Achieving Sustainability in Construction Through Digitally Informed Decisions

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Abstract The environmental impact of buildings on the planet is expected to increase as world population continues to grow. Sustainability in construction becomes of crucial importance for the future of the planet and its inhabitants. Energy and material resources throughout the building's life cycle represent the key to controlling its impact. Industry 4.0 contextualizes a situational framework where it will be possible to predict and simulate at an early stage the material and energy dimensions of the life-cycle assessment. The articulation between the information model (BIM) and the construction industry guarantees efficiency, less waste and better use of resources. Digital simulations ensure informed design decisions enabling a more efficient relationship between the building and the general comfort of its users, as well as its HVAC systems in combination with the generation of its own energy. The BIM model also informs material decisions regarding environmental impact. Human-centred buildings with low impact materials and almost zero energy can be data-driven designed consciously. The correct digital technology articulated with the Industry 4.0 principles regarding the sustainability of the built environment, guarantees conscious buildings that can play their role in cities creating an ecosystem with a positive contribution to the human habitat, not only reducing its environmental footprint but also contributing to its energy and material dimension.

Keywords Life-cycle assessment · Circular economy · Near-zero energy buildings · Digital fabrication · BIM

1 Introduction

Buildings are an integral part of the environment. As a species, the human being represents a rare case of ability to adapt the environment to its needs. He builds his own habitat from natural resources that he extracts and transforms. This ability

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presents some advantages however not without bringing disadvantages originated from the transformation of the environment. The advantage is being able to survive and explore all continents with their biotic and abiotic climates and systems, through technology. The ability to control their own climate is using layers that protect against the elements and more extreme climatic situations. The shelter these new habitats offer has become a vehicle for exploration and occupation of the planet. Construction has always accompanied and continues to accompany the daily life of the human being from the building to the built environment, each at its scale and function in interaction and symbiosis. Cities currently represent the habitat of about 80% of the world's population, with buildings representing the human habitat for about 85% of their time. However, the understanding of ecosystems is still a field of study, which is not answered by some of the observed phenomena. Evolution as a species has always occurred in contact with nature. The complexity of ecosystems and the very need for protection from the environment, which is seen as hostile, comes with a compromise that ended up representing some disadvantages. The current distance from the natural elements, compromises the well-being in several degrees, for the most diverse reasons. The ability to transform the ecosystem and create one's own habitat, puts the adopted solutions in a position of imbalance and, often, confrontation in relation to the behaviour of natural phenomena that allows the harmony of the place. This imbalance is the result of the distance of holistic thinking that accompanies the diversity of natural phenomena and contributes to the balance of Biomes.

The transformation and creation through construction needs matter and energy, elements and resources abundant in nature, which can be of exhaustible or renewable nature. The ability to transform the habitats that will be subsequently occupied is always dependent on these resources. For centuries, the source was predominantly local and almost always renewable materials and energy sources. Transformation depended on human effort and labour, sometimes assisted by animals, and using simple devices powered by renewable energy sources such as wind and water.

This whole paradigm was gradually replaced by the first industrial revolution, which began shortly before 1800 in the United Kingdom. The dominance of energy from non-renewable and polluting sources such as coal began. The era of steam and large-scale transformation from very intense and powerful energy resources replaced the previous paradigm. This moment allowed a crucial advance in the way matter and energy were articulated and combined. The transformation capabilities increased and grew exponentially, allowing enormous advances in all areas of knowledge and research, entering the era of the fossil fuels and of the machine. However, it has brought a cost, introducing topics that were previously unknown to humanity, such as air pollution and the depletion of material resources due to the inability to replace them in the case of renewable sources as well as due to the rapid rate of extraction. New issues regarding the health and lower quality of life of our habitats represented serious problems that characterized the period.

Still within this revolution the assembly line emerged and efficiency in the transformation process was accelerated. This moment led to the second industrial revolution: Industry 2.0. The machine evolved from steam and coal to internal combustion and electric motors in the production lines, resulting in a transformation capacity that continued to grow from more powerful and efficient processes. However, air pollution remained and spread both from raw material processing units as well as from energy processing units such as coal and oil-based power plants. The speed and amount of raw material extraction grew in line with the transformation capabilities and market demand.

The advent of the computer drove the third industrial revolution, resulting in more effective and efficient mass production through programming, planning and control of production chains that allowed mass customization. The era of working with ever-increasing databases and ever-faster calculations and analyses has accelerated product production. This large-scale global phenomenon required more energy to work, which increased the number of power transformation units and consequent air pollution.

The growing exploitation of material and energy resources has always resulted in a negative and constantly expanding global environmental impact. The expansion and evolution of the industry have compromised its own sustainability by the rate of depletion of resources and by-products generated from a philosophy and paradigm of linear production focused on the economic dimension. Emissions of greenhouse gases throughout its chain, ranging from the extraction stage, transportation and production to the creation of waste considered garbage, are a constant threat to mankind due to the changes they cause both directly and indirectly, ranging from air quality to changes on a planetary scale.

Industry 4.0 takes these issues into account and incorporates notions of sustainability on a global scale in areas such as environmental impact from, e.g. energy efficiency throughout the production chain alongside the reduction of waste and transformation residues, economic impact with emphasis on process planning that allows for greater material and energy savings as well as shorter delivery times and social impact with a focus on safer and more comfortable working environments, for example.

One of the key points to incorporate and address these issues is information, in particular the ability to simulate in a digital environment that provides the ability to design, anticipate, predict and optimize processes and systems. Informed responses with the purpose of making conscious decisions to balance and even reverse processes that are already perceived as harmful to the planet and to the human being. The construction industry incorporates a range of products and processes with diverse origins and differentiated systems that converge and articulate to the final objective that is the building. The digitization of the built object allows its participants to find a common platform for design, simulation and optimization of processes and solutions to achieve the best final result. The BIM methodology allows the creation of models that incorporate the necessary information so that the articulation between people, systems and processes reaches the desired level of energy and material efficiency achieving the minimum possible impact.

The life cycle of the building will be addressed in Sect. 2 associated with the latter issue, with emphasis on the BIM methodology as a process of calculation and forecasting from the information contained in the model.

Section 3 focuses on the importance of human-centred decision-making, raising the question of the abstraction that information can cause when not centred on the relationship of the building with its users and the commitment it can represent. The sustainability of the building is a set of factors that make the building an ecosystemic element that is positioned between the human being and the environment, between the interior and exterior impact.

The problem and articulation between the decisions taken in the balance between materials and energy will be presented in Sect. 4.

The materialization of the building, i.e. its construction and respective processes, framed in the principles of Industry 4.0, based on the BIM model will be addressed in Sect. 5.

2 Building Life Cycle

Life-cycle analysis is crucial to attain the buildings, or rather, the built environment's sustainability. From the city to the simple structure scale, without understanding the complexity of the system, nor all the phases of its life cycle, it cannot be said that the impact of the building on the environment can be assessed.

The question of information is essential as an element of analysis, of thought and as an engine for decision-making still in the design phase. When talking about information and building, the BIM methodology appears as a central element in the process (see Chapter "Building Information Modelling and Information Management"). The ability to extract information from the model and, at the same time, insert information into it, provides the design team with data that can keep track of all their decisions.

Life-cycle analysis is a complex process that uses databases and calculations that can be articulated and processed in the BIM model for further analysis according to the intended scope (Fig. 1).

This methodology allows working with input and output databases that inform the model and the project team. The increasing interaction and articulation between the BIM software and other applications and databases make this flow increasingly fluid and graphically evident as an element of analysis. Provided adequate information, these same software applications in articulation allow the calculation of material and energy impact factors. From the direct interaction in real time or the integration of subapplications within the core tool, the project team is able, from the first steps of design, to make informed decisions on the environmental impact dimension from the energy and material aspects of the complex system that is the building. The articulation between energy and materials is one of the key points for the balance and efficiency of the building towards the environment. One can consider the definition of life-cycle thinking [1] when referring to the design and decision-making phase, based on the interaction that the BIM methodology enables and adding to the design thinking process those elements that support its environmental impact.

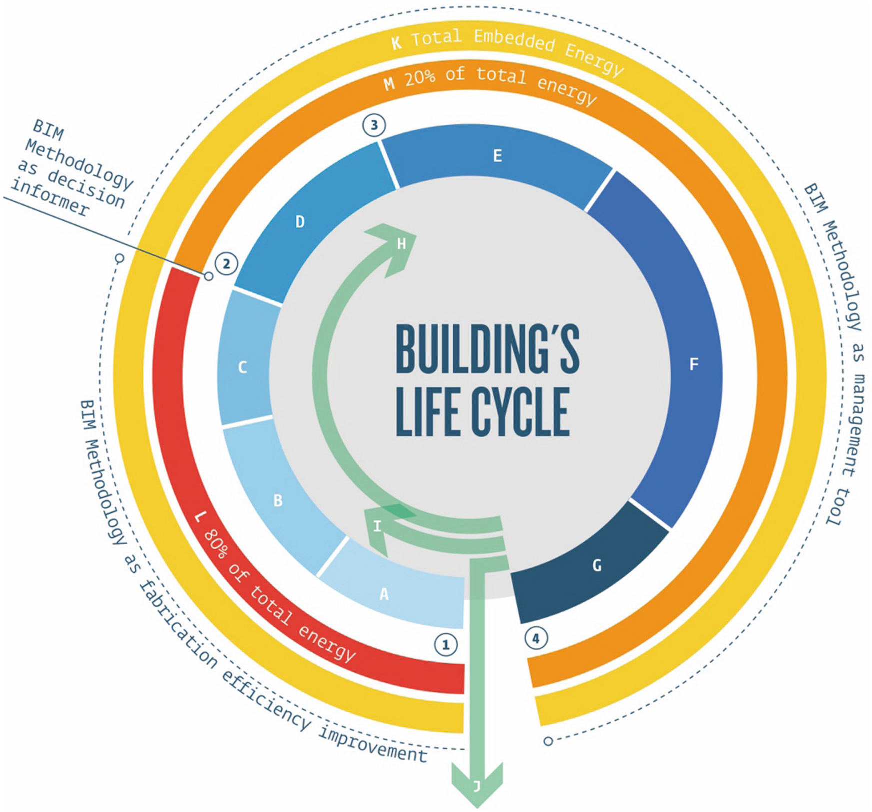

Fig. 1 Building's life cycle by material embedded energy and the BIM methodology role. **a** Raw material extraction, **b** transportation to the factory, **c** transformation, **d** transportation to the site, **e** on-site application, **f** maintenance, **g** demolition, **h** reuse, **i** recycle, **j** disposal, **k** total embedded energy, **l** primary energy consumption (PEC) 80% of total energy, **m** energy embedded in materials during transport, construction, maintenance and demolition—20%., 1 Cradle, 2 Gate, 3 Site, 4 Grave

2.1 Site Analysis—The Urban Scale

From the site analysis, BIM can add valid information for informed decision-making, which can open doors to less obvious solutions considering factors such as sun exposure, the behaviour of air flow and, shading elements, allowing the designer to be more profoundly aware of the potential and genesis of the site.

The link between the BIM and other peripheral software applications, such as those dedicated to geographic information systems (Chapter "Multi-disciplinary Use of Three-Dimensional Geospatial Information"), allows a fast and effortless incorporation of crucial data in the model and its subsequent analysis in a very wide range of themes and situations, as seen in Fig. 2.

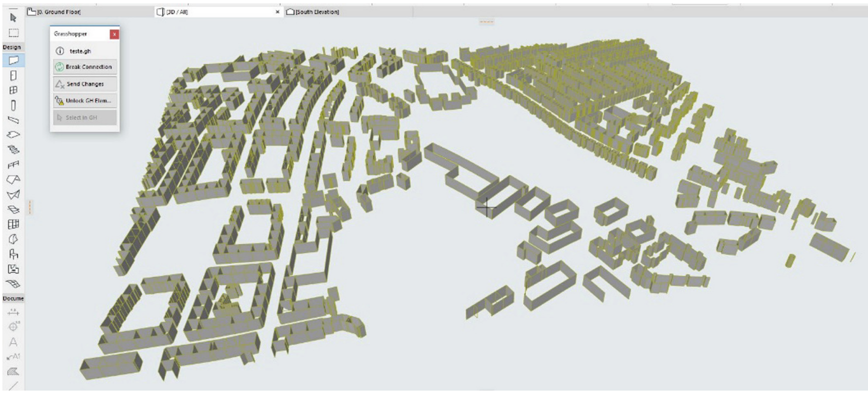

Fig. 2 Automatic generation BIM model connected to GIS software in real time

Based on this initial model, obtained almost automatically, it is then possible to analyse solar availability, airflow patterns, moisture, cloudiness and even generate psychrometric and bioclimatic graphs (Fig. 3) that inform the designer even before starting to design using the climatic and microclimatic characteristics of the site. The charts presented in Fig. 3 allow the decision-making team to analyse the importance and relevance of each passive system for a particular climate and situation. The adoption of these solutions can be incorporated in the building by its form for example, guaranteeing the proper solar incidence or wind exposure, for example. They also allow the selection of the correct and most efficient system for a particular case. For further information on psychrometric and bioclimatic graphs, the books Architectural Science by Szolokay [2] and Design with Climate by Olgyay [3] provide a solid foundation.

The connection between the BIM software and the GIS database was, in the case of the example given in Fig. 2, established through a plugin that works inside a visual programming software (grasshopper) that incorporated the data available online and converted it to native BIM elements.

This set of information enables informed decisions to be made based on specific data and in many situations leads to the generation of ideas and solutions. Within the Industry 4.0 framework, this ecosystem articulation of software applications centralized in the BIM model is the principle of response to issues of global sustainability and integration of the building as a positive and model element in its context.

From this point, the life cycle of the building starts from a premise of energy efficiency in order to guarantee its occupants the highest possible degree of comfort using the energy potential of the site.

Being the next step the form factor and the location of the building footprint, elements whose decision by the designer will be informed by a diversity of factors.

The energy availability of the construction site is of crucial importance to the placement of the building volume, as seen in Fig. 4. In this case, the colour gradient

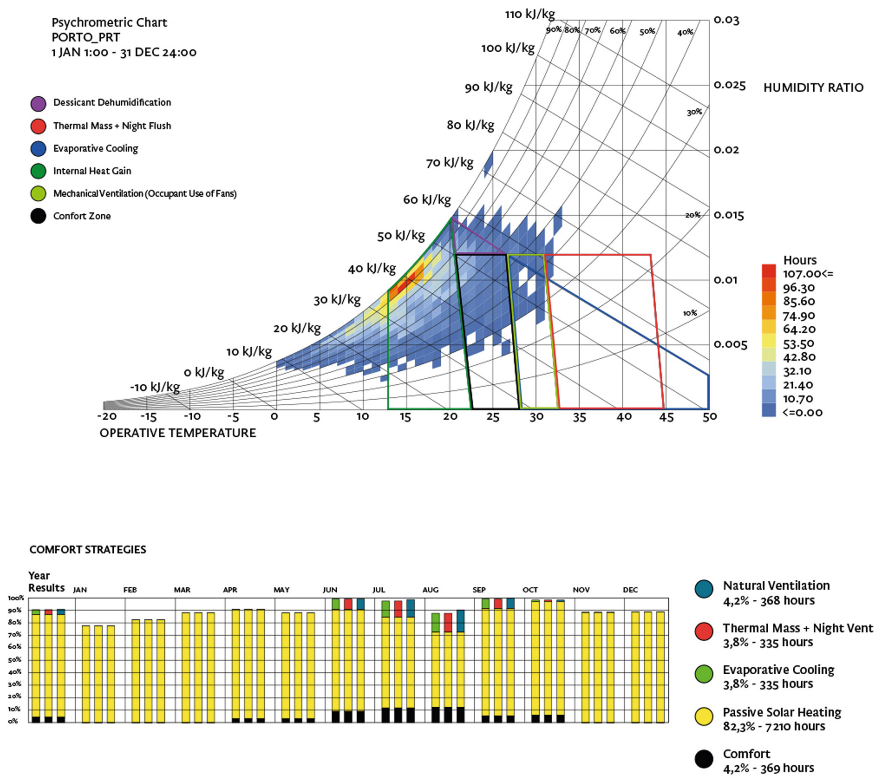

Fig. 3 Psychrometric and bioclimatic charts

shows the solar incidence from less to more as blue to red correspondingly. The darker the blue, the lower the value and the darker the red the higher the value. The same methodology can be used to address wind behaviour and patterns recurring to computational fluid dynamics (CFD) applications, providing the designer with a clear understanding of the site as far as natural ventilation is concerned.

The amount of information available can often be overwhelming and make the decision difficult when there are multiple objectives to be achieved. At this stage, the use of multi- or single-objective optimization algorithms can help finding several solutions that can be analysed and crossed by the design team in order to find the best answer for the intended purposes. These algorithms can be based on different methods to problem solving. Some are genetic algorithms, also known as evolutionary solvers, like the ones incorporated in Galapagos as can been seen in Fig. 5, with or without the pareto principle for multiple goals. Some also include particle swarm and advanced machine learning techniques to find good solutions or even implement the self-adaptive differential evolution with ensemble of mutation strategies.

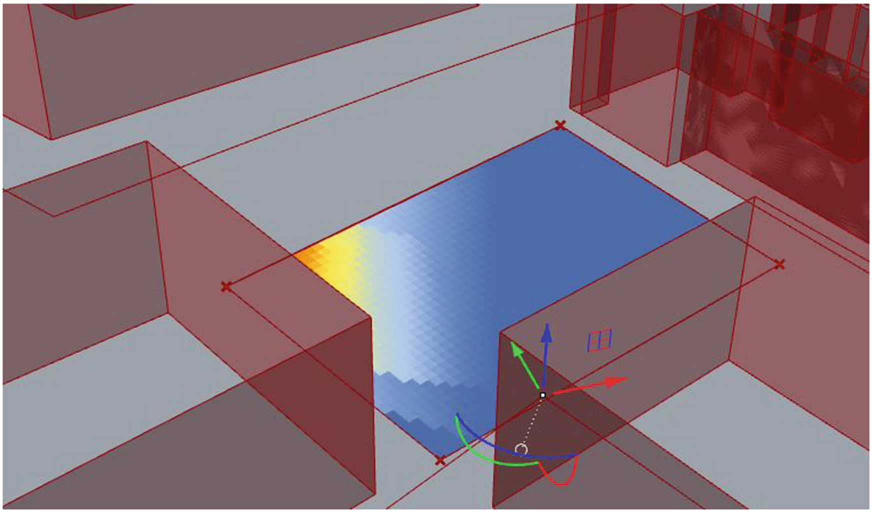

Fig. 4 Site analysis—solar availability

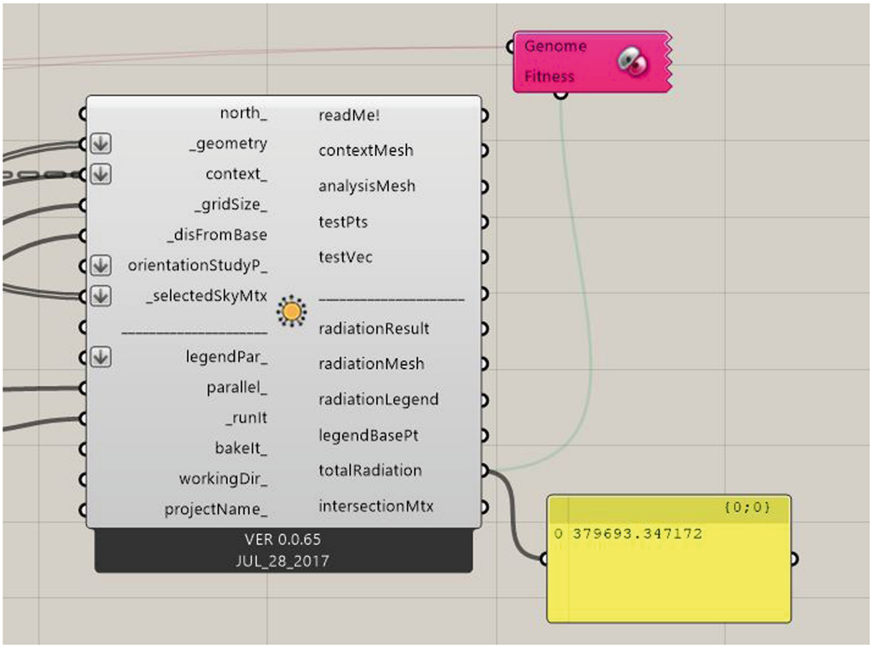

Fig. 5 Optimization algorithm partial components

Applications like Octopus use the SPEA-2 and HypE algorithm from ETH Zurich, Opossum uses model-based RBFOpt and evolutionary CMA-ES while also including the multiobjective RBFMOpt, and the multiobjective MACO (Ant Colony), MOEA/D, NSGA-II and NSPSO (particle swarm) algorithms from the Pygmo 2 library. Meanwhile Optimus application recurs to self-adaptive differential evolution with ensemble of mutation strategies (jEDE) and Wallacei X employs the NSGA-2 algorithm as the primary evolutionary algorithm, and utilizes the K-means method as the clustering algorithm. The balance between these algorithms is based on speed and the optimal outcome. By default, evolutionary algorithms are slow and can give different outcomes for the same problems. The development of the algorithms focuses on faster and more reliable and accurate results.

In the context of this section, the objectives may vary between building placement, form factor and building skin orientation to achieve the balance between solar exposure, ventilation efficiency and projected shadows informing the design team of an array of solutions to meet their criteria.

Figure 5 presents part of a grasshopper definition using Galapagos as the evolutionary solver with the objective of balancing solar radiation between the hot and the cold period of the year. The other component, present on the same image, is from Ladybug and is called radiation analysis that allows the calculation of the radiation falling on input geometry using a sky metrics. The result is the total radiation in Kwh falling in the input test geometry which represents the objective of the solver.

If, for example, the objective is, in a cold climate, finding the solution of greater solar exposure throughout the year reducing the energy demand of the building for heating, the designer can analyse a series of form factor solutions generated from visual programming software applications articulated in real time with the BIM software.

These programs already allow the construction with the BIM software native tools from parametrically generated geometry (see Chapters "Introduction to Computational Design: Subsets, Challenges in Practice and Emerging Roles" and "Advanced Applications in Computational Design").

In this first phase, the integration of considerations and solutions that integrate energy efficiency from the form factor combined with other constraints proves to be a point of great importance for the impact that the building will have on its life cycle.

2.2 *The Building Scale*

At this point, the design solution must consider the combination of the necessary energy to ensure the comfort of its occupants articulated with the material impact. The definition of the building elements begins to take shape and the designer can use tables and calculations to assess in real time the most appropriate systems with the least impact. Factors such as suitability, embedded carbon, maintenance requirements, performance, chromatic values and the very expression of the building can be analysed and controlled within the BIM model.

The articulation with databases or the insertion of the necessary data within the model helps in decision-making with the objective of minimizing the amount of CO_2 emitted until the construction phase, corresponding to the gate, and also considering the subsequent demolition that corresponds to the grave (Fig. 1).

The complex system that a building represents, from all its constituent elements, will have to be the target of a reflection that always integrates various perspectives that must be contemplated, in order to achieve the final result in the most efficient way. A low impact construction system is based on the material factor, wood versus steel for example, but without ever neglecting the waste factor. The optimization of all elements will allow faster manufacturing and execution on the construction site. Sustainability focuses on doing more with less, being a material, an energy or a labour issue. Less waste, less energy, less time for the same outcome represent more overall sustainability.

Prefabrication and off-site construction play an important role solving these factors, by the control and the dialogue between the design and the production chain made possible. This integration and optimization can also be achieved by parameterizing the solutions with peripheral software applications in direct articulation with the model. Under this paradigm, structural elements, walls, floors, doors, windows, cladding, when optimized, allow minimal waste and faster execution while considering environmental and economic sustainability. Less disposal material, more efficient transformation and production methods, shorter and simpler construction and assembly periods, emphasis on dry construction systems, all represent more material sustainability due to less embedded energy, less waste and bigger reuse potential. Depending on the construction system and the considerations of the design team, these elements can still be disassembled ensuring their reuse or recycling.

The available object library bases with assembly and construction systems for BIM software applications allow the designer once again to integrate these solutions in a realistic way with sufficient detail to inform the construction team of all the details required for their good construction. The importance of these libraries relies on the ability to inform on various degrees of precision the solutions to be adopted, both during construction, maintenance as well as during the disassembly of the building, from gate to grave. All the components are present and identified facilitating all the processes involving the building life cycle.

From this point with the formal decisions and materials already advanced and optimized, it is possible to measure and calculate the interior comfort conditions both from software applications embedded in the BIM software as well as from peripheral applications that interpret information and data from the BIM model and weather files.

This information can inform the designer about the consequences of the choices already made. The optimization algorithms can, at this particular point, also play an important role as indicators of the solutions that best solve this challenge.

Simple aspects such as the layout and general dimension of the exterior glazed spans contribute simultaneously to the energy and material impact of the final result, without neglecting the building's appearance. This balance is essential to achieve environmental, economic and social sustainability.

Information on factors such as the thermal resistance of the building envelope, the amount of light entering the spaces, the acoustic behaviour of the surroundings, answering questions of human comfort in parallel to questions of energy, needs to overcome the limitations of natural systems always in combination with the question of material impact and the optimization of waste and residues in the construction phase.

The amount of information present after all the environmental data inputs, design decisions and calculations can be obtained graphically and/or from tables and inform the design team of the most balanced solution and of all the decisions that are made.

This awareness and methodology in the design phase allows us to anticipate and prevent, in a fast and cost-effective way, problems that are much more difficult and expensive to implement when faced during the construction phase or even when adapting something that has already been built, sometimes even generating waste of energy material when adhered later.

3 Human-Centred Design

Industry 4.0 is a direct evolution of the previous industrial revolutions and focuses on the globalization of culture and consequently the industry's requirements. This globalization includes economic issues of the sustainability of the industry itself, which involves the sustainability of the planet, social issues and is the expression of technological evolution that has strengthened the ties and distances of the planet.

To achieve these goals, and the construction of our habitat is no exception, information is a key point for decision-making that allows the industry to transform from the construction of a linear system to a circular system and even to a more integrated system with ecosystemic principles, always with the objective of a more adequate habitat for all our needs. However, information does not cease to appear to us in an abstract way and often ends up being the centre of our focus. It is important that the design team does not lose sight of the fact that all the effort to meet the goals proposed by Industry 4.0 do not deviate from the ultimate purpose which is the integration of the human being with his habitat.

The distancing from natural elements, more unpredictable and less controllable, has made the modern city, more focused on functional issues, creating a built environment based on materials such as concrete and asphalt. The preference given to the convenience of moving by car, within this habitat, brought great advantages and changed the paradigm of our lives but not without a price. Phenomena, such as urban heat islands and air quality, lack of green spaces and noise pollution, along with everyday situations such as traffic jams, improper parking in pedestrian areas, massive buildings that only contain cars, are undesired consequences of a progress that was not human-centred.

One of the precautions that must be taken when working with the BIM methodology connected with databases and at the same time generating results that also appear as data is to never lose sight of the fact that buildings and cities are the habitat and ecosystem that is chosen and designed for ourselves. Data does not always clearly and holistically indicate the way forward being only part of a design process.

It is important to avoid the mistake of looking for the most efficient solution for a certain aspect of the construction, such as energy requirements, without considering the nuances of heat and cold peaks that so often are not noticed in the averages of the analyses.

Always bear in mind that the feeling of interior comfort depends on factors that are articulated and related to each other such as natural light, temperature from passive heating, glare and visual quality of spaces, humidity, which influences so much our thermal sensation, and acoustic quality so often neglected.

Air flows caused by differences in air pressure and density, when heated naturally, for matters of quadrants and natural ventilation, adapted to the use of each building or each room, are not always easy to study and solve. If one never loses track of the human being in the core of design decisions, even if informed by the data generated by BIM programs, all these aspects are always present in the decision-making and analysis of our design decisions.

Even before beginning the design of the building, it is possible to perceive from the analysis of the site the differences of microclimate in relation to the climate of the region. The building can then become an element that counteracts this tendency in urban heat island situations, for example.

By using the informed model and all the analysis tools that are combined with the BIM program, it is possible to analyse and create informed solutions that will counter some trends that the current state of the site may represent, thus contributing to the mitigation of harmful effects on humans and the environment where the building is located. The phenomenon of an urban heat island poses problems of discomfort for those who inhabit it but extends to the energy needs of the building so often calculated on the basis of general climatic data of the area not on the basis of data of the microclimate of the place where it was built and located. Another under-exploited situation is the effect after construction that the building will have on the site, i.e. whether the building contributes to increase or decrease this phenomenon. Our built habitat is always a work in progress, and it makes no sense not to use the technology available now in order to make and create an environment more adapted to the actual needs.

Economic sustainability is of crucial importance, however, when the balance sheet is distorted by this factor being the only one to be considered without a broader view of the long-term effects, the results are uncontrolled and unpredictable even if they are often well intended. At the building's scale, the consideration of thermal factors for better energy efficiency without considering all the other factors of human comfort can compromise the initial objective by the behaviour of its occupants to create a more comfortable environment by overloading the mechanical systems of air conditioning and ventilation.

Considering all these factors, the building can effectively become an element of sustainability based on ecosystemic principles within a logic of positively contributing to its occupants and their environment. Only in this way can the Industry 4.0 be achieved in the articulation between all the databases and information calculated and generated by the BIM software to achieve the balance centred on human needs that is known at present. When the degree of complexity of the building system becomes too high, and the design team tries solutions until achieving the balance with this primary objective, artificial intelligence can help, from multiobjective optimization algorithms, in the search for this balance within the constraints and freedom given by the designer. The feedback of this process, more rapidly, can always be analysed and integrated into the final solution. Sometimes it opens doors to solutions beyond the designer imagination.

The most important focus is never to neglect the human needs factor as the ultimate purpose element for sustainability.

4 Design Stage—Informed Decisions

The sum of the overall environmental impact of the building up until the grave stage can be measured in CO_2 resulting in a chart like the one shown in Fig. 6. The embedded energy is the result of material selection and construction, while operational energy is the result of all the building's systems needs through its lifespan.

It is a complex task to find the optimal solution with the goal of carbon neutrality. Concepts such as nearly zero energy buildings (NZEB) point the way to the energy balance of construction and can contribute to lower the CO_2 emissions derived from the operational needs. Nonetheless the carbon footprint from materials is not accounted for in the previous concept.

Sustainability must be addressed as the overall emissions, bringing light to the reduction of material and energy environmental impact.

4.1 Energy

The building's energy dimension in the Industry 4.0 context gains crucial importance as an act of analysis and design. Energy is an element that is present in the whole life cycle of the building and of our built environment. It is present in various forms and represents a transversal element in decision-making to achieve sustainability. It is present in materials from their extraction, transport, transformation, construction or application, maintenance and demolition or disassembly. It is also present in the operation of the building throughout its life cycle of use (see Fig. 1).

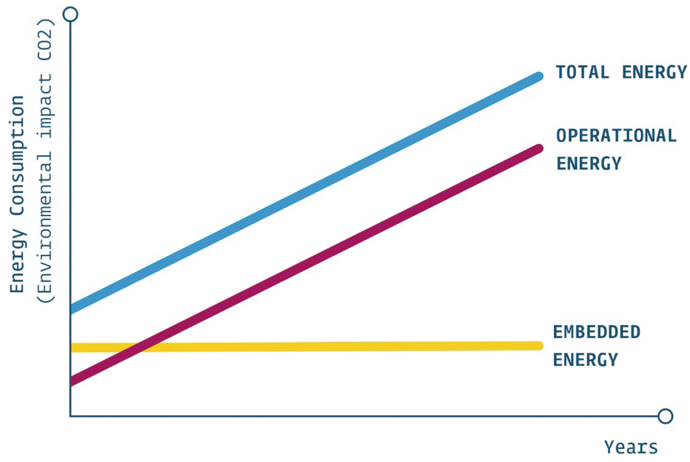

Fig. 6 Building lifespan environmental impact

In the case of energy embodied in materials, it represents one of the environmental impact factors that can be measured in units of emitted carbon dioxide up to the construction phase (PEC, see Fig. 1). In the case of the use of the BIM methodology, the model can de articulated with databases and the impact of materials on this dimension can be calculated. This analysis informs the designer of the environmental footprint that the building represents and which can be minimized or optimized. Its presence will be constant throughout the life cycle of the building. A simple material decision can incorporate a difference of environmental impact which, at the level of the construction scale, results in significant outcomes. Table 1 is based on the Bath University inventory database and clearly allows the comparison between the most common insulating materials used today in construction. It is possible to work with the amount of embodied carbon during the decision-making, since all have practically the same insulating coefficient. Polystyrene emits twenty times as much CO_2 as cork and five times the amount of rockwool, values that when multiplied by the surface area of application represent considerable differences.

The other energy dimension that can be controlled from the design phase onwards is the need for operational energy combined with the building systems. The balance with the factors discussed in the previous sections of efficiency and passive optimization of the building from local potential can minimize these energy requirements.

The BIM model allows the analysis and integration of these systems and what impact it has from the energy point of view. The building will have to be connected to the grid, but it will have the possibility to produce all or part of the energy needed. This solution can also be studied and worked on from the same model.

The European Union even requires the energy balance of buildings to be close to zero, i.e. the building must use the grid when it is unable to generate the energy it needs and return surplus energy to the grid when conditions so permit. Considering

Table 1 Building insulation materials comparative environmental impact

Material	PEC—MJ/Kg	EC $kgCO_2/kg$
Insulation		
Cork	4.0	0.19
Rockwool	16.8	1.05
EPS	88.6	2.5
XPS	88.6	2.5

the NZEB principle in this way the building will be neutral in relation to the energy dimension in the urban ecosystem. If this factor at the neighbourhood level is considered, more sustainable results can be achieved due to the compensation conditions that the quarters represent. If some areas may be limited by surrounding factors, or even solar orientation, others will be privileged and may compensate and balance the block instead of considering only the building object isolated or articulated solely with the grid. This solution can be more energy efficient from the point of view of ensuring that consumption is local, avoiding the injection into the grid with the losses that this may represent.

The use of parametric strategies in direct connection with the BIM model allows the best of both worlds, like the case presented in Fig. 7. The top half of the picture shows the visual programming definition with the inclusion of the geometry on the left, the solar analysis and volume selection components in the middle and the results on the left. The bottom half is the model of the whole urban block with the graph displaying the resulting amount of energy corresponding to the solar incidence in Kwh/m^2.

Once again, it is a bouncing between the scale of the building and the urban scale. On the energy dimension, this integration shows a great potential to make our cities, our habitats, more sustainable through the energy independence of their built elements and networks.

However, if energy sustainability effectively is the goal to achieve, one cannot simply concentrate on their production and consumption. The environmental impact that energy represents must be considered: the carbon dioxide emitted at its source. The true autonomy of buildings and cities cannot compromise the environment, i.e. it cannot come at such a high price as the CO_2 emitted. Digital models can inform us of this factor and enable the design team to provide cleaner, more efficient solutions and even compensation measures.

Looking only at the energy issue, the emissions inherent to its generation cannot compensated. Some answers to this question can be found in the material dimension. An ecosystemic and sustainable building is a system that self-regulates, balances and contributes to the regulation and balance of the surrounding systems.

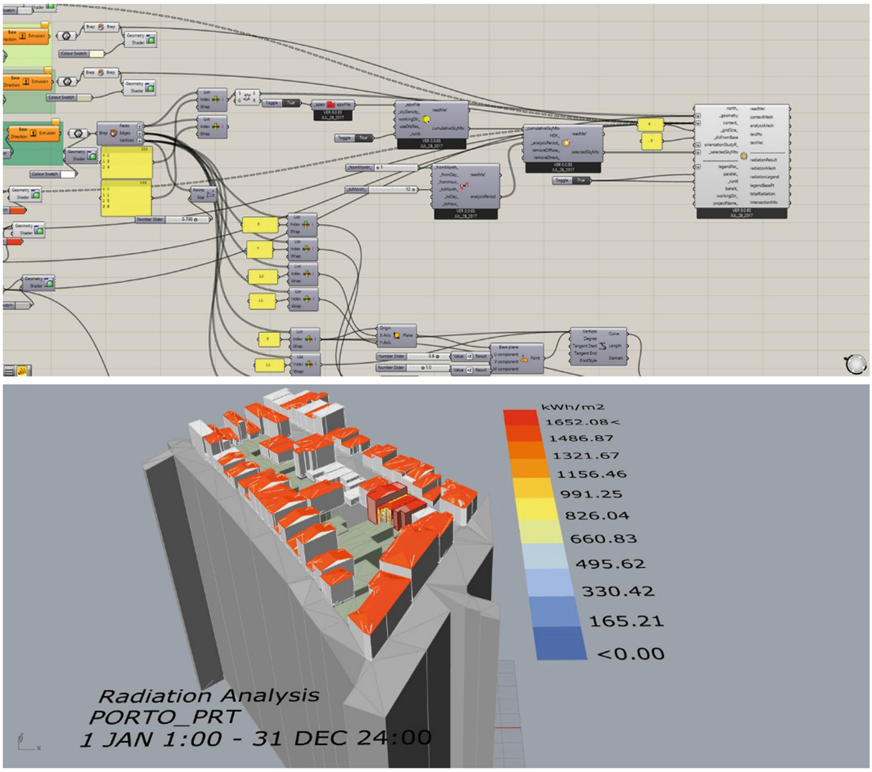

Fig. 7 Neighbourhood analysis

4.2 Materiality

The tangible physical component of the building comprises its materials. These are responsible for many factors that define the characteristics of the building. Their physics, their appearance, the way they interact directly and indirectly with the environment. They can be transparent or opaque, allow light and energy to enter in the form of radiation or prevent thermal flows between the inside and outside. They have texture, colour, shape, patterns and are on the whole what is called, once organized, the building. The same can be applied to the city. All materials contain a tangible component which is the matter that constitutes them, but also a less visible component which is the energy needed to obtain it in a way that it can be used for construction. From wood, earth, minerals to crude oil, they all go through a process of greater or lesser complexity undergoing transformations until they exist as a part of the built system.

This whole process requires more or less effort which translates into material and energy resources. In this way, in order to achieve material sustainability, origin of material resources and the amount of energy required for their processing will have

Solution A

Concrete and Brick

MATERIALS		
Name	**Embodied Carbon**	**Embodied Energy**
Brick		
	121 663,06 kgCO_2	1 520 788,29 MJ
Concrete		
	14 307,48 kgCO_2	98 948,91 MJ
Concrete - Structural		
	250 326,32 kgCO_2	2 427 406,78 MJ
Gravel		
	145,12 kgCO_2	2 408,94 MJ
Insulation - Plastic Hard		
	18 550,24 kgCO_2	474 061,80 MJ
Membrane - Rainproof		
	9 474,36 kgCO_2	235 942,18 MJ
Membrane - Vapor Barrier		
	4 158,69 kgCO_2	165 270,34 MJ
Plaster - Gypsum		
	5 085,80 kgCO_2	70 418,83 MJ
Plaster - Lime Sand		
	5 708,56 kgCO_2	37 624,60 MJ
Reinforced Concrete - Structural		
	102 162,16 kgCO_2	983 627,44 MJ
Timber - Floor		
	8 389,94 kgCO_2	186 414,08 MJ
TOTAL	**539 971,75 kgCO_2**	**6 202 912,18 MJ**

Solution B

Wood

MATERIALS		
Name	**Embodied Carbon**	**Embodied Energy**
Concrete		
	14 307,48 kgCO_2	98 948,91 MJ
Gravel		
	145,12 kgCO_2	2 408,94 MJ
Insulation - Mineral Hard		
	36 757,61 kgCO_2	472 279,61 MJ
Membrane - Rainproof		
	9 474,36 kgCO_2	235 942,18 MJ
Membrane - Vapor Barrier		
	4 158,69 kgCO_2	165 270,34 MJ
Plaster - Gypsum		
	5 085,80 kgCO_2	70 418,83 MJ
Plaster - Lime Sand		
	5 708,56 kgCO_2	37 624,60 MJ
Reinforced Concrete - Structural		
	51 081,08 kgCO_2	491 813,72 MJ
Timber - CLT		
	0,00 kgCO_2	409 746,53 MJ
Timber - Floor		
	8 389,94 kgCO_2	186 414,08 MJ
TOTAL	**135 108,65 kgCO_2**	**2 170 867,74 MJ**

Fig. 8 Material impact quantification

to be considered. The project team will have to be aware of all these factors in order to make balanced choices that can minimize the environmental impact of the building without compromising its performance. These options, once again, appear in the form of information that will have to be integrated, calculated and quantified in the BIM model.

The connection between the BIM software and material environmental impact databases is a crucial point of integration of this data into the model information.

From this point, the automatic extraction of quantification tables of the energy and CO_2 incorporated in the materials that combined result in the overall impact of the building (Fig. 8). The safest and most frequent data on material impact refers to the cradle to the gate phase, which corresponds to the primary energy consumption, the question of the application on site, i.e. the construction itself, being the target of a specific study for each case depending on the construction systems, the site and the availability of construction systems that need more or less operational energy.

A comparative chart can be created to confront material decisions since the early design stages, like the example presented in Fig. 8, where solution A uses a brick and concrete construction and solution B recurs to wood as a substitute.

The resulting emissions correspond to values four times higher in the case of solution A compared to solution B. The timber structural system was the CLT solution. The data used was handed by the manufacturer and corresponds to the certificates available under the EU normative. The balance between the CO_2 captured, the sustainable energy resources used in the production chain and the final product are less than 0, so this was the considered value even though the values corresponding to the embedded energy are positive.

The impact of materials extends throughout their useful lifetime in the form of building maintenance. Industry 4.0 integrates concerns about the environmental impact of building materials but at the same time the sustainability of resources.

This last issue allows us to point out two subjects that are becoming increasingly important in this dimension of the building, the first being material availability versus material depletion and the second being material reuse. It is not the intention to deplete our resources and it is our aim to have a circular economy.

The renewal of material resources and the reintroduction of materials into the production and construction chain corresponding to recycling, and the direct reuse of material resources, play a very important role in achieving the targets of Industry 4.0. Replacing non-renewable raw materials with raw materials that can grow in nature represents a paradigm shift that even allows the construction industry to deal with a new situation. Working with and dealing with inexhaustible material resources, which allows its availability to be controlled, will have a very positive impact on the production chain. The example of wood, a resource that is gaining considerable ground in the construction industry, for its performance and sustainability, not forgetting that in its growth phase it is a carbon sequestration system, represents the availability of viable sustainable materials. One may even consider that wood in its raw state is carbon negative. Its potential and processing capacity allow its use in previously unimaginable situations. The construction or assembly process itself is significantly less from the energy point of view and allows, if the design team takes this into account, its reuse after the disassembly of the building. Although this material has been used in construction for centuries, the ability of the industry to rearrange, transform and even reinvent it has allowed it to be used in situations that were not previously considered.

Another important element is the cataloguing of materials resulting from demolitions that can be reinserted directly into the design of new buildings. The reintroduction of building elements can be incorporated into BIM digital models from libraries that facilitate their incorporation into building elements and their quantification in maps and prescription and description books of building components.

The creation and existence of these databases represent an important key in the process of reusing materials. They represent the shortening of the material production chain and contribute to the material sustainability of the final result.

If considered for example the considerations of the design team in respect of the structural system to be used in the building, with the digital models, using the BIM methodology, we can take this option in an informed manner. The relationship between the calculation for each system and quantification of the environmental impact from the material used in each of the options is increasingly faster and clearer from the integration and articulation of the BIM software with programs for the calculation and quantification of energy and carbon incorporated. For example, the weighting between three structural systems can be considered: reinforced concrete, iron and wood. In the preliminary design phase, it is possible to calculate the performance of each of the systems versus the quantity of material and the impact factor of each of the solutions. The speed of construction can also be considered a determining factor in the economic aspect of the construction. This information allows us to substantiate the decision of the construction system from various parameters that allow us to achieve a greater degree of sustainability in the economic and environmental dimensions.

The same can be applied immediately and directly to the digital model for the thermal performance component. If thermal insulation solutions are considered based on polymers versus mineral wool versus cork, a simple substitution of the compounds of the constructive elements of the built environment, followed by a thermal analysis and quantification of the environmental impact from the energy and carbon incorporated, allows the project team to ponder in a similar way to that described in relation to the structural system.

In both cases, it is also possible to add the performance of the systems to fire and in the case of thermal insulation, to add the dimension of the acoustic behaviour.

The objectives of Industry 4.0 can only be truly achieved with informed decisions at the various dimensions of the building, being the construction materials the key component as they affect the initial impact and overall performance.

5 From Digital Model to Construction

One of the greatest challenges faced in the building process is the materialization of the project during the process of construction. All the complexity and logistics associated with this phase represent one of the key points in achieving the desired outcome.

Project communication, which can be poorly interpreted, the contingencies encountered on site, the uncertainties and inconsistencies of the project mean compromises and changes and adaptations during the construction process. These issues mean a compromise of the economic dimension due to the loss of financial resources, which are allocated to adaptation processes, the environmental dimension due to waste of material and the social dimension due to the wearing out that it causes to the teams involved.

Industry 4.0 aims to achieve goals that allow for a margin of error in all processes by ensuring that these dimensions of sustainability are not compromised. The BIM model allows the project team, at this point, to create a situation with a level of development (LOD) as close as possible to what will be built (as built). Working with real dimensions within a holistic approach to the building of the combination of all materials and systems allows the project team to predict and anticipate the good finish and resolution of intersections of all components of the building.

By transporting this digital model to the building site, the information that each one of the participants in the construction process needs to guarantee their work without compromising what is designed is guaranteed. The BIM model even allows the extraction of information for the entire logistical process of work preparation and the construction site in its various phases guaranteeing the efficiency necessary for the best final result.

Improved preparation by accessing the information directly from the model being able to predict the logistics and coordination and even optimize the placement of material during the whole process will result in less energy demands and less time. The model can also inform on material quantities and construction systems in real time as long as it is updated throughout the construction period, thus allowing the coordination to be more accurate with less margin for error and produce less waste. A greater organization and transparency in the processes guarantee a smoother construction with fewer errors and surprises. The whole team can have access to the BIM model and predict compatibility issues, timings, creating a smoother and more efficient working force. This will save time, material and money. All these aspects contribute highly to a more sustainable building with a smaller footprint.

The separation of information by each discipline, from the same base model, ensures that the different participants need less coordination between them, allowing a smoother and safer flow.

From the model and the separation of its parts and components, a direct communication with the material and component industries from the digital environment can be established, ensuring greater accuracy of the elements, to be applied on site with less material and energy waste.

Direct communication from digital files with the component manufacturing industries reduces the human error factor and interpretation, which guarantees a more reliable passage of information. Some brands and suppliers provide software programs and libraries, which can be integrated into the BIM model, with the necessary information for the project team to be informed of the capacities and limitations of its components. A direct relationship is established between the manufacturer and the designer from the digital environment which is then returned for production and on-site application.

Systems with greater customization capacity can also be integrated from the same means and processes and then separated from the BIM model and sent to production units. The minimization of errors and the systematization of processes allows greater economic, environmental and social sustainability.

5.1 The Prototyping Capability

This innovation is reflected in the form, materials, typologies and their articulation to achieve the whole that is the building. Its various parts and components require a design that often challenges the standards and availability of solutions on the market. These customized solutions are often associated with higher costs for the building, which is often a hindrance for the project team and results in a setback for the performance and final outcome of the building.

Solar shading solutions for example often need custom shapes and design solutions and can even be kinetic or moveable. The benefits for the building overall performance both for the user with more thermal and glare control, providing more comfort, as for the high energy operational loads needed without these elements through its lifespan, justifies the prototyping.

From the BIM model, one can communicate directly with processes that allow us to validate, materialize and test these solutions. The characteristics of these components can be analysed from the articulation with computer programs that test for example their resistance and thermal conductivity still during the design phase. These analyses allow us to move forward with greater guarantee and certainty for the final solution. The materialization of these solutions can even be obtained from the communication of the BIM model with 3D printers.

Since the material dimension is crucial to the sustainable solution, the different parts of the objects to be produced can be grouped and distributed in a layout that allows maximum use of the base material. All the components can be assembled easily through identification methods and direct interaction with the model through augmented reality. Sustainability is achieved by saving time and material as well as simplifying assembly processes.

From this process, prototypes can be created which allow their testing in a realistic environment and which can then be presented to the industry for manufacture. The potential to create innovative solutions and patents makes the advance of construction a safer and more guaranteed situation. Solid and feasible results can be achieved in a relatively economical and fast way.

This ability endows the construction industry with processes that allow its technological advance and the evolution of construction in an exponential manner. The easier it becomes to test new solutions and implement them in the construction industry, the more efficient and sustainable solutions become available.

5.2 Customized Prefabrication with Minimum Waste and High Execution Speed

Because of the advantages of prefabrication, such as control and precision, speed and minimal waste of materials and energy, prefabrication has never ceased to be a hypothesis to be considered for integration into the construction.

Digital models are a great potential for the prefabrication solution from modular systems, even if they are customized solutions.

Direct communication with industries and assembly systems is a very relevant step to achieve this ultimate goal.

The BIM model can be optimized to inform a production line. Within the parameters and technological limits, the customization of solutions is no longer a waste of time and material. The human factor is removed from a large part of the process, allowing greater autonomy in the transformation and assembly chain.

The controlled environment and the nature of factory assembly lines contribute to sustainable construction solutions by saving time and material, allowing an easier disassembly at the grave phase of the buildings life cycle, less intensive maintenance as it relies on dry construction methods and easier reuse of material. The advantage at the material level is broad, ranging from nearly zero waist (wood

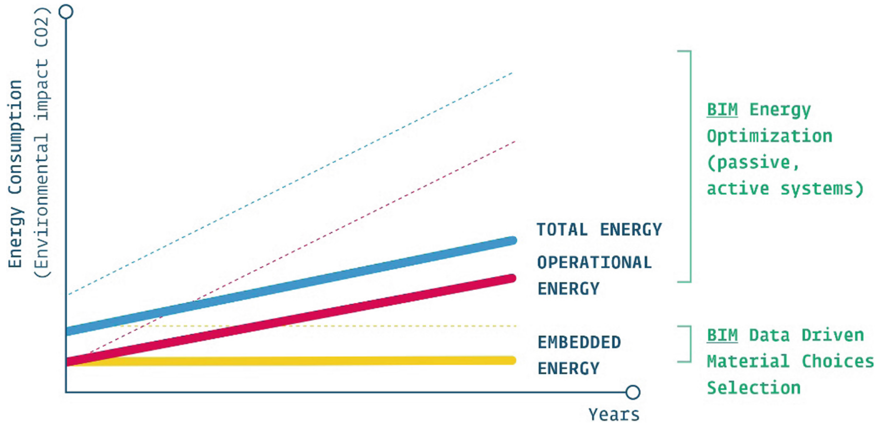

Fig. 9 Building lifespan environmental impact improvement

industry for example) to the reintroduction of the components directly in the construction process as the demolition consists of disassembly. The controlled fabrication processes also contribute to less energy needs as the production is fast and more efficient with less errors and loss.

6 Final Considerations

Achieving sustainability in construction through digitally informed decisions represents the Industry 4.0 goal and is now a challenge.

Figure 9 is derived from Fig. 6 and tries to explain the importance factor of informed design decisions and how the BIM methodology can be a crucial tool to achieve the pretended goals.

Lowering material and energy embedded carbon as well as shifting our habitat paradigm to one that embraces an ecosystemic role provides the guidelines for a more human-centred future.

Are buildings going to be able to "give back" energy? Or even purify the air that we breathe? Sustainability must incorporate all the technical solutions but also be the cradle of ideas for the future.

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