control of infiltrations.	[39]	Thermal
	Intervention with glued vapor barrier.	[44]	Thermal
Linear thermal bridge.	External intervention of over cladding.	[44]	Thermal
Vertical temperature gradient causes enormous heat losses.		[38]	Thermal

Attachment E.

	Thermal projects								
Criteria	Insulation confining wall	Insulation perimetric wall	Insulation shop office roof	Insulation paint central roof	Cool roof	Air delayers	Adiabatic refrigerators	Radiant heaters	Glass substitution
Investment cost (€)	66’000	15’980	179’157	9’438	77’266	165’000	13’680	2’795	142’000
Variation of operational costs (€)	-3099	-1047	-20579	-1400	8983	-18513	+292	3659	-2550
Pay Back Time (y)	21.3	15.25	8.71	6.76	100	8.9	100	100	27
Variation of maintenance operation	C	C	A	B	C	D	D	D	B
Impact of the installation phase	H	H	M	M	L	M	VL	M	VH
Visual comfort	C	C	C	C	C	D	D	D	B
Thermal comfort (heating season)	B	B	C	C	D	A	C	A	B
Thermal comfort (cooling season)	B	B	C	C	B	B	A	C	B
Indoor air quality	C	C	C	C	C	B	B	C	C
People's satisfaction	C	C	C	C	B	C	A	A	B
Visual impact	C	C	C	C	A	E	E	E	B

Emission CO_2 (ton)	23	7.83	153.73	-10.4	-67	182	-0.74	-9.3	56
Reliability	VH	VH	VH	VH	VL	H	M	M	VH
Technical Life (y)	12	12	12	12	3	15	10	8	30
Lead time (w)	20	20	5	3	4	10	8	3	16
Layout flexibility	A	A	A	A	A	B	A	B	A

	Lighting projects			**Logistics projects**		
Criteria	Upgrade environment lighting	Increasing lux for process lighting	Upgrade process lighting	Demolition hanging conveyors	Refurbishment doorways	New internal layout
Investment cost (€)	145’000	10’506	60’252	145’000	29’000	35’518
Variation of operational costs (€)	-35481	+3600	-8500	0	0	-11242
Pay Back Time (y)	4.1	100	7.03	100	100	3.15
Variation of maintenance operation	B	B	B	B	A	D
Impact of the installation phase	M	H	M	VH	H	VH
Visual comfort	A	A	C	B	C	C
Thermal comfort (heating season)	C	C	C	C	B	B
Thermal comfort (cooling season)	C	C	C	C	C	B
Indoor air quality	C	C	C	B	B	B
People's satisfaction	B	A	C	B	B	A
Visual impact	A	D	C	A	C	D
Emission CO_2 (ton)	90	9.13	21.55	0	0	1.15
Reliability	H	M	H	VH	M	M
Technical Life (y)	11	11	11	100	8.18	100
Lead time (w)	4	1	4	30	4	6
Layout flexibility	B	D	D	A	B	C

	Liveability projects				
Criteria	Roof waterproofing	Increase ACR	Refurbishment dressing rooms	Refurbishment bathrooms	Smoking room
Investment cost (€)	104’000	5’670	260’000	32’500	49’000
Variation of operational costs (€)	0	+12486	0	0	+673
Pay Back Time (y)	100	100	100	100	100
Variation of maintenance operation	A	D	A	A	D
Impact of the installation phase	M	L	VH	H	M
Visual comfort	C	C	A	A	B
Thermal comfort (heating season)	C	D	C	C	D
Thermal comfort (cooling season)	C	D	C	C	B
Indoor air quality	B	A	C	C	C
People's satisfaction	A	A	A	A	B
Visual impact	C	C	A	B	D
Emission CO_2 (ton)	0	-93.2	0	0	-1.71
Reliability	H	H	M	M	M
Technical Life (y)	10	100	20	20	100
Lead time (w)	6	4	24	6	12
Layout flexibility	A	A	A	A	D